SPIE. OPTICS+ OPTOELECTRONICS

INTERNATIONAL YEAR OF LIGHT 2015

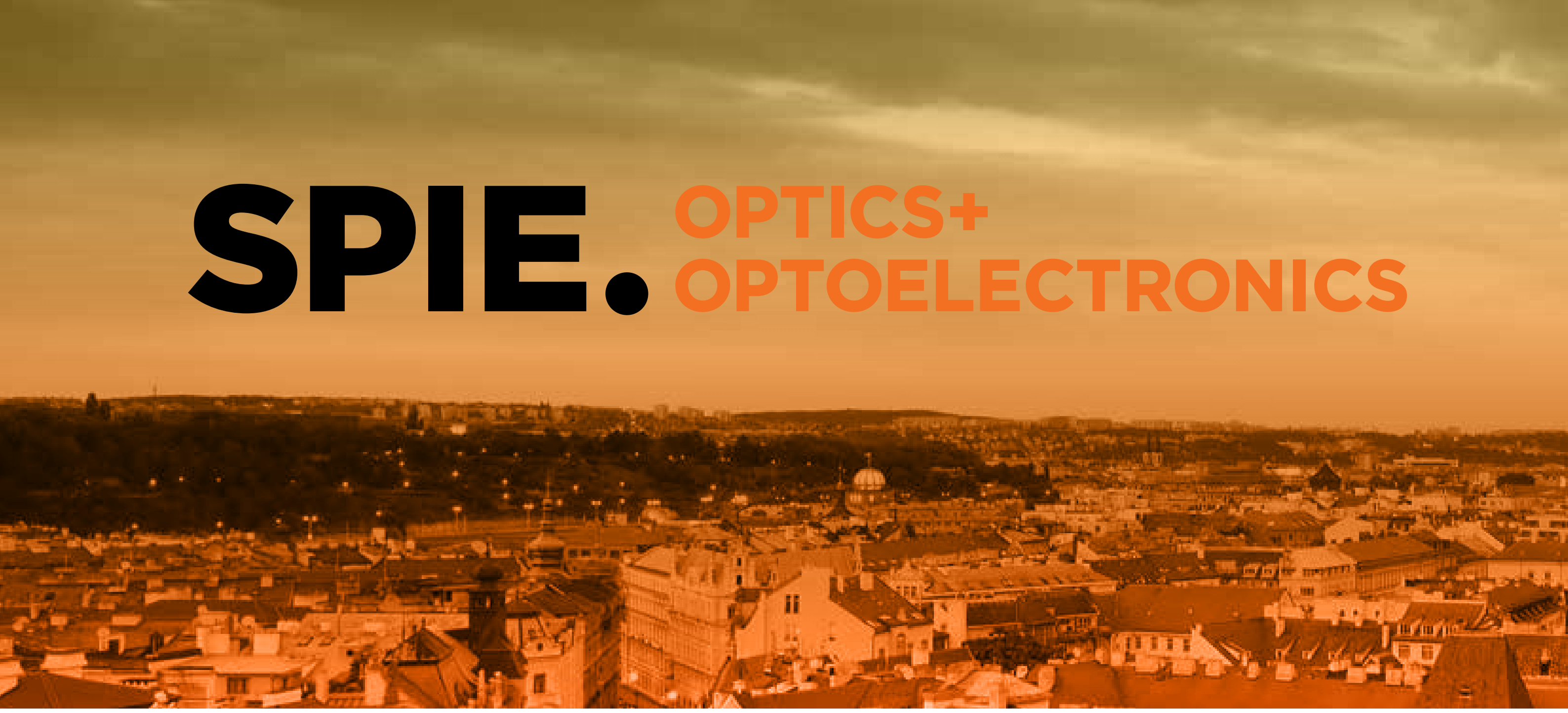
2015 TECHNICAL SUMMARIES.

WWW.SPIE.ORG/OO15

Conferences:
13–16 April 2015

Exhibition:
14–15 April 2015

Clarion Congress Hotel Prague
Prague, Czech Republic



SPIE. OPTICS+ OPTOELECTRONICS

2015 Symposium Chairs:

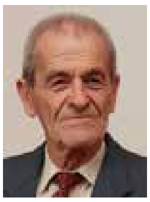
Jiri Homola
Institute of Photonics and Electronics of the ASCR, Czech Republic

Chris Edwards
Central Laser Facility, Science and Technology Facilities Council, United Kingdom

Mike Dunne
SLAC National Accelerator Lab./Linac Coherent Light Source, (USA)

Ivo Rendina
CNR/Istituto per la Microelettronica e Microsistemi, Italy

Honorary Chair:



Miroslav Miler
Institute of Photonics and Electronics of the ASCR, Czech Republic

SPIE would like to express its deepest appreciation to the symposium chairs, conference chairs, programme committees, session chairs, and authors who have so generously given their time and advice to make this symposium possible.

The symposium, like our other conferences and activities, would not be possible without the dedicated contribution of our participants and members. This programme is based on commitments received up to the time of publication and is subject to change without notice.

STEERING COMMITTEE

Miroslav Hrabovský, Univ. Palackého v Olomouci, Czech Republic

Miroslav Miler, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

Bedřich Rus, Institute of Physics, ASCR v.v.i., Czech Republic

Wolfgang Sandner, Max-Born-Institut (Germany) and Laserlab Europe

Pavel Tománek, Brno Univ. of Technology, Czech Republic

TECHNICAL COMMITTEE

Saša Bajt, Deutsches Elektronen-Synchrotron (Germany)

Francesco Baldini, Istituto di Fisica Applicata Nello Carrara (Italy)

Konrad Banaszek, Univ. of Warsaw (Poland)

Mario Bertolotti, Univ. degli Studi di Roma La Sapienza (Italy)

Sandra G. Biedron, Colorado State Univ. (USA)

Paul Bolton, Japan Atomic Energy Agency (Japan)

Jirí Ctyroký, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

Pavel Cheben, National Research Council Canada (Canada)

Mike Dunne, Lawrence Livermore National Lab. (USA)

Chris Edwards, Central Laser Facility, Science and Technology Facilities Council, (United Kingdom)

Eric Esarey, Lawrence Berkeley National Lab. (USA)

Antonio Fimia-Gil, Univ. Miguel Hernández de Elche (Spain)

Florian J. Grüner, Univ. Hamburg (Germany)

Joseph W. Haus, Univ. of Dayton (USA)

Joachim Hein, Friedrich-Schiller-Univ. Jena (Germany)

Jiri Homola, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

Miroslav Hrabovský, Univ. Palackého v Olomouci (Czech Republic)

IN MEMORIAM

Alan Michette

2009 Optics + Optoelectronics Symposium Chair

Member of the Symposium Steering Committee

2007–2013 Programme Committee Member of the EUV and X-ray Optics: Synergy between Laboratory and Space Conference

Contents

Conference 9502: Metamaterials

Wednesday - Thursday 15–16 April 2015

Part of Proceedings of SPIE Vol. 9502 Metamaterials X

9502-1, Session 1

Hyperbolic plasmonic metamaterials: engineering nonlinearities and spontaneous emission *(Invited Paper)*

Wayne Dickson, Greg A. Wurtz, Anatoly V. Zayats, King's College London (United Kingdom)

Hyperbolic metamaterials, in particular those based on aligned plasmonic nanorod arrays, provide wealth of exciting applications with unusual linear and nonlinear properties, polarization control, spontaneous emission control and many others. Providing 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 nanophotonic applications concentrating on spontaneous emission control and nonlinear optical properties design.

9502-2, Session 1

All-dielectric nanophotonics and metamaterials *(Invited Paper)*

Yuri S. Kivshar, The Australian National Univ. (Australia)

Recent developments in the physics of metamaterials stipulated a birth of a new branch of nanophotonics dealing with optically-induced magnetic response of high-refractive-index dielectric nanoparticles rather than metallic components. Unique advantages of dielectric nanostructures over metallic plasmonic structures are their low dissipative losses that provide new and competitive alternatives for nanoantennas and optical metamaterials. The talk will review this new, rapidly developing field of nanophotonics and discuss interesting physical effects ranging from "magnetic light" and engineering of magnetic response to magnetic Fano resonances and all-dielectric nonlinear metasurfaces.

9502-3, Session 1

PT-symmetry related functionalities in metamaterials and plasmonics structures *(Invited Paper)*

Anatole Lupu, Institut d'Électronique Fondamentale (France); Henri Benisty, Institut d'Optique Graduate School (France); Aloyse Degiron, Institut d'Électronique Fondamentale (France)

The advent of metamaterials during the past decade dawned the era of new artificial optical material with a range of intriguing and unusual properties not encountered in natural media. For the moment many of the applications related to metamaterials properties are limited to the microwave domain. One of the essential factors preventing their use in the optical domain is related to the metal absorption losses usually harmful in optics. A disruptive paradigm of the Parity-Time Symmetry (PT-symmetry) concept is that combination and modulation of gain and loss can be advantageously used for obtaining additional functionalities in metamaterial and plasmonic structures, beyond the simple idea of loss compensation.

These functionalities are associated with two inherent properties of PT-symmetric systems:

(i) abrupt evolution of propagation constants $\beta'+i\beta''$ in the vicinity of "exceptional points" which characterizes transition between purely real ($\beta''=0$) and complex ($\beta''\neq0$) eigenvalues. The variation of the effective detuning (i.e. the propagation eigenvalue difference) can be advantageously exploited for the implementation of a switching or modulation through the variation of the gain-loss level [1,2]. This avenue would largely mitigate the lack of electro-optical tunability in metamaterials and plasmonics.

Our theoretical findings also predict a remarkable feature, genuinely connected to the PT-symmetry. The gain level required for switching can be reduced by increasing the loss contribution, with a penalty that turns out to be quite affordable on the transmission level [1].

(ii) spatial non-reciprocity, different from that based on the Faraday magneto-optical effect Some essential properties of PT systems, such as spatial non-reciprocity, can be also obtained without any gain by using a totally passive approach, provided that an appropriate amount of losses is judiciously incorporated in the system [3]. This can further extend the passive type PT-symmetry approach from the optical to the THz or the microwave domain where the realization of gain media is less handled or more problematic.

The PT-symmetry paradigm could thus provide major boost to metamaterials and plasmonics and is expected to foster a new generation of tunable, reconfigurable and non-reciprocal devices.

References:

1. A. Lupu, H. Benisty, and A. Degiron, "Switching using PT symmetry in plasmonic systems: positive role of the losses," Opt. Express 21, 21651-21668 (2013).

2. H. Benisty, A. Degiron, A. Lupu, A. De Lustrac, S. Chénais, S. Forget, M. Besbes, G. Barbillon, A. Bruyant, S. Blaize, and G. Lérondel, "Implementation of PT symmetric devices using plasmonics: principle and applications," Opt. Express 19, 18004-18019 (2011).

3. A. Lupu, H. Benisty, and A. Degiron, "Using optical PT-symmetry for switching applications," Photonics Nanostruct. Fundam. Appl. 12, 305-311 (2014).

9502-4, Session 1

Radiation control of Babinet-inverted optical nanoantenna integrated with plasmonic waveguide

Yeonsang Park, Jineun Kim, Young-Geun Roh, Chang-Won Lee, Samsung Advanced Institute of Technology (Korea, Republic of)

Optical nanoantennae have already been established as useful devices in the control of electromagnetic waves, and are used for the detection and subsequent radiation of resonant light in a dipole-like pattern in the sub-wavelength scale. In addition, it has been shown that various Yagi-Uda antennae designs can be used to direct radiation in a highly confined spatial direction. Here, a Babinet-inverted optical nanoantenna integrated with a metal-insulator-metal (MIM) plasmonic waveguide is designed and fabricated. It is then demonstrated that this device can couple the plasmon guide mode to the resonant antenna feed directly, thus radiating incident radiation to free space in a dipole-like pattern. Using a 3D finite-different time-domain (FDTD) simulation, it is found that the coupling efficiency of the integrated nanoantenna is 19%. In addition, it is confirmed, both experimentally and through simulation, that an auxiliary groove structure added to the device allows for radiation 'steering' in a manner similar to that of the Yagi-Uda antenna. It is also determined that the groove can function as either a reflector or a detector, depending on the groove depth. Hence, it is apparent that the designed and fabricated Babinet-inverted optical nanoantenna integrated with a plasmonic waveguide has potential for use with various plasmonic devices, and will thus be an essential component in plasmonic integrated nanocircuits in the future.

9502-5, Session 2

Nanoplasmonics suggests the existence of a new fundamental scale *(Invited Paper)*

Alexander Figotin, Anatoli Babin, Univ. of California, Irvine (United States)

Plasmonics has grown in recent years into a well established area of research with a great potential. Our interest to this area roots in mechanisms involved in plasmonic resonance responses and implied pretty narrow spatial dimension range between 1nm and 25nm. We entertain an idea that the very existence of surface plasmons with sizes in that range suggest a possibility of a new fundamental scale such as the size 5nm of a free electron in our neoclassical theory. This theory features a new spatial scale - the size a_{e} of a free electron. This scale is special to our theory and does not appear in either classical EM theory nor in the quantum mechanics where electron is always a point-like object. Our current assessed value for this scale is a_{e}≈100a_{B} where a_{B} is the Bohr radius, and consequently a_{e}≈5 nm. In our theory any elementary charge is a distributed in space quantity. Its size is understood as the localization radius which can vary depending on the situation. For instance, if an electron is bound to a proton in the Hydrogen atom then its the size of is approximately 1 Bohr radius, that is a_{B}≈0.05 nm, and when the electron is free its size is a_{e}≈100a_{B}≈5 nm.

Interestingly, the upper bound 25 nm is the skin depth and that implies that a nanosystem of size smaller than 25nm is transparent to the external field. The same transparency should hold for a nanostructured surface indicating such a surface is better for nearly ideal field electron emission. There is an experimental evidence showing that the highest current densities were obtained for nanotips with sizes ?1nm yet another important fact supporting a possibility of a fundamental nonoscale.

9502-6, Session 2

Symmetry breaking in the second harmonic field of self assembled metallic nanostructures *(Invited Paper)*

Alessandro Belardini, Alessio Benedetti, Marco Centini, Eugenio Fazio, Mario Bertolotti, Concita Sibilia, Univ. degli Studi di Roma La Sapienza (Italy); Joseph W. Haus, Andrew M. Sarangan, Univ. of Dayton (United States)

Here we present both an overview of different nonlinear optical phenomena occurring in nanopatterned materials and new results on the symmetry induced second harmonic signal from metallic nanowires. A discussion about symmetry breaking in artificial chiral metamaterials is presented, while the experimental evidence was given by second order nonlinear optical measurements on different samples.

Chirality is the symmetry property of systems that cannot be superposed to their mirror image. Chiral systems are usually present in nature such as in proteins, sugars, DNA, so that chirality become a very much studied property due to its potential applications in different areas, as analytical chemistry, crystallography, molecular biology, and new chiral materials may find application for example in polarization control devices.

Recent nanofabrication techniques allow producing artificial chiral metamaterials. In particular, it is possible to prepare samples with so-called planar or two-dimensional chirality by using self-assembled techniques that allow low-cost and large-area sample production.

Recently very strong chiral behaviour has been demonstrated in metamaterial systems consisting of basic elements that by themselves are not chiral but chirality is drawn extrinsically from the mutual orientation of the wave propagation direction and the two dimensional metamaterial (extrinsic chirality) [1-8]. The arising of chiral behaviour due to proper alignment of achiral samples with respect the measurement setup was originally discovered and studied in the linear optics regime, but non-linear optical characterisation techniques in particular the second harmonic generation (SHG) show a dramatic enhance of the visibility of this phenomenon.

New SHG measurements on regular array of tilted nanowires (NWs) produced by grazing evaporating gold on a silicon substrate were presented and discussed.

The surface composed by tilted wires can induce an optical chiral response of the whole sample when the light impinges on the sample on an out-of-normal incidence angle. The measurements were performed by using circular polarised laser excitation at the wavelength of 800nm and by observing the second harmonic response at the wavelength of 400nm in different polarization states.

The second harmonic generation process, like other second order effects, is critical dependent on the symmetry of the involved parameters, so it results to be very sensitive to the symmetry breaking at the interfaces of investigated samples and particularly it results to be order of magnitude much sensitive about the chiral behavior of nanostructures with respect analogue linear optical measurements.

1. E. Plum, X.-X. Liu, V. A. Fedotov, Y. Chen, D. P. Tsai, and N. I. Zheludev, Phys. Rev, Lett. 102, 113902 (2009).

2. C. W. Bunn, Chemical Crystallography, Oxford Univ. Press, New York, (1945).

3. R. Williams, Phys. Rev. Lett. 21, 342 (1968).

4. J. B. Pendry, Science 306, 1353 (2004).

5. M. Decker, M. W. Klein, M. Wegener, S. Linden, Opt. Lett. 32, 856 (2007).

6. J. K. Gansel, M. Thiel, M. S. Rill, M. Decker, K. Bade, V.

7. Saile, G. von Freymann, S. Linden, and M. Wegener, Science 325, 1513 (2009).

8. M. Wegener and S. Linden, Physics 2, 3 (2009).

9502-7, Session 2

Resonant nanostructures in graphene for terahertz metamaterials *(Invited Paper)*

Philippe Tassin, Chalmers University (Sweden); Nian-Hai Shen, Thomas Koschny, Iowa State University (United States); Maria Kafesaki, University of Crete (Greece); Costas Soukoulis, Iowa State University (United States)

There has been quite some interest in graphene metamaterials and plasmonics in the past few years. In this contribution, we will review graphene metamaterials and plasmonics at terahertz frequencies. We will draw conclusions regarding the feasibility and advantages of graphene in plasmonic and metamaterial structures. We will highlight the ease of changing the Fermi level in graphene, which may lead to a new generation of tunable metamaterials and plasmonics technology. In particular, we take a look at split-ring resonator metamaterials made from graphene and we compare them to gold-based metamaterials. We find that graphene's huge reactive response derived from its large kinetic inductance allows for deeply subwavelength resonances, although its resonance strength is reduced due to higher dissipative loss damping and smaller dipole coupling. Nevertheless, tightly stacked graphene rings may provide for negative permeability and the electric dipole resonance of graphene meta-atoms turns out to be surprisingly strong. Based on these findings, we present a terahertz modulator based on a metamaterial with a multilayer stack of alternating patterned graphene sheets separated by dielectric spacers.

9502-8, Session 2

Bright solitons in optical cavities with internal resonances

Vladimír Kuzmiak, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Alex V. Yulin, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

In our paper we consider a system consisting of a planar Fabry-Perot resonator filled with metallic nanoparticles embedded into a nonlinear host medium. The nanoparticles act as dominating source of the

nonlinearity arising from the field enhancement in the vicinity of the metallic surfaces. Simultaneously, the dispersion occurs mainly due to the cavity mode. We show that the coupling between the cavity mode and localized surface plasmon excitations associated with nanoparticles results in a strong hybridization of the modes and in the splitting of the dispersion relation. We found that in the case of focusing nonlinearity there may exist solitons nestling on both the upper and the lower branches of the dispersion characteristics. It was discovered that the cavity supports complex solitary waves possessing two characteristic scales, so called dual-core solitons. To estimate the realistic parameters of the system we used an effective medium approach which describes the cavity in terms of the effective dielectric function. We demonstrated on the example of Ag coated nanoparticles that for sufficiently high pump power the active material compensates for the losses and thus sufficiently large enhancement of the surface plasmon field can be achieved in the vicinity of the nanoparticles. This opens a possibility to describe the dynamics of the dissipative solitons by using a relatively simple mathematical model.

9502-19, Session 2

Cherenkov radiation generated in transformation-optical metamaterials

Vincent Ginis, Jan Danckaert, Irina Veretennicoff, Vrije Universiteit Brussel (Belgium); Philippe Tassin, Chalmers Univiversity (Sweden)

In this contribution, we explore the generation of light in transformation-optical media. When charged particles move through a transformation-optical material with a speed larger than the phase velocity of light in the medium, Cherenkov light is emitted. We show that the emitted Cherenkov cone can be modified with longitudinal and transverse stretching of the coordinates. Transverse coordinates stretching alters only the dimensions of the cone, whereas longitudinal stretching also changes the apparent velocity of the charged particle. These results demonstrate that the geometric formalism of transformation optics can be used not only for the manipulation of light beam trajectories, but also for controlling the emission of light, here for describing the Cherenkov cone in an arbitrary anisotropic medium. Subsequently, we illustrate this point by designing a radiator for a ring imaging Cherenkov radiator. Cherenkov radiators are used to identify unknown elementary particles by determining their mass from the Cherenkov radiation cone that is emitted as they pass through the detector apparatus. However, at higher particle momentum, the angle of the Cherenkov cone saturates to a value independent of the mass of the generating particle, making it difficult to effectively distinguish between different particles. Using our transformation optics description, we show how the Cherenkov cone and the cut-off can be controlled to yield a radiator medium with enhanced sensitivity for particle identification at higher momentum.

9502-9, Session 3

Near-field thermal memory device *(Invited Paper)*

Min Qiu, Zhejiang Univ. (China); Sergey A. Dyakov, Jin Dai, Min Yan, KTH Royal Institute of Technology (Sweden)

Using a formalism combining the scattering-matrix and Greens functions methods, we investigate the thermodynamics of the radiative heat transfer in a multilayer nanostructure. We have shown that for a two-plate configuration of silicon carbide in vacuum, the intensity of radiative heat exchange is mainly determined by the vacuum distance between plates while the thickness of plates does not play a crucial role. This affects the characteristics of the time evolution of temperature of the sink plate. The threshold inter-plate distance which separates heating and cooling regimes for the sink plate is found.

Furthermore, we study the concept of a memory device based on the thermal bistability effect in the system of two closely separated parallel plates of SiO_2 and VO_2 which exchange heat by thermal radiation. As for the VO_2 plate, having metal-insulator transition at 340 K, it can have two thermo-dynamical steady-states. These two states can be switched by using an external laser impulse. It can be thus used as a thermal memory device.

9502-10, Session 3

Hot electron photoemission from plasmonic nanoantennas: photoelectric metamaterials and giant photogalvanic effect

Alexander V. Uskov, Igor E. Protsenko, P.N. Lebedev Physical Institute (Russian Federation) and Advanced Energy Technologies Ltd. (Russian Federation); Igor V. Smetanin, P.N. Lebedev Physical Institute (Russian Federation); Renat S. Ikhsanov, The State Atomic Energy Corp. ROSATOM (Russian Federation); Sergei V. Zhukovsky, DTU Fotonik (Denmark) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Andrey B. Evlyukhin, Laser Zentrum Hannover e.V. (Germany); Viktoriia E. Babicheva, Purdue Univ. (United States); Andrei V. Lavrinenko, DTU Fotonik (Denmark); Michael E. Guzhva, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation) and Saint-Petersburg State Polytechnical Univ. (Russian Federation)

Enhanced photoemission of hot electrons from plasmonic nanoantennas attracts much attention due to its potential application in Schottky barrier photodetectors in order to achieve higher device sensitivity and spectral selectivity [1]; in solar cells with the goal to enhance their photovoltaic efficiency by harvesting solar photons below the semiconductor bandgap energy; in (nano-)photoelectrochemistry and (nano-)photochemistry, including, in particular, water splitting; and in molecular electronics – i.e. in many areas of science and technology where the generation of hot photoelectrons and their subsequent utilization play a principal role. We are presenting the results of our studies of the electron photoemission from nanoantennas. We have investigated various photoemission mechanisms and have put forth the concept of photoelectric metamaterials, applying this concept to arrays of nanoparticles of various shapes. If the nanoparticle shape lacks the center of symmetry, we have shown that photoemission has a directional character (giant plasmonic photogalvanic effect).

In particular, we have compared volume and surface mechanisms of photoelectric effect from metal nanoparticles, and show that the surface mechanism can dominate in internal photoemission in the IR band, which is of interest for plasmonic photovoltaic applications [3]. For the first time, the role of so-called transition absorption in EP is highlighted.

Further, we have developed the theory of EP from plasmonic nanoparticles, and calculated the photoemission cross-section for nanoparticles of various shapes [4]. We have modeled EP in ensembles of nanoparticles with weak coupling to each other. Already in this case, we show that the quantum efficiency of photoemission can reach several tens of percents, depending on the Schottky barrier height. Moreover, we show that collective effects, resulting from coherent interaction of particles through near and far electromagnetic fields, can further enhance the coupling of nanoparticles to IR light increasing EP. Narrow Fano resonances in photocurrent spectrum can appear in this case. Fabrication of Schottky diodes with incorporated gold or silver nanoparticles and their characterization is in progress to support the model.

Finally, we have demonstrated that electrons emitted from plasmonic nanoantennas without central symmetry (such as nanocones) can have a dominant direction of their momentum, and this can constitute giant photogalvanic effect in plasmonic metamaterials, greatly exceeding the photogalvanic effect in naturally occurring non-centrosymmetric crystals [5].

[1] M.W. Knight, H. Sobhani, P. Nordlander and N.J. Halas, “Photodetection

with Active Optical Antennas", Science, 332, 702, (2011).

[2] T.P. White and K.R. Catchpole, "Plasmon-enhanced internal photoemission for photovoltaics: Theoretical efficiency limits", Appl. Phys. Lett., 101, 073905 (2012).

[3] A.V. Uskov, I.E. Protsenko, R.Sh. Ikhsanov, V.E. Babicheva, S. V. Zhukovsky, A. V. Lavrinenko, E. P. O'Reilly, and Hongxing Xu, "Internal photoemission from plasmonic nanoparticles: Comparison between surface and volume photoelectric effects", Nanoscale, 6, 4716 (2014).

[4] I.E. Protsenko and A.V. Uskov, "Photoemission from metal nanoparticles", Physics-Uspekhi, 55, Issue 5, pp. 508-518 (2012)

[5] S.V. Zhukovsky, V.E. Babicheva, A.B. Evlyukhin, I.E. Protsenko, A.V. Lavrinenko, and A.V. Uskov, "Giant Photogalvanic Effect in Metamaterials Containing Non-Centrosymmetric Plasmonic Nanoparticles", Phys. Rev. X, 4, 031038 (2014).

9502-11, Session 3

Enhancement of light absorption in polyazomethines due to plasmon excitation on randomly distributed metal nanoparticles

Piotr Wróbel, Tomasz J. Antosiewicz, Tomasz Stefaniuk, Arkadiusz Ciesielski, Univ. of Warsaw (Poland); Agnieszka Iwan, Institute of Electrical Engineering (Poland); Aleksandra A. Wronkowska, Andrzej Wronkowski, Univ. of Technology and Life Sciences in Bydgoszcz (Poland); Tomasz Szoplik, Univ. of Warsaw (Poland)

In photovoltaic solar cells, metal nanoparticles embedded in semiconductor layer allow for enhancement of solar-to-electric energy conversion efficiency due to enhanced light absorption via a prolonged optical path, enhanced electric fields near the metallic inclusions, direct injection of hot electrons, or local heating [1]. Here we pursue the first two avenues. In the first, light scattered at an angle beyond the critical angle for reflection is coupled into the semiconductor layer and confined within this planar waveguide up to possible exciton generation. In the second, light is trapped by the excitation of localized surface plasmons on metal nanoparticles leading to enhanced near-field plasmon-exciton coupling at the peak of the plasmon resonance. We report on results of a numerical experiment on light absorption in polymer/fullerene blends, using the 3D FDTD method, where exact optical parameters of the materials involved [2,3] are taken from our recent measurements [3,4]. In simulations we investigate light absorption in randomly distributed metal nanoparticles dispersed in polyazomethine-fullerene blends, which serve as active layers in bulk-heterojunction polymer solar cells. In the study Ag and Al nanoparticles of different diameters and fill factors are diffused in four air-stable aromatic polyazomethines with different chemical structures (abbreviated PAZ1-PAZ4) [2,3] mixed with phenyl-C61-butyric acid methyl ester (PCBM) and spin coated on a 100 nm thick Al layer deposited on a fused silica substrate. Optical constants of the active layer are taken from spectroscopic ellipsometry and reflectance measurements using a rotating analyzer ellipsometer (V-VASE, J.A. Woollam Co., Inc.) performed in the wavelength range from 225 nm to 1240 nm. The permittivities of Ag and Al particles of diameters from 20 to 60 nm are assumed to be equal to those measured on 100 to 200 nm thick metal films in [4] and [5,6], respectively.

Acknowledgements: the Polish NCBiR for financial support under the 2012-2015 project PBS1/A5/27/2012; TJA thanks the Polish FNP for the project HOMING PLUS/2013-7/1.

1. B. Iandolo, T. J. Antosiewicz, A. Hellman, I. Zoric, On the mechanism for nanoplasmonic enhancement of photon to electron conversion in nanoparticle sensitized hematite films, Phys. Chem. Chem. Phys. 15, 4947 (2013).

2. A. Iwan, B. Boharewicz, K. Parafiniuk, I. Tazbir, L. Gorecki, A. Sikora, M. Filapek, E. Schab-Balcerzak, New air-stable aromatic polyazomethines with triphenylamine orphenylenevinylene moieties towards photovoltaic application. Synt. Met. 195, 341 (2014).

3. A. Iwan, E. Schab-Balcerzak, K.P. Korona, S. Grankowska, M. Kami?ska. Investigation of optical and electrical properties of new aromatic polyazomethine with thiophene and cardo moieties toward application in organic solar cells. Synt. Met. 185-186, 17 (2013).

4. P. Wróbel, T. Stefaniuk, M. Trzcinski, A. A. Wronkowska, A. Wronkowski, T. Szoplik. Ge wetting layer increases ohmic plasmon losses in Ag film due to segregation. ACS Appl. Mater. Interfaces, submitted.

5. G. Schulz. The Optical Constants of Silver, Gold, Copper, and Aluminum. I. The Absorption Coefficient k. J. Opt. Soc. Am. 44, 357 (1954).

6. L. G. Schulz, F. R. Tangherlini. Optical Constants of Silver, Gold, Copper, and Aluminum. II. The Index of Refraction n. J. Opt. Soc. Am. 44, 362 (1954).

9502-12, Session 3

Optical activity of catalytic elements of hetero-metallic nanostructures

Tomasz J. Antosiewicz, Univ. of Warsaw (Poland) and Chalmers Univ. of Technology (Sweden); S. Peter Apell, Carl Wadell, Christoph Langhammer, Chalmers Univ. of Technology (Sweden)

Interaction of light with metals in the form of surface plasmons is used in a wide range of applications, such as refractive index sensing, plasmon-enhanced spectroscopy, or solar cells. In these applications usually the scattered component is maximized in order to achieve the best possible working parameters, while absorption is considered parasitic and sought to be minimized. However, recent work has shown that the absorption decay channel of surface plasmons has interesting and potentially significant uses. For example, it has been demonstrated [1-3] that localized surface plasmons can excite hot electrons in metals, which can later be utilized in a number of ways. One of the most exciting ones is plasmon-assisted photocatalysis [4]. Plasmon-assisted photocatalysis on noble metals has the benefit of providing hot electrons via the localized surface plasmon resonance (LSPR) and simultaneously the catalytically active site [1,4]. However, noble metals (narrowly defined as the classic plasmonic metals Au and Ag) are limited in terms of their catalytic properties and other materials, such as transition metals, offer a wider range of reactions catalyzed by their surfaces. Unfortunately, transition metals exhibit rather poor plasmonic properties (low field enhancements, low resonance quality factors) and additionally exhibit LSPRs only in the UV for nanometer-sized particles. This mismatch between the LSPR and the solar maximum implies low solar harvesting efficiencies.

Here, we describe recent results of optical properties of hetero-metallic nanostructures designed in such a way as to enhance light interaction with the catalytic elements of the nanostructures [5,6]. We excite a hybridized LSPR that matches the spectral characteristic of the light source and at the same time maximizes light absorption in the catalytic metal element of the nanostructure. We show that visible light absorption in the catalytic nanoparticles can be enhanced by more than one order of magnitude, depending on the metal [7]. This effect implies increased hot electron generation and, under appropriate conditions, can lead to enhanced catalytic rates.

[1] P. Christopher, H. Xin and S. Linic, Nature Chem. 3, 467–472 (2011).

[2] C. An, J. Wang, J. Liu, S. Wang and Q.-H. Zhang, RSC Adv. 4, 2409–2413 (2014).

[3] S. Mukherjee, F. Libisch, N. Large, O. Neumann, L. V. Brown, J. Cheng, J. B. Lassiter, E. A. Carter, P. Nordlander and N. J. Halas, Nano Lett. 13, 240–247 (2013).

[4] M. J. Kale, T. Avanesian and P. Christopher, ACS Catal. 4, 116–128 (2014).

[5] C. Wadell, T. J. Antosiewicz and C. Langhammer, Nano Lett. 12, 4784–4790 (2012).

[6] T. J. Antosiewicz, S. P. Apell, C. Wadell and C. Langhammer, J. Phys. Chem. C 116, 20522–20529 (2012).

[7] T. J. Antosiewicz and S. P. Apell, submitted.

9502-13, Session 3

Observation of terahertz radiation absorption in CdSe quantum dots

Petr Onushchenko, Institute of Silicate Chemistry (Russian Federation); Mikhail K. Khodzitsky, Alaudi K. Denisultanov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Aleksei Onushchenko, S.I. Vavilov State Optical Institute (Russian Federation)

Semiconductor quantum dots (QDs) have drawn much attention for past years due to their size-dependent properties. QDs have a variety of applications such as high-speed signal-processing filters, optical fiber amplifiers, low threshold lasers, solar cells, etc [?]. Special interest is connected with development of quantum dot and quantum well photodetectors in terahertz frequency range [2]. We have studied CdSe QDs in a silicate glass matrix using terahertz time-domain spectroscopy techniques. Similar work was conducted by Mandal and Chikan [2], they studied chemically charged n-type CdSe QDs of two different sizes (3.2 and 6.3 nm diameter) in a sample cells made of high resistivity silicon windows in the frequency range of 2.0-7.0 THz. Unlike [2], we used samples with QD radii ranging from 1,5 to 4,5 nm in the frequency range of 0.1-2.0 THz. QD sizes were determined using small-angle X-ray scattering technique (SAXS). We obtained data on dispersion of absorption coefficient, complex refractive index, complex permittivity and penetration depth. Distinct absorption features demonstrating high-energy shift with QD size decrease have been observed for the first time. This effect may be used for design of tunable metamaterial absorbers for terahertz frequency range.

[1]Wang, Feng, et al. “Exciton polarizability in semiconductor nanocrystals.” Nature materials 5.11 (2006): 861-864.

[2] Alihosseini, Faramarz, V. Ahmadi, and A. Mir. “Design and analysis of a terahertz resonant tunneling quantum ring in a well photodetector.” Telecommunications (IST), 2012 Sixth International Symposium on. IEEE, 2012.

[3] Mandal, Pankaj K., and Viktor Chikan. “Plasmon-phonon coupling in charged n-type CdSe quantum dots: A THz time-domain spectroscopic study.” Nano letters7.8 (2007): 2521-2528.

9502-34, Session 3

Plasmonic nano-antennas for spectral emissivity engineering

Mathilde Makhsiyan, ONERA (France) and Lab. de Photonique et de Nanostructures (France); Patrick Bouchon, Julien Jaeck, ONERA (France); Charlie Koechlin, ONERA - The French Aerospace Lab (France); Fabrice Pardo, Jean-Luc Pelouard, Lab. de Photonique et de Nanostructures (France); Riad Haidar, ONERA (France)

Metal-Insulator-Metal (MIM) structures are known to exhibit a spectrally tunable and total absorption ?(?) in subwavelength volumes. According to Kirchhoff’s law, an absorbing structure behaves like a grey body with an emissivity ?(?) = ?(?), that is expected to display the same properties than the absorption. We have experimentally demonstrated that MIM patches can be used to tailor the infrared emissivity of a metallic surface. By patterning only a few percent of a gold mirror with nanoantennas, we show that it is possible to spectrally and spatially engineer its emissivity and obtain any desired emissivity profile, according to the targeted application.

In clean room, we have fabricated several samples of MIM patches with various dimensions and combinations. From top to bottom, our MIM patches are composed of a patterned layer of gold rectangles, a continuous layer of silicon dioxide and a continuous layer of gold which thickness is bigger than the gold skin depth, so that the structures have no transmission and only work in reflection. The absorption spectra of the structures were first measured experimentally and show a fair agreement with the computations. Then, thanks to a bench composed of a Fourier transform infrared spectrometer (FTIR) and a high resolution infrared camera, we have heated the structures up to 373K and characterized, both spectrally and spatially their emissivity. We show that by controlling the dimensions of the patch, we control the emission wavelength in the whole [3 - 5.5] µm band. Moreover, the combination of several MIM patches in the same subwavelength period leads to the design of a wideband emitter and an emission over a 1.5 µm band has been observed. We also show the possibility to design two adjacent zones with completely different emissivities.

9502-31, Session PS

Effective medium approximation of anisotropic materials with radiative correction

Jaroslav Vlcek, Petr Otipka, Michal Lesnák, VŠB-Technical Univ. of Ostrava (Czech Republic); Ivo Vávra, Institute of Electrical Engineering (Slovakia)

A measurable magneto-optic (MO) activity of nanoparticles made out of noble metals is observed when the localized plasmon waves are excited in the presence of external magnetic field. The origin of MO effect consists in the resonance of permittivity that has been recently demonstrated [1]. We confirmed these observations for more general Au nanostructure on SiO_2/Si substrate theoretically and by experimental way [2]. The heterogeneous layer is formed as a field of randomly distributed spheroidal nanodots of various size (the diameter from 2 to 22 nm) having the same height 4 nm and parallel symmetry axis.

These properties enable to apply the Bragg-Pippard model of effective medium approximation (EMA), for which the size of dots (height, diameter) and fill-factor of nanodots were specified using the transmission electron microscopy (TEM) image processing. Actually, this model is extended about the magnetic dipole moments interaction simulated using discrete dipole approximation (DDA) via geometrical averaging.

Derived computational algorithm has been successfully validated by comparison with the results published elsewhere. It leads to better agreement with experimental data in the form of Kerr angles in polar configuration at visible spectral region 400 – 800 nm under perpendicular incidence. Obtained out-puts also illustrate the fact that extinction peak of plasmon excitation is located at the resonance wavelength of permittivity.

References

[1] B. Sepúlveda, J. B. González-Díaz, A. García-Martín, L. M. Lechuga, and G. Armelles, Phys. Rev. Lett. 104, 2010, 147401

[2] J. Vl?ek, P. Otipka, M. Les?ák, D. Hrabovsk?, I. Vávra, Adv. Sci. Eng. Med. 6, 2014, 1-6

9502-32, Session PS

Synthesis, shaping and functionalization of plasmonic gold octahedra

Cheng-An J. Lin, Chen-Li Yang, Hans B. Lao, Tzu-Yun Huang, Tzh-Yin Hou, Chung Yuan Christian Univ. (Taiwan)

Plasmonic gold nanomaterials with simple geometric shape such as rod, cubic and octahedra have gained many attentions in past decade. Localized surface plasmon resonances are collective electron charge oscillations in gold nanomaterials when excited by light. Spherical nanoparticles offer isotropic oscillating properties which contribute to the intense absorption in the wavelength of 530 nm. Gold nanorods show additional longitudinal absorption which can be tune from red to near infrared. The shape properties of Gold octahedra seem to lie in between nanoparticles and nanorods. Precise control of nanomaterials growth and shaping is important to fit the need of industrialization. In this work, we present a facile method to fabricate the uniform gold octahedra by using microwave. The controllable synthesis of uniform-sized gold octahedron was influenced by the reaction rates. By adding acid or base, different

sizes of gold octahedron can be produced. Gold precursor ($HAuCl_4$) can further etch the edge of gold octahedral, resulting in high-quality of gold nanoparticles. Hyperspectral dark-field microscopy was also used for monitoring dynamic of the Rayleigh scattering. In conclusion, a simple microwave process of anisotropic growth followed by isotropic etching could be used to design spherical crystals of other metals, which might find uses as building blocks for optical sensors and circuits, probes for biomedical applications.

9502-33, Session PS

Localized surface plasmon resonance with Pt nanorings fabricated by nanosphere lithography

Hee Woong Shin, Tae Hoon Park, Min Ju Kim, Tae-Ho Lee, Byeong Ryong Lee, Kyeong Heon Kim, Tae Geun Kim, Korea Univ. (Korea, Republic of)

Plasmonic metallic nanostructures are characterized by their strong interaction with resonant photons through an excitation of surface plasmon resonance (SPR). This optical phenomenon is associated with collective oscillation of conduction electrons excited by the electromagnetic field of light. The resonant wavelength and SPR intensity depend not only on the nature of the metal, but also on the size and shape of metallic nanostructure. The unique capacity of plasmonic nanostructures to concentrate electromagnetic fields, scatter electromagnetic radiation, convert the energy or scatter electromagnetic radiation of photons makes them suitable for various applications. Plasmonic metals have been used in single-molecule spectroscopy, molecular sensing and detection in biological systems, surface-enhanced Raman spectroscopy, solar cells, and many others.

Recently, split-ring resonators and the related closed ring resonators are also of great interest to the nanophotonics community because of their strong electric and magnetic resonances. Referred to as 'nanorings' in the literature, it is possible to form SPRs active at infrared, visible and even ultraviolet wavelengths. Now, a challenge faced by many research groups is the routine, fast, accurate and scalable fabrication of appropriately shaped nanostructures. Usually, electron beam and focused ion beam lithography methods are used for research purposes. However, these one-by-one lithographic approaches are slow and difficult to make nanostructures on a large scale.

In this paper, to solve these problems, we employed a nanosphere (NS) lithography method to form uniform two dimensional (2D) hexagonal array of nanorings. The NS lithography has advantages such as low cost and easy fabrication of periodic nanostructures on a large scale. We fabricated a Pt nanoring arrays using SiO_2 nanospheres of 150 nm, 300 nm and 500 nm diameters and analyzed SPR properties by measuring absorption resonance.

We measured top-view field emission scanning electron microscope (FESEM) and atomic force microscopy (AFM) images of the Pt nanoring arrays. These pictures showed uniform 2D arrays of 200 nm, 350 nm, and 550 nm diameter nanorings. We also measured absorption resonance of the Pt nanoring arrays using a UV-Visible spectrometer. The plasmon resonances at 255 nm, 287 nm, and 309 nm wavelength were respectively measured in the 200 nm, 350 nm, and 550 nm Pt nanoring arrays. We found that the plasmon resonance peak shifts to the red spectral region as the pattern size increases. Also, the plasmon peak of the 200 nm diameter Pt nanoring array is more intense and sharper, as compared with that of the 550 nm diameter Pt nanoring array. We analyzed the experimental results using a finite-difference time-domain (FDTD) simulation method, which matched well each other. In this study, we proved that SPRs of the nanoring structure depend on the nanoring pattern size in both experiment and simulation. We believe that the SPR peaks of the Pt nanoring array can be selectively controlled by changing the size in the deep-ultraviolet region.

9502-35, Session PS

Polarization-Dependent Transmission through Microwave Metamaterials

James Vedral, Univ. of Colorado at Colorado Springs (United States); David Lee, The MITRE Corp. (United States); Randall Musselman, U.S. Air Force Academy (United States); Anatoliy O. Pinchuk, Univ. of Colorado at Colorado Springs (United States)

Low loss negative index metamaterials were designed and tested for X, Ku and K microwave frequencies bands. S-shape split ring resonators (SSRR) unit cell was used to design a slab of negative index metamaterial in the X, Ku and K frequencies bands. HFSS microwave simulations were compared with experimentally tested S-parameters and showed a good match between the theory and experiment. Negative index of refraction of the metamaterial slab was proved by angle and frequency dependent measurements in an anechoic chamber with a prism cut from the metamaterial slab. Negative index of refraction was retrieved from the angle and frequency dependence of the transmitted intensity of the microwave beam through the metamaterial prism. Near-field electromagnetic intensity measurements were conducted by using a Kapton film and an infrared camera. The near-field distribution of the electromagnetic intensity were compared with theoretical simulations by using HFSS simulations.

9502-36, Session PS

Three-dimensional frequency selective surfaces consisting of double circular ring elements

Baris Akaoglu, Fulya Bagci, Sultan Can, Asim E. Yilmaz, Ankara Üniv. (Turkey)

In this study, three dimensional frequency selective surfaces consisting of copper double circular ring elements are presented by full-wave simulations and microwave-domain experiments for the frequency range between 0.5 – 8.5 GHz. The ring elements are made cylindrical by giving different magnitudes of height in the perpendicular direction. The analyses are performed for the double concentric cylinders for which the inner or outer cylinders are shifted in position or changed in height. The investigated three dimensional frequency selective surfaces are fabricated, fixed inside a holder and placed between the transmitter and receiver horn antennas facing each other in order to measure the scattering parameters. The heights of the cylinders are shown to have an important effect on the transmission characteristics. As the height of the cylinders increase, an additional inductance along the cylinders starts to affect resonance characteristics of the structure. The frequency of the first resonance increases, whereas that of the second resonance decreases when the heights of the double concentric cylinders are both increased by the same amount. This behavior is also observed when the inner (outer) cylinder is moved along the perpendicular direction with respect to the outer (inner) cylinder and also when the height of the outer cylinder is increased. In contrast, when the height of the inner cylinder is increased, both of the resonances shift to the lower frequencies. However, it should be noted that this opposite behavior is relatively weak and can be benefited for finer tunings of the resonance frequencies. The results obtained from the commercial full-wave simulation programs, CST Microwave Studio and Ansoft HFSS, are elucidated by calculating the equivalent inductances and capacitances, and are confirmed by microwave experiments. By tuning the investigated geometric parameters of the dual band frequency selective surface structure, the resonance frequencies may be tuned close to each other so that the structure can be used in applications which require two resonances in close range. In addition, this work demonstrates that extra degrees of freedom provided by three dimensional designs compared to two dimensional designs allow more flexibility in controlling the resonance characteristics.

9502-37, Session PS

2D acoustic metamaterial for potential invisible using

Zhenda Lei, Rongxiang Cao, Hongwei Sun, Jiangsu Automation Research Institute (China)

This paper presents modeling, and analysis techniques of acoustic metamaterial panel for Invisible Using. For a unit cell of an infinite metamaterial panel, governing equations are derived using the extended Hamilton principle. 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, we explain the negative effective mass and negative effective stiffness in acoustic metamaterials.

9502-38, Session PS

Plasmonic organic thin-film solar cell: light trapping by using conformal vs. non-conformal relief gratings

Hamid Keshmiri, Jakub Dostálek, AIT Austrian Institute of Technology GmbH (Austria)

We witnessed increasing interest in organic polymer-based photovoltaics (OPV) over the last years. In order to enhance the power conversion efficiency (PCE) of this type of solar cells that is limited by the weak absorption probability in inherently thin absorber layers, light harvesting schemes including those relying on plasmonics were proposed. This paper investigates the using of periodically corrugated metallic electrode that is in contact with the absorber layer for broadband light management in OPV. It utilizes diffraction coupling to surface plasmon polaritons which exhibit penetration depth excellent matching the thickness of typically used absorber (about 100 nm). As a realistic model system, we chose the (probably) mostly used bulk hetero-junction active layer composed of P3HT (poly (3-hexylthiophene)):PCBM (phenyl-C61-butyric acid methyl ester). Such absorber is implemented to a solar cell by using a stack of layers including aluminum metallic electrode, LiF, P3HT:PCBM, PEDOT (poly (3, 4-ethylenedioxythiophene)):PSS (poly (styrenesulfonate)), and ITO electrode on the top. The finite difference time domain simulations (FDTD) are employed for a design of diffractive corrugation of Al electrode in order to confine incident light energy in the absorber layer. We will discuss the spectral dependence of the enhancement of absorption probability of light with AM-1.5G spectrum in the absorber and the competing dissipation in other layers, particularly Al. The results show, that the using of Al which is typically assumed to be plasmonically less favorable metal than Au and Ag allows enhancing the absorption probability in the active layer by more than 20 % by using a relief diffraction grating with optimized period and modulation depth. Such performance is comparable to Ag. Let us note that this absorption enhancement translates to external quantum yield improvement which is directly proportional to the maximum shortcut current and PCE of a solar cell. Extensions of this concept for further increasing the PCE above this value will be addressed.

9502-40, Session PS

Photonic structures in photoresist and PDMS surface patterned by AFM lithography

Jana Durynová, Sofia Slabeyciusova, Dusan Pudis, Daniel Jandura, Univ. of Zilina (Slovakia)

Atomic force microscopy (AFM) is a very high-resolution type of scanning probe microscopy employed in many configurations, with demonstrated resolution on the order of nanometer. One of the configurations of AFM - scanning probe AFM lithography is a very useful and promising technique for nanofabricating and nanostructuring of soft surfaces. The surface nanostructuring is a nanowriting process based on mechanical scratching of the sample surface with a cold cantilever tip and enables vector or raster writing mode.

Polydimethylsiloxane (PDMS) is very promising material in soft lithography achieving resolution in nanometer scale. PMDS shows unique elastic and optical properties, what favors PDMS for tunable optic devices and direct integration with optical fibers and planar technologies on the chip. We use PDMS for fabrication of optical devices for applications in waveguide optics. Its surface patterning by two-dimensional (2D) photonic structures leads to unique optical properties of devices as Y-splitters and waveguides with surface relief Bragg gratings. In this study, we want to use AFM lithography for fabrication of new types of optical components and sensors based on PDMS and other polymers.

This contribution demonstrates surface modification of thin photoresist layers and PDMS membranes with spatial resolution better than 20 nm. We provided few different 2D arrangements of surface patterning with aim to prepare 2D photonic structures with various symmetries in the thin S1828 photoresist layer using AFM lithography. Consequently, we used the imprinting technique for transferring the photoresist pattern to the PDMS membrane surface. Also we use other technique of the direct AFM scratching of PDMS membrane surface at nanometer scale. Finally, prepared 2D photonic structures in photoresist and PDMS surfaces are characterized by AFM.

9502-41, Session PS

Optimization of dipole structures for detection of organic compounds

Henrique Vilhena, Scott McMeekin, A. Sheila Holmes-Smith, Glasgow Caledonian Univ. (United Kingdom); Nigel P. Johnson, Univ. of Glasgow (United Kingdom)

Metamaterials are being increasingly used as highly sensitive detection devices. The orderly design of these structures and the ability to effect changes in response through small changes in the geometry of their constituent elements allow for the enhancement of known analysis techniques such as Infrared or Raman spectroscopy. High electromagnetic fields have been shown to occur in features such as small gaps and sharp tips and these so called "hot-spots" are the main focus of recent work in Surface Enhanced Raman Spectroscopy (SERS). The main difficulties lie in the small dimensions (≤100 nm) necessary to attain a significant response at the typical Raman pump wavelengths. Also the small size of the gaps is a challenge when it comes to prevent "bridging" between the structures during the fabrication process. In this work we show, through simulations, that carefully controlling the length of dipolar structures as well as the gap between these dipoles a resonant response can be achieved close to the pump Raman wavelengths. Also, we see that changing the asymmetry of the dipole pair shifts the resonant peaks first to longer then to shorter wavelengths. Experimental results supporting the simulations will also be presented. We believe these structures to be suitable for the SERS detection of very small amounts of organic compounds.

9502-42, Session PS

Design of plasmonic circular grating with broadband absorption enhancements

Nan-Fu Chiu, Cheng-Du Yang, Yi-Lun Kao, Chih-Jen Cheng, National Taiwan Normal Univ. (Taiwan)

Surface plasmon polaritons (SPPs) are surface electromagnetic waves that propagate in the metal/dielectric interface. This phenomenon gives rise to a spectrally selective optical response of polarized electron resonance and a local field enhancement in the nano-optics. Plasmonic technology is very popular in recent years, the development of technology is quite extensive, often discussed in the various scientific reports, such as: light emitter diode, solar cells, laser, biosensor, nano-antennas, plasmonic emitter, etc.

We have investigated the effect of concentric circles geometry on the performance of focusing plasmonic circular grating (PCG)-coupled surface-omnidirectional absorption. We wish to highlight the essential characteristics of plasmonic circular grating nanostructure to assist researchers in developing and advancing suitable organic solar cells (OSC) for unique applications. Exactly how plasmonic enhancement and the absorption characteristics of the organic materials (P3HT:PCBM and PEDOT:PSS) interact with each other is also examined. We present experimental and numerical studies of broadband absorption enhancement in plasmonic circular metallic gratings.

In our experiments, we prepared a two dimensional (2D) pattern of nanostructure by an electron beam lithography system (ELS-7500EX, ELIONIX Co.). The high-resolution positive electron-beam photoresist (PR), PMMA 950, was first spin coated on the ITO-glass substrate to form a resist layer having thickness of 100 nm, and then pre-baked at 180? for 2 minutes. After exposing to the electron beam of 50 KV, nonstructural gratings having elongated two-dimensional ring pattern structure of 250 nm line width and 500 nm pitch width. The exposure was carried out for 2 ?sec and gradual increase 0.05 ?sec by a pixel map of 60000?60000 dots to give a total exposure area of 1.2?1.2 mm2.

We show that the grating can result in broadband optical absorption enhancement, due to the excitation of plasmonic mode and broadband anti-reflection effect. The overall optical absorption can be greatly enhanced up to ~2 times as compared to a planar ITO glass without grating.

9502-43, Session PS

Surface doping by functional graphene nanostructures for organic solar cell applications

Chi-Chu Chen, Nan-Fu Chiu, National Taiwan Normal Univ. (Taiwan)

Present graphene with Particular structure and excellent material properties is widely used in solar cells?

It application of best performance is organic thin film solar cells.

High electron mobility of graphene to transport electrons and holes for solar cells is very helpful.

Optical properties of conjugated polymer is new types of solution treatment for semiconductor materials.

The performance and lifetime of conjugated polymer based organic thin film solar cell are critically dependent of the interfacial properties of electrode/polymer contacts.

The conjugated polymer as active components in organic thin film solar cell have received great attention due to their light weight and ease of processing.

Because organic materials has The mass production , relatively inexpensive, soft, and other properties, that make it's has development In the future.

However, this research is still in its early stages and the photoelectric conversion efficiency of the device is not very good.

Different layers of organic commounds to doping different charcterist of graphene film, thermal annealing process after to go on study of device.

We tested 2 groups conjugated polymer layers of different graphene doping and only conjugated polymer layers:

(1), only PEDOT:PSS solution

(2). PEDOT:PSS doping graphene

(3), PEDOT:PSS doping rGO/Au

First, we spin coated 2 groups conjugated polymer of different graphene and only conjugated polymer to Compare (3000rpm 30s) on an ITO substrate.

Then the samples were annealed on hot plate at 200 C for 30 min.

Second ,P3HT:PCBM (weight ratio 1:0.8) dissolved in chlorobenzene was spin-coated onto the conjugated polymer layer.

Then the substrates were annealed at 130 C for 10 min in a N2 filled glovebox.

Third, Ca film (thickness, 100 nm) and Al film (thickness, 100 nm) were evaporated on the substrate to complete most step.

Finally,all devices were encapsulated by glass caps and epoxy in the glovebox for Measurement.

The J V characteristics of the thin film solar cells were measured by using a Keithley 2400 source meter under illumination of 100 mW/cm2(solar simulator equipped with an AM 1.5 filter).

The transmittance spectra of thin film solar cells were measured by using a UV - vis spectrophotometer.

We hope the Ideal PCE of complete experiments can more than 2%.

9502-44, Session PS

Double-layer gold gratings as refractive index sensors and unidirectional couplers for surface plasmon polariton

Chongjun Jin, Sun Yat-Sen Univ (China)

We propose theoretically and demonstrate experimentally a dislocated double-layer metal grating structure, which operates as a unidirectional coupler capable of launching surface plasmon polaritons (SPPs) in a desired direction under normal illumination [1]. The structure consists of a slanted dielectric grating sandwiched between two gold gratings. The upper gold grating has a non-zero lateral relative displacement with respect to the lower one. Numerical simulations show that a grating structure with 7 periods can convert 49% of normally incident light into surface plasmons, with a contrast ratio of 78 between the powers of the surface plasmons launched in two opposite directions. We explain the unidirectional coupling phenomenon by the dislocation-induced interference of the diffracted waves from the upper and lower gold gratings. Furthermore, we developed a simple and cost-effective technique to fabricate the structure via tilted two-beam interference lithography and subsequent shadow deposition of gold. The experimental results demonstrate a coupling efficiency of 36% and a contrast ratio of 43. The relatively simple periodic nature of our structure lends itself to large-scale low-cost fabrication and simple theoretical analysis. Also, unlike the previous unidirectional couplers based on aperiodic structures, the design parameters of our unidirectional coupler can be determined analytically. Therefore, this structure can be an important component for surface-plasmon-based nanophotonic circuits, by providing an efficient interface between free-space and surface plasmon waves.

Furthermore, we also show that the dislocated double-layer gold gratings can be served as refractive index sensor based on the interaction of the Wood's anomaly and localized surface plasmon resonance at normal incidence[2]. The Figure of merit can be over 32 which is among the highest under the detection scheme of normal incidence.

References:

1. Tian-ran Liu, Yang Shen, Wonseok Shin, Qiangzhong Zhu, Shanhui Fan, Chongjun Jin, Dislocated double-layer metal gratings: an efficient unidirectional coupler, Nano Letters 14, 3848(2014) .

2. Yang Shen, Tianran Liu, Qiangzhong Zhu, Jianfang Wang, Chongjun Jin, Dislocated double-layered metal gratings: refractive index sensors with ultrahigh figure of merit, To be submitted.

9502-45, Session PS

Thermal self-oscillations in radiative heat exchange

Sergey A. Dyakov, Jin Dai, Min Yan, Min Qiu, KTH Royal Institute of Technology (Sweden)

We report the effect of relaxation-type self-induced temperature oscillations in the system of two parallel plates of SiO2 and VO2 which exchange heat by thermal radiation in vacuum. The non-linear feedback in the self-oscillating system is provided by metal-insulator transition in VO2. Using the method of fluctuational electrodynamics we show that under the action of an external laser of a constant power, the temperature of VO2 plate oscillates around its phase transition value. The period and amplitude of oscillations depend on the geometry of the structure. We found that at 500 nm vacuum gap separating bulk SiO2 plate and 50nm thick VO2 plate, the period of self-oscillations is 2 s and the amplitude is 4K which is determined by phase switching at threshold temperatures of phase transition.

9502-14, Session 4

Computing the optical properties of plasmonic nanostructures *(Invited Paper)*

Kurt Busch, Humboldt-Univ. zu Berlin (Germany)

An overview of recent progress in applying the Discontinuous-Galerkin Time-Domain (DGTD) Finite-Element approach to plasmonic nanostructures is provided. This includes analyses of modified light-matter interaction in the vicinity of plasmonic nanostructures and of the coupling between nanostructures, the response of nanostructures to complex excitations such as electron beams and focused optical beams, and the development of advanced material models for describing magneto-optical as well as nonlocal and nonlinear properties of plasmonic nanostructures.

Nano-Plasmonic systems provide novel ways for controlling the propagation of light and light-matter interaction via large electric field enhancements, strong field gradients, and coupling to non-radiative plasmon modes. In view of the increasing sophistication of fabrication and spectroscopic characterization, quantitative computational approaches face challenges several challenges. These include the development of material models that describe the magneto-optic, the nonlocal and/or the nonlinear optical response of metallic nanostructures. The above features also lead to strong coupling phenomena between nanostructures and strongly modified light-matter interaction and, therefore, to further challenges for quantitative computations.

The recently developed Discontinuous-Galerkin Time-Domain (DGTD) finite-element method [1,2] represents a computational tool that allows to address many of these challenges. Its adaptive meshing together with high-order spatial and temporal discretization facilitate efficient quantitative analyses of nano-plasmonic systems in terms of transmission/reflection, scattering/absorption cross sections, and/or enhancement [3,4,5]. This basic method has recently been extended to the determination of electron-energy loss spectra [6] which allows the investigation of the coupling between plasmonic nanostructures mediated by the near field [7]. Similarly, advanced materials models for use within the DGTD method have been developed that allow addressing magneto-optical properties of transition metals [8] and nonlinear effects from plasmonic nanostructures such as second harmonic generation [9]. Finally, the DGTD method has been adapted to treat light-matter interaction in complex nano-photonic systems, specifically the investigation of modified lifetimes [10].

REFERENCES

1. J. S. Hesthaven and T. Warburton, J. Comput. Phys. 181, 186 (2002)
2. K. Busch et al., Laser Photonics Rev. 5, 773 (2011)
3. J. Niegemann et al., Photon. Nanostruct. 7, 2 (2009)
4. K. Stannigel et al., Optics Express 17, 14934 (2009)
5. M. Husnik et al., Phys. Rev. Lett. 109, 233902 (2012)
6. C. Matyssek et al., Photon. Nanostruct. 9, 367 (2011)
7. F. von Cube et al., Nano Lett. 13, 703 (2013)
8. C. Wolff et al., Optics Express 21. 12022 (2013)
9. A. Hille et al., submitted (2014)
10. A.W. Schell et al., Nano Lett. 14, 2623 (2014)

9502-15, Session 4

Perfectly matched layer based multilayer absorbers

Tomasz Stefaniuk, Univ. of Warsaw (Poland); Anna Pastuszczak, Univ of Warsaw (Poland); Marcin Stolarek, Piotr Wróbel, Tomasz J. Antosiewicz, Bartosz Wieciech, Rafal Kotynski, Univ. of Warsaw (Poland)

An approximate representation of the Perfectly Matched Layer with a spatially varied absorption strength is introduced and analysed. The PML is realised as a stack of uniform and isotropic metamaterial layers with permittivieties and permeabilities given from the effective medium theory. This approximate representation of PML is based on the effective medium theory and we call it an effective medium PML (EM-PML). We compare the reflection properties of the layered absorbers to that of a PML material and demonstrate that after neglecting gain and magnetic properties, the absorber remains functional. This opens a route to create electromagnetic absorbers related to PML and as an example we introduce a layered absorber for the wavelength of 8um. Broadband layered absorbers evaporated with PVD are also analysed in the same context.

9502-17, Session 4

Revealing plasmonic interaction in both isolated and arrayed dimers and trimers with analytical and numerical approaches

Jan Fiala, Ivan Richter, Czech Technical Univ. in Prague (Czech Republic)

In our previous work, we have developed an analytical model based on a coupled dipole approximation (CDA) technique which reveals interplay between a nanoparticle plasmon resonance and a lattice resonance. It was also shown that under a proper periodicity of a nanoparticle lattice, such arrays can exhibit narrow resonances with asymmetric Fano-type line shapes in the spectra. It has been further known that optical properties of a nanoparticle (NP) array depend on the orientation of the NP and their shape, with respect to impinging light, as well as on their arrangement / assembly. In order to describe the physics of plasmon bounded modes in assemblies of spherical particles, such as dimers and trimers, a simple analytical model of two (dimer) and three (trimer) coupled nanoparticles, based on a near-field dipolar radiating pattern under the classical dipolar limit, was derived as a sub-part of our previously developed CDA model. The model capability consists in a resonance shift predictions according to the particle arrangement with respect to the particles size and their mutual distance. The resonance spectral position predictions are compared with full numerical calculations and, therefore, the limits of classical dipolar restrictions are tested. Additionally, now beyond the classical dipolar limit, such assemblies are arranged in a periodic array while keeping its periodicity much larger than the particle size and their mutual distance. Having rigorously calculated the scattering cross-section of a corresponding oligomer in one period, the cross-section is inserted to the CDA model in order to study the role of lattice and surface plasmon resonances. This work was financially supported by the Czech Science Foundation (project P205/12/G118).

9502-18, Session 5

Reduction of plasmon losses in thin Ag silver films *(Invited Paper)*

Tomasz Stefaniuk, Univ. of Warsaw (Poland)

The appearance of innovative devices in the course of development of plasmonics is possible under the condition that suface plasmon-polariton wave attenuation due to scattering on interface irregularities and due to ohmic losses is reduced. Ohmic losses of free electrons in metal depend on oscillation frequency and temperature and thus cannot be completely eliminated. Wetting films of such elements as Ge, Ni, Ti and Cu are used to smoothen the surface of silver nanolayer and thus limit scattering losses. Due to high adhesion to both a substrate and the deposited silver these wetting films prevent the island growth. Diffusion coefficients in neighbouring volumes of pure metals are small, thus it is possible to preserve sharp interfaces in metal1/metal2 layered structures. The situation is very different with Ge which transports along high-diffusivity paths and segregates into Ag grain boundaries and free surfaces [1]. At temperatures lower than 0.6 TAg melting grain-boundary Ge segregation in polycrystalline silver is of decisive importance. The silver grain size and film smoothness can be optimized through the choice of wetting layer [2] and film deposition at the optimum temperature and rate [3]. To reduce scattering from grain boundaries and voids Ar+ ion beam polishing of the Ag films surface can be used [4]. It is also possible to pull the optical hybrid plasmon-polariton mode from a metallic half-space into the nanometer dielectric gap due to close proximity of the dielectric core [5].

1. P. Wróbel, T. Stefaniuk, M. Trzcinski, A. A. Wronkowska, A. Wronkowski, T. Szoplik. Ge wetting layer increases ohmic plasmon losses in Ag film due to segregation. ACS Appl. Mater. Interfaces, submitted.

2. T. Stefaniuk, P. Wróbel, P. Trautman, T. Szoplik. Ultrasmooth metal nanolayers for plasmonic applications: surface roughness and specific resistivity. Appl. Opt. 53, B237-B241 (2014).

3. T. Stefaniuk, P. Wróbel, E. Górecka, T. Szoplik. Optimum temperature for deposition of ultrasmooth silver nanolayers, Nanoscale Res. Lett. 9, 153-161 (2014).

4. Ee Jin Teo, Noriaki Toyoda, Chengyuan Yang, Bing Wang, Nan Zhang, A. A. Bettiol, Jing Hua Teng. Sub-30 nm thick plasmonic films and structures with ultralow loss. Nanoscale 6, 3243-9 (2014).

5. R. F. Oulton, V. J. Sorger, D. A. Genov, D. F. P. Pile, X. Zhang. A hybrid plasmonic waveguide for subwavelength confinement and long-range propagation. Nat. Photonics 2, 496 – 500 (2008).

9502-20, Session 5

Dielectric negative index metamaterial as plasmonics devices

Vito Mocella, Istituto per la Microelettronica e Microsistemi (Italy); Silvia Romano, Consiglio Nazionale delle Ricerche (Italy)

Electromagnetic surface waves, analogous to the classic surface plasmons can be supported to any interface, providing that the effective permittivities have an opposite sign. Indeed is well known that also purely dielectric metamaterials can exhibit a negative effective permittivity, close to specifically designed resonances. The ellipsometric analysis prove that a negative index PhC behave as an isotropic Lorentz resonator with negative index permeability [1]. The Lorentz model of the negative index PhC in the Fresnel reflection fully describes also the anomalous propagation of the guided mode resonant radiation in a negative index metamaterial [2]. Furthermore, the experimental detection by means of an evanescent-coupling method with a high refractive index prism and the experimental reconstruction of their dispersion curve in (?,k) space confirm the close relationship with surface plasmons localized at metal-dielectric interface [3]. However we show that, using dielectric metamaterials, can be achieved a very strong field enhancement larger than existing nano-antennas with a very small gap. Finally we will discuss how new strategies in light control at the nanoscale can be open using purely dielectric plasmonics devices.

References

[1] P. Dardano, M. Gagliardi, I. Rendina, S. Cabrini, and V. Mocella, “Ellipsometric determination of permittivity in a negative index photonic crystal metamaterial,” Light Sci Appl, vol. 1, no. 12, pp. e42–, Dec. 2012.

[2] S. Romano, S. Cabrini, I. Rendina, and V. Mocella, “Guided resonance in negative index photonic crystals: a new approach,” Light Sci Appl, vol. 3, p. e120, 2014.

[3] E. De Tommasi, A. Chiara De Luca, S. Cabrini, I. Rendina, S. Romano, and V. Mocella, “Plasmon-like surface states in negative refractive index photonic crystals,” Applied Physics Letters, vol. 102, no. 8, p. 081113, 2013.

9502-21, Session 5

Infrared Imaging of Microwave Negative Index Metamaterials

David A. Lee, New Mexico Institute of Mining and Technology (United States); James Vedral, David Smith, Univ. of Colorado at Colorado Springs (United States); Randall L. Musselman, U.S. Air Force Academy (United States); Anatoliy O. Pinchuk, Univ. of Colorado at Colorado Springs (United States)

Low loss negative index metamaterials were designed and tested for X, Ku and K microwave frequencies bands. S-shape split ring resonators (SSRR) unit cell was used to design a slab of negative index metamaterial in the X, Ku and K frequencies bands. HFSS microwave simulations were compared with experimentally tested S-parameters and showed a good match between the theory and experiment. Negative index of refraction of the metamaterial slab was proved by angle and frequency dependent measurements in an anechoic chamber with a prism cut from the metamaterial slab. Negative index of refraction was retrieved from the angle and frequency dependence of the transmitted intensity of the microwave beam through the metamaterial prism. Near-field electromagnetic intensity measurements were conducted by using a Kapton film and an infrared camera. The near-field distribution of the electromagnetic intensity were compared with theoretical simulations by using HFSS simulations.

9502-39, Session 5

The effect of geometry on the quality factor of resonance peak from asymmetric nano-antennas at mid-infrared wavelengths

Ifeoma G. Mbomson, Univ. of Glasgow (United Kingdom); Scott McMeekin, Glasgow Caledonian Univ. (United Kingdom); Richard De La Rue, Nigel P. Johnson, Univ. of Glasgow (United Kingdom)

The effects of two different type of asymmetric nano-antenna that produce distinct resonance peaks were experimentally and numerically observed. At mid-infrared wavelengths broad resonances based upon various metamaterials structures have been previously reported. Here we show that introducing a cross on vertical asymmetric dipole nano-antenna can produce narrower resonance peaks than the dipole alone. Our approach to investigating different asymmetric nano-antenna structures yielded quality factor values more than twice the existing values reported within this region of the electromagnetic spectrum.

9502-22, Session 6

Magnetoplasmonics for active control of light *(Invited Paper)*

Alexandre Dmitriev, Chalmers Univ. of Technology (Sweden)

The combination of magnetism and plasmonics developed into a new burgeoning field - magnetoplasmonics, where the control of non-reciprocity in light’s interaction with a magnetized media is targeted for various applications. The two aspects of magnetoplasmonics are the magnetic control of the plasmonic (optical) response of the system and, vice versa, the influence of optical excitation on spin-orbit coupling. In these both aspects magnetoplasmoincs offers a versatile toolbox in the quest for actively tunable optical and magnetic metasurfaces.

Sub-wavelength manipulation of light on plasmonic metasurfaces using an external stimulus is one of the most intriguing approaches in active nanophotonics. We implement a magnetoplasmonic bottom-up metasurfaces that consist of nanoantennas with combined nanoplasmonic (Au) and ferromagnetic elements (Fe). The former provides efficiently optically excited plasmon modes that strongly polarize the reflected / transmitted light, whereas the latter, when properly positioned at the hot spot of nanoplasmon antenna, gives a ‘handle’ to magnetically modulate the resulting optical response. The ease of manipulation of the magnetization of the nanosized ferromagnetic element by a weak external magnetic field allows us to modulate the phase and amplitude of light at subwavelength scale.

Magneto-optical materials are often used to control the polarization state of propagating waves in integrated optical circuits. The polarization

control originates from the off-diagonal terms in the dielectric tensor of these materials that can be activated by applying the external magnetic field. This gives rise to tunable non-reciprocal propagation of the light waves, an effect that has been intensively studied in optical insulators. Similar effects can be obtained in magnetoplasmonic nanoantennas, where the localized near-field enhancement at the plasmon resonance amplifies the intrinsic magneto-optical effects and allows tailoring it by means of the nanoantenna design. Here we derive simple design rules that can be exploited for the fully 3D magnetoplasmonic nanoantennas in order to obtain magnetically tunable active metasurfaces.

We investigated the magnetoplasmonic response of 2D and 3D nanoantennas in all three conventional magneto-optic Kerr effect (MOKE) geometries, namely longitudinal (L), polar (P) and transversal (T). In the former two cases, the polarization state of a transmitted wave is changed, resulting in a Kerr rotation and ellipticity, while in the latter case the intensity is modulated by the applied magnetic field. The magnitude of the modulation and its sign can be predicted based on the polarizabilities of the nanostructures along their different symmetry axes [1].

[1] V. Bonanni et al., Nano Lett., 11, 5333 (2011); N. Maccaferri et al., Opt. Express 21, 9875 (2013); N. Maccaferri et al., Phys. Rev. Lett. 111, 167401 (2013).

9502-23, Session 6

Meta-atoms with tunable response
(Invited Paper)

Carsten Rockstuhl, Stefan Nanz, Rasoul Alaee, Ivan Fernandez-Corbaton, Karlsruher Institut für Technologie (Germany); Mohammad Albooyeh, Aalto Univ. (Finland); Constantin R. Simovski, Aalto Univ. School of Electrical Engineering (Finland)

The macroscopic properties of metamaterials are in most cases dominated by its mesoscopic constituents. Those unit-cells, which are called meta-atoms, may scatter the light in an unprecedented manner. These scattering properties can be tuned upon request by choosing a suitable geometry and material composition for the meta-atom. To discuss the scattering properties on physical grounds and to tailor them, an abstract notion is required. This notion is provided by the multipole expansion of the scattered electromagnetic field or the current distribution. Using the language of multipoles, we can perceive various meta-atoms that may serve different purposes. In this contribution, we provide an overview of our latest contributions in this context and discuss specifically the physics and the applications of two different classes of meta-atoms.

The first class concerns a meta-atom made of strongly coupled asymmetric plasmonic nanopatches. The meta-atom exhibits a resonant magneto-electric response, in addition to the ordinary electric and magnetic response. With that it behaves similarly as the so-called omega-particle, but with the advantage that the magneto-electric response can be independently tuned and modified with respect to the electric response. While tuning the interference among the different scattering contributions, we show that with a metasurface made from such meta-atoms we can widely control reflection and transmission coefficients and can address regimes such as that of a strongly asymmetric reflectance or perfect absorption.

The second class concerns a meta-atom that is optically active in general scattering directions. This necessarily requires that the meta-atom obeys two requirements. It must lack spatial inversion symmetries and, a condition usually not considered, the structure shall preserve the helicity of light, i.e. there must be a vanishing coupling between the states of opposite polarization handedness among incident and scattered plane waves. We show that both conditions are met if multiple dual scatterers, i.e. scatterers where electrical and magnetic dipolar polarizabilities are exactly the same, are arranged in space to form a chiral meta-atom. A structural implementation is discussed that is based on spheres made from a high permittivity material. This opens entirely new perspectives for dielectric-only meta-atoms and metamaterials.

9502-24, Session 6

Light polarization control on the femtosecond scale using gyrotropic photonic crystals

Margarita I. Sharipova, Alexander I. Musorin, Tatyana V. Dolgova, Andrey A. Fedyanin, Lomonosov Moscow State Univ. (Russian Federation)

Control of polarization is an easy way to govern the light. However, in case of ultrashort pulses with duration of around 100 fs the task might be hard. Our work is aimed at the dynamic changing of laser pulse polarization by using gyrotropic nanostructures, such as photonic crystals. There were two types of photonic crystals in the study: magnetic photonic crystal and liquid photonic crystals. The main difference between these two cases are the non-reciprocity of the Faraday rotation while optical activity is reciprocal effect.

Faraday effect is a phenomenon which is widely used for light propagation control. The effect is non-reciprocal and proportional to the thickness of a magnetic medium. Thus, it can be enhanced in multilayered structures with artificial dispersion and group delay, such as magnetophotonic crystals. The front part of short femtosecond laser pulse interacts with the structure less effectively than the rear one. Until now, however, ultrafast dynamics of magneto-optical effects has always been connected with magnetization changes. The goal of the work is investigating of Faraday effect evolution caused by the pulse interference in the layered structure, consisting of a magnetic defect layer between two Bragg mirrors. For comparison, we investigate cholesteric liquid crystals which naturally organize itself in a polarization-sensitive photonic crystal, which is transparent to the one circular polarization and has a stop-zone for the other.

To detect the time dependence of laser-pulse polarization autocorrelation technique has been used, combined with polarization-sensitive elements. Using photoelastic modulator allowed to measure both rotation and ellipticity of polarization.

To conclude, ultrafast Faraday rotation dynamics in a magnetophotonic microcavity and a cholesteric liquid crystal has been detected. The character of dynamics strongly depends on spectral position of the pulse central wavelength due to the strong artificial dispersion of the medium. The time derivative of Faraday rotation is the greatest when pulse central wavelength is at the center of microcavity mode and much less when it's in the vicinity of this point.

9502-25, Session 7

Theoretical analysis of optical and plasmonic metasurfaces

Roman Antos, Charles Univ. in Prague (Czech Republic) and Nagaoka Univ. of Technology (Japan); Martin Veis, Lukas Beran, Charles Univ. in Prague (Czech Republic); Jan Mistrik, Miroslav Vlcek, Univ. Pardubice (Czech Republic); Takayuki Ishibashi, Nagaoka Univ. of Technology (Japan)

Rigorous coupled wave analysis (RCWA) is employed to analyze the optical response of metasurfaces based on various types of lateral texturing, either relief texturing made by holographic lithography or thin film rectangular patterning including a multilayer system. The analysis is carried out within optical spectroscopy based on spectroscopic ellipsometry (SE) and within direct imaging techniques such as scanning near-field optical microscopy (SNOM) or holographic imaging.

Ellipsometric measurements carried out in a wide spectral range and various incidence geometries are used to determine the geometric properties of periodic textures with high accuracy and to analyze plasmonic processes occurring in metallic metasurfaces or optical processes occurring in common metasurfaces. Indirect observation of the surface plasmon propagation via ellipsometric spectra is demonstrated. As an example, a sine-like relief profile created on an Ni plane surface, with a developed native NiO overlayer, is investigated in detail. The

SE spectra in a near-IR/visible/near-UV spectral range are analyzed to determine the depth and precise shape of the NiO/Ni relief. The precise knowledge of the relief structure and the Ni dielectric function (determined on a reference thin film sample) is then used to simulate the propagation of surface plasmon polaritons along the metasurface at the SE-measurement configuration and to identify this process with the measured spectra.

Various optical responses of shallow rectangular patterns are analyzed by RCWA and an approximate local modes method (LMM) based on scalar diffraction theory. The diffraction effects of the edges of nanoscale elements patterned within the metasurfaces are investigated with respect to the spectroscopic response and optical imaging techniques. A numerical modification of the LMM is proposed, taking into account the edges' diffraction effects. The modified LMM is then used to demonstrate how the edge effects affect the ellipsometric spectra, the SNOM images, and the holographic images reconstructed via an aperiodic metasurface working as a spatial light modulator. The analysis can help in evaluating the quality of the lithographic techniques, as well as evaluating the performance and reliability of the imaging techniques.

9502-26, Session 7

Circular dichroism from Fano resonances in planar chiral oligomers

Ben Hopkins, The Australian National Univ. (Australia); Alexander N. Poddubny, Ioffe Physical-Technical Institute (Russian Federation) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Andrey E. Miroshnichenko, The Australian National Univ. (Australia); Yuri S. Kivshar, The Australian National Univ. (Australia) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

The widespread desire for strong optical interactions with chiral molecules and proteins, present in many forms of biologicals and pharmaceuticals, has made nanoscale chiral materials and particles some of most imminently-applicable devices in the broader field of optical metamaterials. At the same time, a growing proportion of metamaterial research is being devoted toward planar metasurfaces; ultrathin functional surfaces that are unhindered by the structural design constraints of three-dimensional fabrication. Here we present a new form of circular dichroism produced by switching the loss mechanism of a plasmonic nanostructure between far-field radiation and near-field material absorption [1], both of which are key (and easily observable) forms of chiral response. Importantly, this effect is able to exist in planar systems and we show it is fundamentally linked to eigenmode interference, a consequence of which is that it can be amplified through Fano resonances. Using this amplification, the relative magnitude of such circular dichroism in absorption and scattering cross sections can easily be an order of magnitude larger than that typically reported in the extinction of three-dimensional nanostructures. This work subsequently projects both metasurfaces and planar nanoparticle arrays into the realm of chiral optical devices, opening up a host of new opportunities to capitalize on their resonant mechanics and implicit design freedom.

In addition to this, we introduce a new approach to circular dichroism starting from a ground-up description of its origin in terms of the current distributions that are induced by circularly polarized plane waves. This analysis allows us to deduce why the circular dichroism can exist in planar structures in spite of reciprocity. We also focus on rotationally-symmetric structures because they exhibit absorption and scattering invariance to linear polarisations [2], a practicality which is necessary to ensure the independence of a cross-section to the phase between LCP and RCP light. Under this constraint we are able to analytically derive design principles to intuitively identify and demonstrate that planar chiral oligomers are an obvious nanoparticle geometry that exhibits Fano-resonance-enhanced circular dichroism.

References

[1] B. Hopkins, A. N. Poddubny, A. E. Miroshnichenko, Y. S. Kivshar, "Circular dichroism induced by Fano resonances in planar chiral oligomers" unpublished , 2014 (arXiv:1412.1120)

[2] B. Hopkins, W. Liu, A. E. Miroshnichenko, Y. S. Kivshar, "Optically isotropic responses induced by discrete rotational symmetry of nanoparticle clusters" Nanoscale 5: 6395-6403, 2013.

9502-27, Session 7

Asymmetric and symmetric coupling of surface-plasmon-polariton waves to planar interfaces with periodically patterned slanted columnar thin films of silver

Jhuma Dutta, Subramaniam Anantha Ramakrishna, Indian Institute of Technology Kanpur (India); Akhlesh Lakhtakia, The Pennsylvania State Univ. (United States)

Manipulation of surface plasmon polariton (SPP) coupling efficiencies and propagation direction is an important reqirement for developing modern plasmonic technology. In a symmetric plasmonic grating structure, normally incident light equally couples to SPPs propagating in two opposite directions, which leads to poor SPP coupling in both the directions. This symmetric SPP coupling might be a limiting factor for developing efficient functionalized plasmonic circuits. One of the ways to increase this coupling is by phase-shifting the incidence light to one direction which helps to provide efficient coupling in one direction. Several methods are proposed in the literature for the unidirectional SPP coupling to facilitate the control of surface plasmon waves [1,2].

We have demonstrated in our earlier work that dielectric slanted gratings, fabricated by the oblique angle deposition (OAD), function as blazed diffraction gratings [3]. In case of a metallic slanted grating, this blazing action provides for directional coupling to SPP waves. We used here a simple and cost-effective OAD to deposit silver columnar thin films (CTFs) on one dimensional dielectric grating patterned by laser interference lithography on photoresist on a fused silica substrate. Angle resolved transmittance measurements are performed in the 500-900 nm wavelength range on the fabricated structure. From these, the SPP dispersions as a function of polarization and azimuthal angle between the incidence and the morphologically significant plane were obtained. In the morphologically significant plane (xz plane), the broken structural symmetry possesses different coupling for SPP, when light incident on it from one side of the substrate normal than from the other side. Asymmetric diffraction due to the blazing effect and asymmetric angular scattering due to the slant angle of the silver nanorod arrays give rise to asymmetric coupling of incidence light to SPP waves. Electromagnetic 3D photonic simulations confirm that by varying the geometrical parameters such as slant angle, aspect ratio and porosity of the diffractive structure, one can control the transmittance for the left and right incidence, which can characterize the degree of the asymmetry.

On the other hand, when the structure is rotated by 900 with respect to the incidence plane, the incident wave can not sample the asymmetry in the structure as they are oriented in other plane (yz plane). So, there is a complete symmetry in the spp dispersion and possesses parabolic dispersion with respect to the incidence angle. The Bruggeman Homogenization formalism was used to homogenize the silver CTFs which reveals them to be hyperbolic biaxial materials, and the dispersion of SPP waves was adequately described through the homogenization model.

[1] N. Bonod, E. Popov, L. Li, and B. Chernov, "Unidirectional excitation of surface plasmons by slanted gratings", Opt. Express, 15, 11427, 2007.

[2] B. Bai, X.Meng, J. Laukkanen, T. Sfez, L. Yu,W. Nakagawa, H. P. Herzig, L. Li, and J. Turunen, "Asymmetrical excitation of surface plasmon polaritons on blazed gratings at normal incidence", Phys. Rev. B 80, 035407, 2009.

[3] J. Dutta, S. A. Ramakrishna, and A. Lakhtakia, "Periodically patterned columnar thin films as blazed diffraction gratings", Appl. Phys. Lett., 102, 161116, 2013.

9502-28, Session 7

High-field enhancement factor in dielectric photonic structure

Silvia Romano, Consiglio Nazionale delle Ricerche (Italy); Carlos A. Pina-Hernandez, abeam Technologies, Inc. (United States); Stefano Cabrini, The Molecular Foundry (United States) and Lawrence Berkeley National Lab. (United States); Ivo Rendina, Vito Mocella, Istituto per la Microelettronica e Microsistemi (Italy)

Strong enhancement of the electric field is very useful in a large portion of applications, such as nonlinear interactions, molecular scattering, fluorescence, surface-enhanced Raman spectroscopy, amplification and lasing, sensing [1, 2]. Usually this is achieved by employing Surface Plasmon Polaritons phenomenon, which propagate at the interface between a metal and a dielectric layer. However, metallic materials are not the only way to have optical field enhancement and many works have focused the attention on field enhancement in structured dielectric surfaces [3,4]. Here we will illustrate the possibility to achieve extremely high field enhancement, up to 6 orders of magnitude larger than intensity of the incident beam, in a thin structured dielectric layer. Theoretical and experimental results about the particular coupling mechanism in a suitable Silicon Nitrate photonic crystal will be reported. The structure, fabricated by using electron beam lithography, consists of a square lattice of holes in Si_3N_4 and its transmissions spectrum is acquired in a supercontinuum laser setup. The coupling effect is connected to the so called photonic bound states in the continuum [5] whose lifetimes are predicted to approach infinity.

References

1. X. Guo, J. Biophoton. 5, 483 (2012).

2. E. C. LeRu, Blackie E, M. Meyer, and P. G. Etchegoin, J. Phys. Chem. C, vol. 111, no. 37, pp. 13794–13803, Sep. 2007.

3. L. K. Ausman and G. C. Schatz, J. Chem. Phys. 129, 054704 (2008).

4. S. Romano, S. Cabrini, I. Rendina, and V. Mocella, LSA 3, e120 (2014).

5. C. W. Hsu, B. Zhen, J. Lee, S.-L. Chua, S. G. Johnson, J. D. Joannopoulos, and M. Solja?i?, Nature, vol. 499, no. 7457, pp. 188–191, Jul. 2013.

9502-29, Session 7

Plasmonic planar antenna for spectral and spatial manipulation of the polarization

Mathilde Makhsiyan, Quentin Lévesque, ONERA (France) and Lab. de Photonique et de Nanostructures (France); Patrick Bouchon, ONERA (France); Fabrice Pardo, Lab. de Photonique et de Nanostructures (France); Julien Jaeck, Riad Haidar, ONERA (France); Jean-Luc Pelouard, Lab. de Photonique et de Nanostructures (France)

The ability to control the polarization state of an electromagnetic wave is at the core of many various applications. The emergence of plasmonic metasurfaces has attracted a wide attention by their ability of providing an efficient and local control of the polarization at a subwavelength scale. We demonstrate both theoretically and experimentally that plasmonic planar antennas based on metal-insulator-metal (MIM) resonators can efficiently convert the linear polarization of light in the infrared and offer a spatial and spectral control of the polarization in reflection.

First, rectangular MIM antennas, which are known to provide an efficient manipulation of light, have been studied for their ability of polarization conversion. Then, we show that L-shaped antennas, which are the combination of two orthogonal rectangular antennas, lead to a more efficient control of the polarization and to the design of an efficient and wideband linear polarization conversion. Indeed, a nearly total polarization conversion over a 1μm-wide band with a mean polarization conversion efficiency of 95% has been demonstrated (Lévesque et al., Appl. Phys. Lett. 104, 111105 (2014)). We show that this conversion is due to two localized resonances in the L-shaped antenna, which wavelengths can be engineered thanks to the geometry of the structure and the angular independence of this conversion has been reviewed. We have studied that it is also possible to modulate the spectral response of the structure by combining several L-shaped antennas in the same subwavelength period.

Eventually, we have generalized the previous concepts by introducing V-shaped antennas that present the advantage of being able to control the orientation of the reflected polarization and then provide an efficient manipulation of the linear polarization that paves the way for the design of efficient planar optical components in the infrared.

9502-30, Session 7

Generation of red color and near infrared bandpass filters using nano-scale plasmonic structures

Ahmed Sokar, Franz X. Hutter, Joachim N. Burghartz, Institut für Mikroelektronik Stuttgart (Germany)

The generation of different colors out of camera chips is previously and still done using the spectral filter (RGB), which is called Bayer-Pattern or pigments-based filter and placed on top of the pixel area, facing the incident light. These filters are based on organic color coating, which are stacked using Add-on process. In case of Complementary Metal Oxide Semiconductor (CMOS), the filter process is not applied on the fab line, due to compatibility issues which add further cost on the camera.

This thesis investigates the realization of color filters in the visible range and near infrared spectrum for the purpose of substituting the stacked-based filter or Bayer-pattern one with a new filter based on materials compatible with the CMOS process. The filters studied in this thesis are based on nano-structured CMOS-compatible metals such as Aluminum (Al), Titanium Nitride (TiN), Chromium (Cr), and alloys like Aluminum-Silicon (AlSi).

A 150nm thick Al layer, sandwiched between silicon dioxide, SiO_2, layers is used to achieve resonance wavelengths at 700nm and 950nm. Three parameters are used for tuning the two filters, i.e., aperture area, the period, and the holes arrangement (square or rhombic lattice). The three parameters affect the tradeoff between the bandwidth of the filter and its transmission at the peak resonance.

The filter is based on the principle of Surface Plasmon Polaritons, where the electromagnetic waves of the incident light couples with the free charges of the metal at the metal-dielectric interface. Extraordinary enhancement transmission (EOT) has been seen when the metal is structured with apertures such as rectangular, circular, cross, bowtie, etc. The resonance frequency in that case depends on the shape of the aperture, material used, i.e. the refractive index and extinction coefficient, the size of the apertures, the period of the array, and the surrounding material, i.e. the cap and the substrate.

The two filters show EOT with transmission between 30% to 50% and low dependency on the incident angle, i.e. from 0 to 30o degree. Moreover, the filters show almost no difference in the Transverse Electric (TE) and Transverse Magnetic (TM) modes which provides narrower band pass filter.

Conference 9503: Nonlinear Optics and Applications

Monday - Tuesday 13–14 April 2015

Part of Proceedings of SPIE Vol. 9503 Nonlinear Optics and Applications IX

9503-1, Session 1

Novel mechanisms of optical harmonic generation on excitons in semiconductors

(Invited Paper)

Dmitri R Yakovlev, Walter Warkentin, David Brunne, Johannes Mund, Technische Univ. Dortmund (Germany); Victor V. Pavlov, Anna V. Rodina, Roman V. Pisarev, Ioffe Physical-Technical Institute, Russian Academy of Sciences (Russian Federation); Manfred Bayer, Technische Univ. Dortmund (Germany)

Nonlinear optics of semiconductors is an important field of fundamental and applied research, but surprisingly the role of excitons in the coherent processes leading to optical harmonics generation has remained essentially unexplored. Here we report results of a comprehensive experimental and theoretical study of second- and third-harmonic generation (SHG and THG) involving the exciton resonances in GaAs and ZnO semiconductors [1,2]. Additional to crystallographic signals caused by the symmetry of the crystal lattice and exciton wavefunctions, SHG and THG signals induced by external magnetic and electric fields on the exciton resonances have been found. It is found that different exciton states, e.g. 1s(A,B), 2s(A,B), 2p(A,B), and 1s(C) excitons in ZnO, have very different dependences on magnetic field and electric field. Also they show different polarization properties measured as rotational anisotropy diagram with linear polarization for fundamental and harmonic-generated light. A microscopic theory of SHG generation through excitons is developed, which shows that the nonlinear interaction of coherent light with excitons has to be considered beyond the electric-dipole approximation. Depending on the particular symmetry of the exciton states SHG can originate from the electric- and magnetic-field-induced perturbations of the excitons due to the Stark effect, the spin as well as orbital Zeeman effects, or the magneto-Stark effect. The importance of each mechanism is analyzed and discussed by confronting experimental data and theoretical results for the dependences of the SHG signals on photon energy, magnetic field, electric field, crystal temperature, and light polarization. The developed experimental approach and analysis can be applied to other semiconductors.

[1] M. Lafrentz, D. Brunne, B. Kaminski, V.V. Pavlov, A.V. Rodina, R.V. Pisarev, D. R. Yakovlev, A. Bakin, and M. Bayer, Phys. Rev. Lett. 110, 116402 (2013).

[2] M. Lafrentz, D. Brunne, A. V. Rodina, V.V. Pavlov, R.V. Pisarev, D. R. Yakovlev, A. Bakin, and M. Bayer, Phys. Rev. B 88, 235207 (2013).

9503-2, Session 1

Modal method for Second Harmonic Generation in nanostructures

Sébastien Héron, Patrick Bouchon, ONERA (France); Fabrice Pardo, Jean-Luc Pelouard, Lab. de Photonique et de Nanostructures (France); Riad Haidar, ONERA (France)

Late results show that periodic nanostructures exhibit large enhancement factors allowing exaltation of nonlinear processes inside the structure. Besides, for emitting purpose, nonlinear generation must also be coupled to the external medium, dramatically increasing tailoring constraints. To conceive such nanostructures, we present a method based on the B-Spline Modal Method (BMM) (Bouchon, P., Pardo, F., Haïdar, R., & Pelouard, J. L. (2010), JOSA A, 27(4), 696-702) which computes the Second Harmonic (SH) field in periodic multilayered media under the undepleted pump approximation.

A periodic multilayered medium infinite along one direction is considered. The electromagnetic modal method decomposes the various fields on a B-Spline basis. It has less memory requirement through the use of a non-uniform mesh and sparse matrices. First, the eigenmodes of each layer are found and then the continuity relations for the fields are solved at each interface to find the corresponding scattering matrices. In the case of SH generation, eigenmodes and scattering matrices are computed both for the fundamental and the doubled waves, assuming that these modes are not disturbed by nonlinear processes. Then, each nonlinear layer of the structures is decomposed into sub-layers of sufficiently small thickness (typically greatly inferior to the wavelength). This discretization allows to determine the fundamental field in every point of the nonlinear medium, and thus to fully determine the value of the nonlinear polarization. The latter, which is assumed to be constant across every sub-layer, writes itself as the product of the second order nonlinear susceptibility and the square of the fundamental field. At this point, the sub-layer acts as a source for the second harmonic field. Their separate contributions are found through solving continuity relations for the electromagnetic fields at the border of each sub-layer. Eventually, the total SH field is found by integrating all the contributions of the nonlinear layers of the system.

This method is able to deal with any nonlinear process under the undepleted pump approximation, as it is possible to write the nonlinear polarization from the value of the linear fields involved. Besides, this hypothesis can be overcome by taking into account subsequent Difference Frequency Generation (DFG).

9503-3, Session 1

Degenerate four-wave mixing and two-photon induced gratings in colloidal quantum dots CdSe/ZnS

Alexander M. Smirnov, Maria V. Kozlova, Vladimir S. Dneprovskii, Lomonosov Moscow State Univ. (Russian Federation)

The features of nonlinear and electro-optical processes has been discovered in the case of two-photon resonant excitation of the excitons (electron – hole transitions: 1Sh3/2?1Se 1Ph3/2?1Se) in colloidal CdSe/ZnS quantum dots. Self-diffraction arises for two laser beams intersecting in the cell with colloidal CdSe/ZnS quantum dots (QDs) due to the dynamic phase grating formatting.

The calculated induced change in the refractive index is sufficient to form a phase diffraction grating. Such a large value of ?(3) as compared to the third-order nonlinear susceptibility for the solvent (hexane) is due to the increase in ?(3) occurring when the intermediate resonance is attained in a medium transparent for laser radiation.

In order to identify physical processes responsible for the induced grating formation and the diffraction efficiency self-diffracted pulse intensity dependences on the incident pulse intensity were measured for two samples of colloidal QD CdSe/ZnS, which frequency of the fundamental exciton transition is tuned to the high-frequency and low-frequency region from the double laser frequency.

The discovered cubic dependence of the self-diffracted pulse intensity on the incident pulse intensity was explained by four-wave mixing process. Discovered above 5-th index of power dependence of the self-diffracted pulse intensity on the excitation pulses intensity we explained by the increasing magnitude of two-photon absorption (due to shifting of two photons energy of laser radiation to the exact exciton absorption resonance by red Stark shift of the exciton absorption), accompanied by the growth absorption by two-photon excited carriers that leads to the induced amplitude grating formation in addition to the phase grating.

The nonlinear change in the refractive index can be caused by the bound electrons and the two-photonexcited carriers that is ?n??n^b+?n^f. The nonlinear change in the refractive index due to the bound electrons is given by the formula ?n^b. The contribution from the refraction associated with the two-photon-excited carriers ?n^f to the nonlinear change in the refractive index can be characterized by the effective (dynamic, inertial) fifth-order nonlinear susceptibility. The contribution of

the nonlinear refractive index ?n^f becomes significant at a high intensity of the exciting laser pulse. The total change in the refractive index can be represented in the form: ?n=?I+?I^2 .

As part of the self-diffraction theory, the diffraction efficiency of self-diffraction from the induced grating is determined by the square of the refractive index modulation and the corresponding change of the optical path d?n (where d - thickness of the induced gratting): ? ~(?n)^2. It can be shown that the of the self-diffracted pulses intensity depends on the incident pulse intensity as follows: Id=I (?I+?I^2)^2. At moderate intensities of the incident pulses ?I? ?I^2, the dependence is cubic; at high intensities (?I^2??I) - dependence of the fifth power. For intermediate magnitudes of the intensity dependence can assume more complicated form. Apparently, due to the bound electrons the significant factor of diffraction efficiency is a sign of nonlinear refractive index change.

9503-4, Session 1

The analytical approach to optimization of active region structure and efficiency of quantum dot laser

Vladimir V. Korenev, Artem V. Savelyev, St. Petersburg Academic Univ. (Russian Federation); Alexey E. Zhukov, St. Petersburg Academic Univ. (Russian Federation) and Ioffe Physical-Technical Institute (Russian Federation); Mikhail V. Maximov, Ioffe Physical-Technical Institute (Russian Federation) and St. Petersburg Academic Univ. (Russian Federation); Alexander V. Omelchenko, St. Petersburg Academic Univ. (Russian Federation)

Long-wavelength semiconductor InAs/InGaAs quantum dot (QD) lasers emitting via ground state (GS) optical transitions of quantum dots (QDs) near 1.3 mkm are needed for the wide range of practical applications, from optical coherence tomography and aesthetic surgery to ultrafast data transmission. At the same time, due to the usage of such light sources in compact devices (tomographs and notebooks), it is particularly important to optimize size and structure of their active regions in order to minimize their energy consumption. However, currently existing models can offer only numerical approach to the task that does not allow to elucidate key parameters affecting lasing spectrum width, to reveal key dependences on them and to optimize their values.

In order to overcome this obstacle we introduce an analytical optimization method basing on the analytical approach to GS-lasing phenomenon in the case of low homogeneous broadening. It is shown that in the case of lasers with only several layers of QDs there always exist optimal values of the laser cavity length, dispersion of inhomogeneous broadening, which allow one to obtain lasing spectrum of a given width at minimum injection current. In the case of multi-layered structures the optimal dispersion is so large that in all practically attainable range of dispersions its increase results in the decrease of injection current corresponding to the lasing spectrum f a given width.

Moreover, it is shown that the optimization of dispersion plays the key role, while the optimization of laser cavity length, which has its optimal value corresponding to the minimum operation current for single- as well as for multi-layered structures, is just a fine-tune. Power conversion efficiency of quantum dot laser optimized in such a way is practically equal to its maximum value and achieved at minimum injection current.

9503-5, Session 2

SHG from artificial metasurfaces *(Invited Paper)*

Concita Sibilia, Univ. degli Studi di Roma La Sapienza (Italy)

No Abstract Available

9503-6, Session 2

Three wave mixing enhancement in metal-dielectric-metal resonators

Sébastien Héron, Patrick Bouchon, ONERA (France); Fabrice Pardo, Lab. de Photonique et de Nanostructures (France); Arthur Baucour, ONERA - The French Aerospace Lab (France); Riad Haidar, ONERA (France)

Nonlinear optics processes benefit from local enhancement of the electric field provided by nanostructures. In particular, metal-insulator-metal nanostructures are known to enhance the electric field of typically 2 orders of magnitude (Pardo, F., Bouchon, P., Haïdar, R., & Pelouard, J. L., Physical review letters, 107(9), 093902, (2011)). We explore the case where GaAs and InP are used as the insulator material in these resonators, and demonstrate that they can generate a second harmonic field with an efficiency equal to the one obtained by a thick layer of GaAs or InP.

Then, we explore the various ways to further enhance the efficiency of second harmonic generation. This can be done in a peculiar way by selecting a multi-resonant nanostructure, able to enhance the field not only at the fundamental frequency, but also at the doubled frequency. In particular, we follow the original idea of J.P. Van der Ziel (Applied Physics Letters, Vol 26, No. 2, 1975) to match the TE and TM modes, and demonstrate a one order of magnitude gain.

9503-7, Session 2

Integrated ring grating nanoprism structure for efficient coupling of propagating and localized surface plasmons

Nancy Rahbany, Wei Geng, Rafael Salas-Montiel, Sylvain Blaize, Renaud J. B. Bachelot, Univ. de Technologie Troyes (France); Christophe Couteau, Univ. de Technologie Troyes (France) and Nanyang Technological Univ. (Singapore)

Controlling and enhancing surface plasmon launching, propagation, and localization has been one of the key goals in the fields of plasmonics, nanooptics and nanophotonics [1]. In addition, metallic nanoparticles and nanoantennas have been intensively studied due to their capability to increase electromagnetic field confinement [2] leading to a remarkable enhancement of the fluorescence rate and quantum yield of emitters placed in their vicinity [3]. However, the diffraction of light limits the optical resolution as well as the localization of electromagnetic fields in confined volumes, which is essential in numerous applications ranging from optical electronics to nanofabrication and sensing devices. In this work, we introduce a novel plasmonic structure consisting of a metallic nanoprism integrated in the center of a ring diffraction grating. The ring grating is responsible of generating surface plasmon polaritons (SPPs) which propagate along the ring diameter and couple with localized surface plasmons (LSPs) present at the nanoprism tip. We will first present numerical FDTD simulations as well as experimental optical characterization results that were done to study ring grating structures fabricated using Electron Beam Lithography (EBL). Plasmon-emitter coupling was also studied upon exciting dye molecules placed inside the rings. Our proposed concentric integrated structure makes use of the high energy of propagating SPPs and the sub-wavelength confinement of LSPs to achieve efficient optical nano-focusing at the nanoscale, which can be implemented to study the fluorescence enhancement and lifetime reduction of emitters placed at the tip. This work can be extended and applied at a smaller scale aiming to reach the strong coupling regime between emitters and our integrated ring grating-nanoprism system.

[1] Barnes, W. L., et al. "Surface plasmon subwavelength optics." Nature 424.6950 (2003): 824-830.

[2] Maier, S. A., et al. "Local detection of electromagnetic energy transport below the diffraction limit in metal nanoparticle plasmon waveguides." Nature materials 2.4 (2003): 229-232.

[3] Kinkhabwala, A. et al. "Large single-molecule fluorescence

enhancements produced by a bowtie nanoantenna." Nature Photonics 3 (2009): 654–657.

9503-8, Session 2

Nonlinear Kerr-type coupled ring resonators with effect of loss

Yasa Eksioglu Ozok, Jirí Petrácek, Brno Univ. of Technology (Czech Republic)

Nonlinear optical systems show rich variety of dynamical phenomena such as optical bistability, self- pulsing, and chaos. Optical bistability has an important role in data processing while optical chaos has attracted significant attention due to its applications in encrypted communications and random number generators where chaotic signals provide secured data transmission [1, 2]. The nonlinearity is usually provided by the Kerr effect, in which the refractive index of the medium changes by the intensity of propagating light. The chaotic behaviour and instabilities were first investigated by Ikeda [3] for a single ring cavity containing a nonlinear medium. By increasing number of rings, i.e. coupled cavities, nonlinear effects are enhanced [4, 5] and offer more control over self-pulsing and chaos [6, 7].

In this work, we investigate the dynamical behaviour of nonlinear coupled ring resonators with non-instantaneous Kerr response and effect of loss which has not been considered in such systems so far. For realization of the system, we consider an all pass filter configuration with two rings. Related to the Kerr effect, system exhibits rich dynamics, transitions from steady state to Hopf bifurcations and chaos are observed. We generalize the map presented [3] and obtain a set of difference-differential equations. We evaluate steady state solutions and consider time evolution of these solutions to have a view of dynamical character. The system is highly sensitive for the values of detuning from resonance and input power. The onset of self-pulsing states is affected by loss and finite relaxation time. The chaotic behaviour dominates the system even at small input powers.

[1] A. Argyris, D. Syvridis, L. Larger, V. Annovazzi-Lodi, P. Colet, I. Fischer, J. Garcia-Ojalvo, C. R. Mirasso, L. Pesquera, and K. A. Shore, Nature 438, 343 (2005).

[2] A. Uchida, K. Amano, M. Inoue, K. Hirano, S. Naito, H. Someya, I. Oowada, T. Kurashige, M. Shiki, S. Yoshimori, K. Yoshimura, and P. Davis, Nat. Photon. 2, 728 (2008).

[3] K. Ikeda, Opt. Commun. 30, 257 (1979).

[4] A. Melloni, F. Morichetti, and M. Martinelli, Opt. Quantum Electron. 35, 365 (2003).

[5] Y. Chen and S. Blair, Opt. Express 12, 3353 (2004).

[6] B. Maes, M. Fiers, and P. Bienstman, Phys. Rev. A 80, 033805 (2009).

[7] J. Petracek, Y. Eksioglu, and A. Sterkhova, Opt. Commun. 318, 147 (2014).

9503-9, Session 2

Organic-inorganic planar hybrid materials for spasers

Nikita A. Toropov, Aisylu N. Kamalieva, Tigran A. Vartanyan, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Noble metal nanostructures are widely used for the development of an optoelectronic components and devices due to collective electronic oscillations or localized plasmons. One of the most significant advantages of these materials is the concentration of resonant electric fields of incident wave in the proximity around the nanostructures. The field enhancement leads, in its turn, to the increased absorption and fluorescence of organic molecules that may be distributed in the close proximity of metal nanoparticles. While the increase of absorption of organic thin films is a rather robust effect, the increase of the fluorescence intensity is much more subtle and a number of authors have reported the fluorescence quenching of molecules on the metallic surface rather than the expected enhancement.

In this work, we strive to obtain a highly fluorescent planar material which may be used for the nanolasers based on localized plasmons. These materials consist of a mixture of organic molecules, polymer, and silver nanoparticles. Silver nanoparticles were preliminary deposited on a sapphire and silica surfaces. These samples were characterized by SEM and absorptive spectroscopy. They were covered by a polymer/dye layer using the spin-coating and evaporation techniques. We used four pairs of different samples. First and second of them are rhodamine layers with and without Ag nanoparticles on the sapphire and silica surfaces. Third and forth types of samples comprise poly(methyl methacrylate) (PMMA) layer on the sapphire and silica surfaces activated by rhodamine molecules with and without Ag nanoparticles. Obtained organic-inorganic planar materials were characterized by confocal luminescent microscopy and spectroscopy.

As a result, we observed the enhancement of the rhodamine absorption for all types of the samples in the near fields of silver nanoparticles. On the other hand, the enhancement of the rhodamine luminescence was obvious only for the samples with Ag nanoparticles and PMMA as a matrix for rhodamine molecules. The fluorescence of the PMMA/rhodamine 6G layer with silver nanoparticles was almost 20-fold more intense than the fluorescence of the rhodamine layer on a bare sapphire and silica surfaces without nanoparticles. We conclude with the statement that the best route to the highly fluorescent planar material is technique that includes preparation of a mixture of PMMA activated by rhodamine layer. We plan to use this result in the development of solid-state spasers.

9503-10, Session 3

Nonlinear interaction between single photons *(Invited Paper)*

Bruno Sanguinetti, Univ. de Genève (Switzerland)

Optical nonlinearities strong enough to allow the interaction of single photon is central to advancing quantum computation and communication applications. Here we present an experiment which demonstrates the parametric nonlinear interaction between two heralded single photons. This is done using a state-of-the-art nonlinear waveguide, allowing high-bandwidth operation at telecom wavelengths. This experiment highlights the potential of quantum nonlinear optics with integrated devices and opens way to new quantum computation and communication tasks.

9503-11, Session 3

Slow and fast light switching in ruby

Rajitha P. Rajan, Hans Riesen, UNSW Canberra (Australia)

Change in the velocity of light has attracted tremendous attention for its applications like optical data storage, signal and quantum-data processing, optical switching, spectral sensitivity enhancement and pulse regeneration. Studies about light propagation have been undergoing since more than a century. It's now well known that any material that has normal or anomalous dispersion generates slow or fast light. We demonstrated an experimental technique to switch between slow and fast light by transient hole burning in ruby. Transient hole burning involves depletion of ground state leading to a highly populated excited state by single frequency laser excitation. This leads to a hole in the absorption spectrum when readout by the laser. The experiment is designed to create drastic variation in refractive index to produce slow and fast light in ruby at the peak of absorption spectrum, Wo of ruby. Hole burning at Wo leads to normal dispersion producing slow light, while fast light is obtained by modulating the laser by a square pulse. Therefore, two spectral holes are burned such that anomalous dispersion prevails at Wo. Hence, probing at position Wo when modulation is switched off and switched on gives slow and fast light respectively.

Narrow spectral holes lead to strong dispersion effects. In this study, the spectral holes were narrowed by applying a low magnetic field B?c of 12 mT which was generated by water-cooled Helmholtz coils. The crystal was mounted on the cold finger of a Janis/Sumitomo SHI-4.5 closed cycle refrigerator bringing down the crystal temperature to 2.2 K. Consequently, the inhomogeneous width of ruby was significantly reduced. An acousto-optic modulator, AOM was used to control the burn pulse and the probe pulse. The burn and probe pulse was generated from the same laser of wavelength 693.57 nm. Gaussian beam of width 160 ns acting as the probe pulse was delayed from the burn pulse of width 100 microsecond by 2 microsecond . The burn pulse was used to burn the spectral hole and the readout using the probe pulse was detected by a Thorlabs photodiode.

We observed a delay of 25 ns and advancement of -10 ns at B//c = 12 mT corresponding to a group velocity of c/829 and negative group velocity of –c/332 respectively. Our present observations can be improved by further narrowing the spectral hole by increasing the magnetic field, which is an ongoing project.

9503-12, Session 3

Optical nanofiber facilitated nonlinear optics effects in cold atoms

Vandna Gokhroo, Ravi Kumar, Síle G. Nic Chormaic, OIST Graduate Univ. (Japan)

Subwavelength diameter optical fibres, otherwise known as optical nanofibres, have recently come to the fore as tools for cold, neutral atom-based quantum networks. To date, optical nanofibres have been used for spectroscopy, manipulation and trapping of cold atoms. The intense evanescent field generated at the waist region even for ultralow input powers in the pW-nW range lend such fibres to studies of nonlinear optics and quantum interference effects in cold atoms. Nonlinear optics phenomena, such as electromagnetically induced transparency [3] and two-photon absorption [4], were previously demonstrated using optical nanofibres in rubidium vapour, but, to date, work on cold atoms has been very limited. It is worth noting that the very high intensity evanescent filed can give rise to an observable AC Stark effect on the hyperfine energy levels and this can be studied using a suitable probe beam.

In this work, we report on a 2-photon excitation process in laser-cooled 87-Rb that gives rise to frequency upconversion. Thence, we study the impact of the high intensity evanescent field on the ground to intermediate state transition at 780 nm. A second transition from the intermediate state to the excited state at 776 nm is used as a probe. We show the first demonstration of Autler-Townes splitting of an atomic transition for atoms around an optical nanofibre and this is achieved for excitation powers as low as 20 nW, while frequency upconversion has been observed for powers as low as 200 pW. These powers are significantly lower than those required when using free-space excitation and probe beams.

The optical nanofibre passes through the centre of a cloud of atoms trapped in a standard magneto-optical trap configuration. Both the 780 nm and 776 nm beams propagate through the nanofibre and are used to excite the atoms from the ground state, 5S1/2 to the excited state 5D5/2 via an intermediate state 5P3/2. The atoms are excited by the 780 nm and 776 nm light via the two-photon process. Relaxation of the atoms via the 6P3/2 state produces 420 nm light. This is coupled into the same nanofibre and detected at one end. The optical nanofibre acts as both an excitation and detection tool. Autler-Townes splitting is observed for different 780 nm powers and we show that it is directly proportional to the square-root of the excitation power. Dephasing terms in the simulated spectrum are used in order to fit with the experimental results. The origin of the dephasing effects is still under investigation and could arise from atom-surface interactions. Such work could lead to advances in quantum gates using cold atoms.

9503-13, Session 3

The design of photonic crystal fiber with novel microstructure for flat supercontinuum generation

Wei Li, Guoying Feng, Shouhuan Zhou, Tian Liang, Sichuan Univ. (China)

The microstructure of the photonic crystal fiber (PCF) and the characteristics of the pump source contribute to the flatness of the supercontinuum generation (SCG). Photonic crystal fibers (PCFs) with different novel microstructures are designed to control the chromatic dispersion for the flat SCG. The model for the evolution process of ultrashort pulse in newly designed PCFs is established and corresponding numerical simulations are carried out. A parameter is proposed to describe the spectrum flatness quantitatively. A comprehensive study of flat SCG is presented in the combination of these PCFs and pump lasers with different parameters. The influences of PCFs' dispersion properties and pulse characteristics, especially the pulse width and pulse peak power, on the flatness of SCG are investigated in detail. The results show that for a given pump laser centered at 1064 nm, with pulse width of 14 ps, average power of 24W, by the use of one of the newly designed PCFs with a normal flat dispersion profile, a flatter spectrum can be obtained. In addition, the propagation characteristics such as the facular evolution and the spectral variation of the SCG out of the collimator in the air are investigated. Finally the focusing characteristics and beam quality of the SCG are studied and discussed.

9503-14, Session 4

Enhanced nonlinear optics in plasmonics and dielectric nanostructures with magnetic response *(Invited Paper)*

Andrey A. Fedyanin, Lomonosov Moscow State Univ. (Russian Federation)

No Abstract Available

9503-15, Session 4

Waves in nonlinear plasmonic slot waveguides: stationary states, bifurcation, stability and temporal evolution

Wiktor Walasik, Institut Fresnel (France); Fangwei Ye, Shanghai Jiao Tong Univ. (China); Alejandro W. Rodriguez, Princeton Univ. (United States); Gilles Renversez, Institut Fresnel (France) and Aix-Marseille Univ. (France)

Merging the fields of plasmonics and optical solitons attracted a lot of attention in the last decades. Devices supporting plasmon-soliton waves propagating along metal/nonlinear dielectric interfaces may be of interest for sensor applications or for plasmon generation since they allow their in-plane excitation unlike the usual Krestchmann-Raether mounting.

The first description of 1D stationary solution composed of a spatial soliton part coupled with a plasmonic wave was given 30 years ago. More recently, several articles have been published on this research topic of plasmon-soliton coupling (Bliokh et al., 2009)(Davoyan et al., 2009)(Milian et al, 2012). Nevertheless, up to now, no experimental results have been published on this issue of soliton-plasmon. The main reason is that for the already proposed structures the required induced nonlinear refractive index change (or peak power) is too high compared to the one attainable for real materials.

In our previous works, we have generalized the work and results published by Ariyasu et al. in 1985 for planar structures made of semi-infinite nonlinear dielectric region (Walasik et al., Phys. Rev. A., 2014a). In the work presented here, we provide a complete study of nonlinear plasmonic slot waveguides (NPSWs) where a nonlinear dielectric core of Kerr type is surrounded by two semi-infinite metal regions as first studied by Feigembaum & Orenstein, 2007.

To realize this study we developed two semi-analytical models to obtain the stationary solutions in NPSWs (Walasik et al., submitted, 2014). For the model where the nonlineary depends only on the tranverse component of the electric field we obtained analytical expressions both for the field profile and for the nonlinear dispersion relations. The two

models allow us to study both the influence of the slot core thickness, and of the permittivites of the core and metal regions (Walasik et al., Plasmonics, 2014b). It is obtained that the higher the refractive index of the core the lower the threshold and the lower the absolute value of the metal permittivity the lower the threshold. It then is possible to design structures where purely nonlinear effects like the bifurcation of an asymmetric mode from a symmetric one in a symmetric structure occurs at low power associated to nonlinear refractive index increase below 10^-3.

To gain physical insight in this study, we also show, as it is expected from theoretical arguments (Akhmediev & Ankeiwicz, 1997) obtained for spatial solitons, how the bifurcation threshold of the plasmon-soliton can be estimated quantitatively using an energy point of view.

Finally, using both theoretical arguments (Mitchell & Snyder, 1993) and numerical simulations of the temporal evolution obtained with two different vector methods (COMSOL & FD-TD), we investigate the plasmon-soliton stability in NPSWs (Walasik et al., submitted, 2014). We show that below the first bifurcation threshold, the symmetric mode is stable and it is unstable abobe while the asymmetric mode is stable at least up to a second bifurcation point. From the numerical simulations, it also appears that the antisymmetric mode is stable at least up to the power associated to the power associated to the second bifurcation point.

9503-16, Session 4

Highly nonlinear sub-micro silicon nitride trench waveguide coated with gold nanoparticles

Yuewang Huang, Qiancheng Zhao, Nicholas Sharac, Regina Ragan, Ozdal Boyraz, Univ. of California, Irvine (United States)

We demonstrate fabrication of a highly nonlinear sub-micro silicon nitride trench waveguide coated with gold nanoparticles for plasmonic enhancement. The fabricated waveguide not only has a remarkable nonlinear refractive index n2 = 1.39 ? 10-19 m2/W, which is five times higher than that of silica, but also exhibits propagation loss, as low as 0.8 ± 0.26 dB/cm, for TM modes at 1550 nm wavelength. Fabrication of this 800 nm wide waveguide started with a 5 ?m pattern on a MEMS grade photomask. By using conventional optical lithography, the wide linewidth was transferred to a <100> wafer, and the wafer was etched anisotropically by potassium hydroxide (KOH) to engrave trapezoidal trenches with an angle of 54.7º. KOH etching not only reduced the trench width to sub-micro scale, but also removed side wall roughness that originated from low-level photomask. Roughness was further mitigated by thermal oxide deposition to form silicon dioxide buffer layers. The silicon nitride waveguide was deposited by low pressure chemical vapor deposition (LPCVD). The merit of this method was to avoid using expensive E-beam lithography for sub-micro scale fabrication, while at the same being capable to pattern large areas. The etching and deposition steps can be altered to cater to CMOS compatible procedure. Gold nanoparticles were then deposited on the waveguide for plasmonic surface enhancement. This was achieved by first depositing a polystyrene-b-poly(methyl methacrylate)(PS-B-PMMA) diblock copolymer film onto the waveguides, via spin coating, to form planar PS-b-PMMA template, with lamellar, sub-micron sized PMMA domains. The PMMA domains were then functionalized with an amine group, by immersing the substrate in ethylenediamine solution. Following this, 20 nm gold particles, functionalized with thiotic acid, were chemically attached to the functionalized PMMA domains using crosslinking chemistry, by immersing the substrate in a nanoparticle solution. The nanoparticles then diffused to the substrate surface, where the crosslinking occurred. Since the particles attached only to the PMMA domains, they were confined to localized regions, therefore forcing the nanoparticles into clusters of various sizesand geometries, such as dimer, trimer, quadrumers, and linear chains. This was in addition to single nanoparticles and large aggregates, which also formed on the substrate. Testing revealed that the device was sensitive to light polarization, and that it embraced lowest propagation in TM mode. The reason lies in that the waveguide structure was symmetric in horizontal direction but asymmetric in vertical direction. The guiding property of the waveguide i.e., mode area, mode confinement, dispersion were revealed by full wave simulation based on FEM method. The silicon nitride waveguide has large nonlinear refractive index, rendering itself promising for nonlinear applications, like four-wave-mixing, wavelength conversion and parametric amplification. Furthermore, the deposited nanoparticles will hopefully facilitate nonlinear effects, and the effects will be measured and compared.

9503-18, Session 4

Second harmonic generation from self-organized ZnO-ZnWO4 eutectic composite

Alessandro Belardini, Grigore Leahu, Marco Centini, Alessio Benedetti, Emilija Petronijevic, Eugenio Fazio, Concita Sibilia, Univ. degli Studi di Roma La Sapienza (Italy); Pawel Osewski, Institute of Electronic Materials Technology (Poland); Dorota A. Pawlak, Institute of Electronic Materials Technology (Poland) and Univ. of Warsaw (Poland)

The novel bottom-up method for manufacturing of nanostructured optical materials called directional solidification of eutectic composites [1] can be used in order to produce crystalline samples that are simultaneously monolithic and multiphase materials forming self-organized micro/nanostructures with peculiar optical properties [2].

Here we study the eutectic composite formed by using as crystal growth method, the micro-pulling down method applied to the eutectic mixture formed by ZnO and ZnWO4. According to the literature, there is one eutectic point in the ZnO-WO3 system where zinc oxide is one of the component phases - only at a molar ratio of substrates 65% of ZnO and 35% of WO3. The melting temperature at the eutectic point is about 1187° C, which is much lower than the melting point of ZnO (1975°C) and WO3(1473°C).

The formed samples (0.3 and 1mm thick) are composed by a crystalline matrix of ZnWO4 with regularly embedded crystalline ZnO lamellas (240nm thick). The XRD measurement confirms the presence of two phases in the eutectic. The first one is zinc oxide, ZnO, which crystallizes in the hexagonal system (wurtzite structure) in the P63mc space group and the second phase is zinc tungstate, ZnWO4 and it crystallizes in a monoclinic.

The test samples show high scattering in the visible range except for a very narrow transmission peak (few nanometers) around 400nm, due to the index matching of the two materials.

We excite the second harmonic generation response by using a pulsed femtosecond laser working at the pump wavelength of 800nm so that the second harmonic signal lies exactly in the narrow transmission band of the eutectic samples.

We observed large second harmonic generation efficiency of the eutectic samples of ZnO-ZnWO4 when compared with a single crystal (0.5mm thick) of pure ZnWO4. The single crystal of ZnWO4 was obtained with the same micro pull down technique.

Measurements of the second harmonic signal as a function of the incidence angle were performed and then compared with the measurements of the transmitted light. The measurements show that it is a phase matching process of the composite structure that gives rise to second harmonic signal.

The presence of the sharp second harmonic generation signal due to phase-matching condition indicates the good optical crystalline properties of the self-assembled sample.

References

[1] D. A. Pawlak, M. Gajc, P. Osewski, K. Sadecka, A. Stefanski, A. K?os: How far are we from making metamaterials by self-organization? The microstructure of highly anisotropic particles with an SRR-like geometry, Adv. Funct. Mat. (2010) 20, 1116.

[2] K. Sadecka, M. Gajc, K. Orlinski, H. B. Surma, I. Jozwik-Biala, A. Klos, K. Sobczak, P. Dluzewski, J. Toudert, and D. A. Pawlak, When eutectics meet plasmonics: Nanoplasmonic volumetric, self-organized silver-based eutectic, Adv. Opt. Mat. 2014 - accepted.

9503-17, Session 5

Experimental mapping of nonlinear dynamics in synchronized coupled semiconductor laser networks

Apostolos Argyris, Michail Bourmpos, Dimitris Syvridis, National and Kapodistrian Univ. of Athens (Greece)

The potential of conventional semiconductor lasers to generate complex and chaotic dynamics at a bandwidth that extends up to tens of GHz turn them into useful components in applications oriented to sensing and security. Specifically, latest theoretical and experimental works have demonstrated the capability of mutually coupled semiconductor lasers to exhibit a joint behavior under various conditions. In an uncoupled network consisting of N similar SLs - representing autonomous nodes in the network - each node emits an optical signal of various dynamics depending on its biasing conditions and internal properties. These nodes remain unsynchronized unless appropriate coupling and biasing conditions apply. A synchronized behavior can be in principle observed in sub-groups of lasers or in the overall laser network. In sub-groups (or cluster) synchronization, clusters of SLs may exhibit isochronous synchronization internally; however, synchronization between these clusters does not occur, or is based on non-isochronous solutions.

In the present work, various experimental topologies that employ a large number of SLs (8 or 16), under diverse biasing and coupling conditions, are built and investigated. The deployed systems incorporate off-the-shelf fiber-optic communications components operating at the 1550nm spectral window. Initial goal of such configurations is to create a synchronization mapping of the network's SL elements, based on the emitted dynamics of the optical signals by considering the different operational conditions of the systems and the mismatch distribution of critical internal and operational parameters of the SLs. The role of emission wavelength detuning of each participating node in the network - at GHz level - is evaluated. Small frequency emission mismatches allow synchronization even at moderate coupling strength. On the contrary, large mismatches - of the order of 40 GHz - dominantly affect the final synchronization output, leading to unsynchronized optical output. Even in such cases and depending on the mismatch distribution, de-synchronization may concern only those SL nodes that have large frequency detuning while the rest nodes maintain synchronization.

9503-20, Session 5

Coherent nonlinear optical microscopy for acquiring structural information of cell cytoskeleton

Hyungsik Lim, Hunter College (United States); Denis Sharoukhov, Hunter College and the Graduate Center of the CUNY (United States)

We present that a nonlinear optical radiation arises from cell cytoskeleton, providing a novel intrinsic imaging contrast. The use of the intrinsic emission is demonstrated for label-free visualization of the nervous systems, especially in the retinal nerves. Second-harmonic generation (SHG) is a nonlinear optics process requiring an ensemble of uniformly oriented molecules with non-centrosymmetric structure. The uniform polarity of microtubules (MTs) in neurons, in particular in axons, allows strong SHG signals to be obtained from the nerve fibers. Using the new imaging contrast, we have demonstrated, for the first time to our knowledge, the visualization of the retinal nerves by SHG microscopy. SHG imaging allows us to measure the structural integrity of MTs in the retinal nerve fibers, which is a significant achievement because the particular cytoskeletal element has been implicated in glaucoma, a neurodegenerative ocular disease. We investigated the optical properties of SHG from MTs were investigated, including the polarization- and wavelength-dependence, to find that SHG from MTs has distinct characteristics. They are advantageous not only for studying MT dynamics but also for acquiring unique molecular information that could not be achieved by other optical contrasts. Specifically, polarization-resolved SHG (p-SHG) was measured and the second-order tensor analysis was performed in order to deduce the molecular conformation of MT. The capability of p-SHG technique could be useful for probing the drug-tubulin interaction. We also tested the feasibility of the new nonlinear optical contrast for investigating MT network in the retina under the conditions that mimic glaucomatous events. Our results indicate that the nonlinear optical readout of SHG provides a novel means to advance our knowledge of the in vivo dynamics of the cytoskeleton, and to elucidate the dynamics of neuronal MT assembly under physiological as well as pathological conditions.

9503-21, Session 5

Selective multiphoton excitation by parametrically shaped laser pulses

Albrecht Lindinger, Freie Univ. Berlin (Germany)

Laser pulse shaping for control of photo-induced molecular processes has attained considerable success in recent years. Various processes like ionization, dissociation, molecule discrimination, or isotope and isomer selection were controlled by tailored laser pulses. Recently, pulse shaping methods were increasingly used in life sciences in order to investigate biologically relevant systems. There, laser pulse shaping is particularly applied to multi-photon excited fluorescence where interference effects are utilized.

This contribution reports on new pulse shaping methods for coherent control of multiphoton processes, which can even be conducted after transmitting optical fibers. Novel pulse shaper schemes for simultaneous phase, amplitude, and polarization pulse control were designed, and a parametric sub pulse encoding was developed [1]. In this approach, the physically intuitive parameters energies, distances, and chirps, as well as the states of polarization of the sub pulses can be controlled. This yields new perspectives of adding the polarization and hence utilizing all properties of the light field in the pulse modulation. The tailored laser pulses enable selective multiphoton induced fluorescence of dye mixtures. Special antisymmetric phase functions are employed for scans of the multiphoton excitation [2,3]. The two photon investigations are extended to selective three photon excitations of UV dyes for contrast enhancement. This enables to directly excite amino acids by three photon processes. Even the arising nonlinear effects in the surrounding liquid at the high laser intensities required for multi photon excitation can be controlled. Moreover, by using polarization shaping two photon transitions could selectively be excited in differing polarization directions. This opens the research field of anisotropy spectroscopy, which yields information about mobility, size and structure of molecular aggregates also in vivo. These methods are extended to pulse shaping of supercontinuum spectra and lead to improved imaging and molecular process control.

In order to operate in realistic environments, applications are demanded were the light is guided to the place of interest. This is realized by transmission of light through optical fibers for endoscopic applications which is relevant for medical treatments like novel endoscopic imaging and therapeutic feasibilities. Yet, it is challenging to transfer laser pulses through fibers due to distortion by linear and nonlinear fiber properties. This is overcome by precompensation using the shaper to transmit tailored pulses through photonic crystal fibers. Moreover, parametrically shaped pulses in phase, amplitude and polarization after the fiber were achieved [4]. This enables to steer molecular processes by utilizing these pulses for optimization of multi-photon ionization processes in molecular systems. Surprisingly, the nonlinear effects of the laser beam propagating through the fiber can be precompensated by backward calculating the Nonlinear Schrödinger Equation. Laser pulse shaping of multiphotonic excitations, also after novel optical fibers, has a high potential for new biophotonic applications in endoscopy and microscopy.

References

[1] F. Weise, A. Lindinger, Appl. Phys. B, 101, 79 (2010).

[2] A. Patas, G. Achazi, C. Winta, and A. Lindinger, J. Opt. Soc. Am. B 31, 2208 (2014).

[3] G. Achazi, N. Hermes, A. Patas, D. Tolksdorf, and A. Lindinger, Eur. Phys. J. D 67, 160 (2013)

[4] F. Weise, M. Pawlowska, G. Achazi, and A. Lindinger, J. Opt. Soc. Am. B 28, 406 (2011).

9503-22, Session 5

All-optical nonlinear information reconstructing via stochastic resonance in image processing

Hongjun Liu, Qibing Sun, Nan Huang, Xi'an Institute of Optics and Precision Mechanics (China)

Recently, the nonlinear optical amplification technology due to its large gain and high signal-to-noise ratio enhancement has been the focus of intensive research in the nonlinear optics and quantum optics, and has been shown a large number of potential applications in different areas of technology. The stochastic resonance refers to the situation where an increase in input noise improves a system's sensitivity to discriminate weak signals, and has a great prospect in optical information processing when it is combined with the nonlinear optical technology. Generally, low level optical signals are overwhelmed by the noise, which lead to an extremely low signal-to-noise ratio (SNR). The stochastic resonance systems have been used for amplifying and filtering signals to improve the detection sensitivity and output SNR. Many optical image formation systems work in bad environments and have to deal with the strong random noise. However, there is still little work has been done in the field of all-optical image processing via stochastic resonance. Here we propose and demonstrate a technique of all-optical nonlinear information reconstructing, in which the nonlinear optical amplification and stochastic resonance are combined to recover noise-hidden images propagating in an optical nonlinear bistable system, which consists of a unidirectional ring cavity and a photorefractive two-wave mixer with an external electric field. The nonlinear interaction of the external random noise, weak signals and bistable system allow the visibility of overwhelmed or lost information to reach to the peak at the expense of noise. Moreover, an optimal system performance can also be obtained by the stochastic resonance with nonlinear tuning, in which the level of the noise is fixed and the coupling is changed by tuning of the crystal length and the applied electric field. The all-optical nonlinear information reconstructing shows good performance in image de-noising and information retrieval.

9503-23, Session 5

Cavity-enhancement realization of the second-harmonic laser at 780nm and the third-harmonic laser at 520nm from a 1560nm EDFA-boosted diode laser with periodically-poled bulk crystals

Junmin Wang, Shanlong Guo, Yulong Ge, Kong Zhang, Jun He, Shanxi Univ. (China)

Combining the telecom-band diode laser and the well-developed Erbium-doped fiber amplifier (EDFA) as well as quasi-phase-matching periodically poled nonlinear crystals, we realized 2-Watt single-frequency continuous-wave (CW) 780nm laser output by using a bowtie-type four-mirror ring-cavity enhanced second-harmonic generation (SHG) of an EDFA boosted 1560nm diode laser with a periodically-poled magnesium-oxide-doped lithium niobate (MgO:PPLN) bulk crystal in the cavity, corresponding to a doubling efficiency of 83%. Typical RMS fluctuation is 1.5% in about 30 minutes. Tuning the 1560nm fundamental-wave laser's frequency, the output 780nm laser can be adapted to rubidium D2 line. Typical continuously tuning range is about 2GHz for the 780nm second-harmonic laser and the doubling cavity can be kept locked. It is much stable and long-life than the semiconductor tapered amplified 780nm diode laser system, and also has much better spatial profile of output laser beam. This doubling laser system can be easily employed to the field for laser cooling and trapping and further manipulating rubidium atoms, and also for 1560nm squeezing light as well as 1560nm entanglement generation and applications.

We also demonstrated 300mW single-frequency CW 520nm laser output through the third-harmonic generation (THG) of the EDFA boosted 1560nm diode laser. THG was realized by using a singly-resonant three-mirror folded-cavity enhanced sum-frequency generation (SFG) from 1560nm and its second harmonic laser at 780nm with a periodically-poled potassium titanyl phosphate (PPKTP) bulk crystal in the cavity. The single-frequency CW 520nm laser can be utilized as a pump source for a follow-up optical parametric oscillator (OPO) or optical parametric amplifier (OPA) to generate the 780nm + 1560nm two-color continuous-variable entangled optical fields, in which 780nm corresponds to rubidium D2 line and 1560nm locates in the optical fiber's low-loss transmission window. The 780nm + 1560nm two-color entangled fields are interesting for implementing quantum network or quantum distributed computation protocol, in which the 1560nm part can be transmitted through optical fiber link while the 780nm part can be stored in and retrieved from rubidium atomic ensemble.

9503-24, Session 5

Complex dynamics of QD light emitting diode with optoelectronic feedback

Kais A. Al Naimee, Istituto Nazionale di Ottica (Italy); Hussein Al Husseini, Univ. of Baghdad (Iraq); Sora F. Abdalah, Istituto Nazionale di Ottica (Italy); Amin Al Khursan, Thi-Qar Univ. (Iraq); Ali H. Khider, Univ. of Baghdad (Iraq); Riccardo Meucci, F. Tito Arecchi, Istituto Nazionale di Ottica (Italy)

We report both experimentally and theoretically the appearance of Mixed Mode Oscillations and chaotic spiking in Quantum Dot Light Emitting Diode. The proposed dimensionless model exhibits homoclinic chaos Furthermore, it is also able to reproduce Mixed Mode Oscillations and chaotic spiking regimes. The chaotic dynamics is completely determined by the variation of the injecting bias current and modulating current of the carrier in the wetting layer, as evidenced by means of the modulation depth of the system and bifurcation diagram. The influence of the injecting current on the transition between Mixed Mode Oscillations and chaos has been also investigated

9503-25, Session 6

Nonlinear scattering of ultrashort laser pulses on two-level system

Sergey V. Sakhno, Valerie A. Astapenko, Moscow Institute of Physics and Technology (Russian Federation)

The presentation is devoted to the theoretical investigation of nonlinear scattering of ultrashort electromagnetic pulses (USP) on two-level system embedded in dielectric or plasmonic matrix.

We consider the scattering of several types of USP, namely, so called corrected Gaussian pulse (CGP), cosine- and sine wavelet pulses. Such pulses have no constant component in their spectrum in contrast with traditional Gaussian pulse. It should be noted that the presence of constant component in the limit of ultrashort pulse durations leads to unphysical results. We consider also scattering of multicycle traditional Gaussian pulses (when constant component is negligibly small) with frequency chirp and analyse the influence of the magnitude and sigh of the chirp on the scattering process in linear and nonlinear regime.

The main purpose of the present work is the investigation of the change of pulse temporal shape after scattering as a function of initial pulse duration and phase, carrier frequency (for CGP) and electric field amplitude at different distances from the target. Numerical calculations are based on the solution of Bloch equations and expression for scattering field strength via dipole moment of two-level system exposed by the action of incident UPS.

Comparison of the obtained results with the linear scattering of UPS was carried out and the limits of applicability of linear approximation are determined.

In our calculation we also account for the influence of matrix material on the electric field strength in the pulse after scattering both for dielectric and plasmonic matrix.

It is shown that nonlinear scattering of USP have characteristic features which differ them from the long pulses scattering.

9503-26, Session 6

Explicit solution of FWM problem under the interaction of co-propagating laser beams in medium with cubic nonlinear response

Vyacheslav A. Trofimov, Igor E. Kuchik, Lomonosov Moscow State Univ. (Russian Federation)

We developed explicit analytical solution of FWM under the laser beam propagation in a medium with cubic nonlinear response in the frame-work of both plane wave approximation and long pulse duration approximation. This solution is based on using the invariants of the problem. Without taking into account the problem invariants it is impossible to develop the explicit solution of considered problem.

The solution allows us to provide a full analysis of modes for FWM in dependence of the interaction parameters. We have shown, in particular, an existence of bistable mode for energy conversion from pump waves to signal wave under certain conditions. In general case, there are more than 6 various modes of four-wave interaction even under the condition of matching of interacting wave.

Knowledge about these modes is very important for explaining of FWM experiments because its result depends on them.

9503-27, Session 6

Propagation of femtosecond pulse with self-similar shape in medium with nonlinear absorption

Vyacheslav A. Trofimov, Irina G. Zakharova, Lomonosov Moscow State Univ. (Russian Federation); Swapan Konar, Birla Institute of Technology (India)

We investigate the propagation of laser pulse with self-similar shape in homogeneous medium with various mechanism of nonlinear absorption: multi-photon absorption or resonant nonlinearity under the detuning of energy transition from central frequency of wave packet, or nonlinear absorption with its saturation. Both types of sign for frequency detuning are considered. This results in appearance of a refractive index grating which induced self-action of a laser pulse. We analyze also the influence of the laser pulse self-modulation due to cubic nonlinearity on existence of the laser pulse propagation with self-similar mode.

We develop analytical solution of corresponding nonlinear eigenfunction problem of laser pulse propagation in medium with nonlinear absorption. This solution is confirmed by computer simulation of eigenfunction problem for Schrödinger equation with considered nonlinearity.

This mode of laser pulse propagation is very important for powerful TW laser pulse propagating in glass.

9503-28, Session 6

The time response of nonlinear chalcogenide fiber Bragg gratings

Lubomír Scholtz, Libor Ladanyi, Jarmila Müllerová, Univ. of Zilina (Slovakia)

Fiber Bragg gratings (FBG) are known as promising devices e.g. for ADD/DROP multiplexers, signal filtering, dispersion compensation or all-optical switching. Due to high third-order optical nonlinearities chalcogenide glasses seem to be excellent candidates for all-optical processing using FBGs. Optical Kerr effects induced in chalcogenide glasses by intensive laser light cause changes in transmission characteristics of FBGs depending on the incident power. In this paper numerical studies of nonlinear chalcogenide FBGs are presented including the time response of the FBG that is important from the point of view of all-optical switching. The simulations are based on the nonlinear coupled mode theory.

9503-29, Session 6

Optical nonlinearities induced by elctric fields in nematic liquid crystals

Victor Stoian, Cristina C. Cirtoaje, Emil Petrescu, Cornelia Motoc, Univ. Politehnica of Bucharest (Romania)

Nonlinear effects induced by an electric field inside a nematic liquid crystal were studied. A planar oriented cell filled with 5CB nematic liquid crystal was subjected to an external voltage, higher than the treshold value for the electric Freedericksz transition. A laser beam was sent perpendicular through the cell and the diffraction patterns consisting of circular fringes was studied. The maximum number of diffraction fringes for different voltage values was measured and the experimental plot were in good agreement with the theoretical assumptions. We also performed a set of dynamical measurments of the fringes evolution from the moment the laser beam was applied until the maximum number of fringes was reached for each voltage and the results were consitent with our theoretical model.

9503-30, Session 6

The accuracy of the DDA (Discrete Dipole Approximation) method in determining the optical properties of black carbon fractal-like aggregates

Krzysztof Skorupski, Wroclaw Univ. of Technology (Poland)

BC (Black Carbon) particles, which are commonly found in the atmosphere, are a product of incomplete combustion of carbon-based fuels. Due to their absorption properties it is assumed that they have an impact on the global warming effect. One of the possibilities of studying the optical properties of BC structures is to use the DDA (Discrete Dipole Approximation) method which is capable of performing light scattering simulations by any shape decomposed into a sufficient number of volume elements (dipoles). However, its reliability decreases when the imaginary part of the complex refractive index is relatively large. The main goal of this work was to investigate the accuracy of the DDA method and to approximate the most reliable simulation parameters. The complex refractive index was adopted from the work by Chang and Charalampopoulos. It has successfully been used in other studies concerning BC structures and meets the criterion proposed by Bond et al. The incident wavelength varied from ?=300 to ?=900 with the step ??=20. For the light scattering simulations the ADDA algorithm was used and the resulting diagrams were compared to the superposition T-Matrix program by Mackowski. The study was divided into three parts. First, the DDA simulations for a single particle (sphere) were performed. The results proved that the meshing procedure might significantly affect the particle shape, and therefore, the extinction diagrams. The volume correction algorithm is recommended for sparse meshes. Otherwise, i.e. when meshes are more compact, an improvement in the accuracy is not guaranteed. When only a single sphere is considered, the orientational averaging procedure has a negligible impact on the results. In the next step large fractal-like aggregates composed of up to 100 primary particles were investigated. The impact of the volume correction procedure cannot be easily predicted. In some cases it can lead to more erroneous data. Differences in particle shapes, which are caused by the meshing procedure, are diminished due to the size of the aggregate. The relative extinction error is related to the total amount of volume elements (dipoles) divided by the number of primary particles and it seems that it does not increase with the aggregate size. Finally, the optical properties of fractal-like aggregates composed of spheres in point contact were compared to much more realistic structures composed of connected, non-spherical primary particles. The results prove that large connections should not be omitted because they can significantly amplify the extinction cross section (even by 60%). This phenomena applies for every structure, regardless of its size. When non-spherical particles are used and the volume of the aggregate is constant, the changes to the extinction cross section are minor and, providing that very accurate results are not needed, they can be omitted.

9503-31, Session 6

Optical and thermoluminescence properties of lithium potassium borate glasses doped with Eu3+ ions

Yasser Alajerami, Al Azhar Univ. (Palestinian Territory, Occupied)

We have reported the dosimetric properties of lithium potassium borate (LKB) doped with different concentrations of Eu3+ ions. The current glasses have been produced by melting the chemical mixtures of Li2CO3, B2O3 and K2CO3 at 1100 oC and then quenched to room temperature. The samples are characterized by X-ray diffraction (XRD), field emission scanning electron microscopy (FESEM) and diffraction thermal analysis (DTA). The luminescence spectra show four characteristic bands at 590, 613, 650 and 698 nm, which attributed to5D0?7F1(yellow), 5D0?7F2(orange), 5D0?7F3(red) and 5D0?7F4(red) transitions of trivalent Eu3+ ions. The glow curve for undoped LKB sample was observed at 180 °C. The Eu3+-doped sample show prominent TL glow peaks at 220°C when heated at a constant heating rate of 5°C.s-1. The proposed dosimeter shows a well-defined glow curve, good linearity, good effective atomic number and minimal fading response.

9503-19, Session PS

Continuous-wave seeded mid-IR parametric system pumped by the high-average-power picosecond Yb:YAG thin-disk laser

Ondrej Novák, Martin Smrz, Taisuke Miura, Hana Turcicova, Akira Endo, Tomás Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Mid-IR wavelength range offers interesting applications in gas sensing, medicine, defense, material processing, and others. One way to generate radiation in this wavelength range is down-conversion in the optical parametric devices. Very low absorption of nonlinear crystals results in low thermal load which promises converted beam of high average power if powerful and high quality pump beam is available. We have developed pump laser of 100-W level average power operating at 100 kHz. The pulses of Yb-fiber laser oscillator at 1030nm wavelength are stretched by a chirped volume Bragg grating (CVBG) from 5 ps to 200 ps and injected into a cavity of regenerative amplifier with an Yb:YAG thin-disk soldered on CuW heatsink. Diode pumping at zero phonon line at wavelength of 969 nm significantly reduces its thermal load and increases conversion efficiency and stability. We have obtained the near diffraction limited beam with power of 85 W before compression. Measured efficiency of CVBG, used for compression, is 88%, which corresponds to the estimated output of 75 W with 2 ps pulsewidth. The output powers over 100 W have been achieved for continuous wave operation. We are going to increase the average power to 100 W for pulsed regime in the near future as well.

We are developing a watt level mid-IR picosecond light source pumped by a beam of the high average power picosecond thin disk regenerative amplifier. Part of the beam pumps optical parametric generator of 10-mm long PPLN, which is seeded by a continuous wave laser diode at 1.9 μm. The seeding of the OPG by continuous-wave laser diode decreases the generation threshold and increases the power of the generated signal by up to two orders. The 3 W pumping gave output of 30 mW. The seed pulse energy temporally overlapping with pump light is approximately 10 fJ. It means that the single pass gain in the PPLN achieved about 10^7. The seed beam determines the spectrum of the amplified beam and the spectrum is narrower compared to unseeded parametric superfluorescence. The corresponding spectrum of the generated idler pulses in the mid-IR was also measured. After the seeded OPG, we obtained an amplified signal from the second stage with the KTP crystal. We have found proper synchronization of pulses and right angular setting of the KTP. We expect to obtain watt level output for initial 50-W pumping. Further measurements of amplification and beam characterizations will be presented. The possibilities of generation even longer wavelength will be discussed.

9503-32, Session PS

Investigations on growth, structure, optical properties and laser damage threshold of organic nonlinear optical crystals of Guanidinium L-Ascorbate

Ravi K. Saripalli, Sanath Kumar, Indian Institute of Science (India); H. L. Bhat, Indian Institute of Science (India) and Ctr. for Nano and Soft Matter Sciences (India); Suja Elizabeth, Indian Institute of Science (India)

Single crystals of Guanidinium L-Ascorbate (GuLA) were grown from aqueous solution by slow-cooling method in a custom-built solution growth setup developed in the laboratory [1]. Large and transparent single crystals of dimensions 5 cm x 1.5 cm x 1.5 cm were obtained. Crystal structure was determined by single crystal XRD. Data collection and subsequent data reduction were carried out with Apex 2 software suite. ORTEP diagram [2] and packing diagrams of GuLA were generated using Diamond software [3]. The structure was solved using direct methods. GuLA crystallizes in an orthorhombic, non-centrosymmetric space group P212121 with four molecules per unit cell. The morphology of the crystal was generated with the help of the software WinXmorph [4] and the interplanar angles were estimated and compared to experimental values. Laue pattern taken along the c-axis showed a clear two-fold symmetry as expected. It is noted that the addition of either inorganic cation such as lithium or an organic cation Guanidinium, changed the structure from monoclinic to orthorhombic.

UV-Visible spectroscopy revealed a UV-cutoff of 325 nm. Second harmonic generation (SHG) conversion efficiency was estimated and compared with other salts of L-Ascorbic acid. GuLA was found to possess a SHG conversion efficiency of 0.6 times that of standard KDP crystals. The low SHG conversion efficiency is comparable to that of L-Ascorbic acid single crystals [5]. However, inorganic salts of L-Ascorbic acid such as Lithium L-ascorbate dihydrate are known to possess high second harmonic generation (SHG) conversion efficiency and are promising nonlinear optical (NLO) materials [6]. It is interesting that unlike the inorganic salts of L-ascorbic acid, an organic salt, Guanidinium L-Ascorbate (GuLA) showed very low second harmonic conversion efficiency. The same trend was noted for other salts of L-Ascorbic acid grown in the lab. An attempt is made to study the reason for low SHG conversion efficiency of GuLA using the theoretical framework proposed by Wampler et al. [7] which relates the efficiency of NLO processes to molecular packing within chiral lattices.

Single shot and multiple shot laser damage thresholds were determined for GuLA using a pump-probe optical setup as 11.3 GW/cm2 and 2.5 GW/cm2 respectively for a laser of 1064 nm wavelength and a 6ns pulse width.

References:

[1] G. Dhanaraj et al., J. Crystal Growth, 113, 456 (1991)

[2] Farrugia, L. J. J. Appl. Crystallogr., 30, 565 (1997)

[3] Brandenburg, K. DIAMOND, 2.1c ed.; Crystal Impact GbR:Bonn, Germany, (1999)

[4] Kaminsky, W. J. Appl. Crystallogr., 38, 566 (2006)

[5] K. Srinivasan and K. Vanitha Devi, Cryst. Res. Technol. 45, No. 9, 946-952 (2010)

[6] K. Raghavendra Rao, C. Aneesh, H. L. Bhat, Suja Elizabeth, M. S. Pavan, and Tayur N. Guru Row, Cryst. Growth Des, 13, 97?105 (2013)

[7] Wampler RD, Begue NJ, Simpson GJ, Cryst. Growth Des., 8, 2589-2594 (2008)

9503-33, Session PS

Measurement of nonlinear refractive index based on multiple configuration of FBG in generating multiwavelength

Mohd Nizam Abdullah, Sahbudin B. H. Shaari, Abang Annuar Ehsan, P. Susthitha Menon, Univ. Kebangsaan

Malaysia (Malaysia)

A reliable method for measurement of the nonlinear refractive index through application of multi wavelength phenomenon. Multi wavelength realisation based on Erbium doped fibre laser (EDFL) is proposed and experimentally demonstrated. A combination of 15 m high efficiency Erbium doped fibre (EDF) and a 20 m Photonic Crystal Fibre (PCF) as main catalyst to suppress the homogenous broadening of EDF and to obtain highly stability of multi wavelength through insertion of a set of fibre Bragg gratings (FBGs) in the cavity. This PCF has zero dispersion of 1040 nm which mismatch from transmission window of 1550 nm. A reliable repeatability of multi wavelength based on multiple configuration of FBGs less than 0.2% obtained. This consistent results influence in determination of nonlinear refractive index by relation of four wave mixing (FWM).

9503-34, Session PS

Infrared optical parametric oscillator based on MgO: PPLN crystal and synchronously pumped by femtosecond Yb:KGW laser

Ieva Pipinyte, Karolina Stankeviciute, Rimantas Grigonis, Mangirdas Malinauskas, Valdas Sirutkaitis, Vilnius Univ. (Lithuania)

Tunable in wide spectral range femtosecond laser pulses are valuable instruments for investigation of various ultrafast processes or nonlinear imaging. Synchronously pumping optical parametric oscillator (SPOPO) allows generation of tunable radiation at low pump energies and high pulse repetition rate. As a nonlinear medium, we chose MgO-doped periodical poled lithium niobate (MgO:PPLN) due to its wide transmission range and large nonlinearity. A compact and efficient Yb:KGW source was employed as a pump source and showed the potential to be a good alternative for often used Ti:sapphire lasers for such devices [1-3]. A 1.5 mm long MgO:PPLN crystal was placed in a four- mirror linear resonator, which was pumped by fundamental harmonic (1030 nm) of Yb:KGW laser, providing 105 fs pulses at 76 MHz repetition rate. Spectral tuning and power characteristics of this SPOPO was investigated, while keeping the constant temperature of MgO:PPLN crystal. Generation of signal pulses tunable in 1.38 – 1.82 ?m spectral range was obtained by changing grating period of the crystal and a cavity length. As soon as SPOPO's cavity was aligned properly and synchronous pumping condition was fulfilled, visible and near infrared radiation was observed. Spectral analysis showed that this radiation corresponds to various combinations of second harmonic and sum frequency generation occurred together with parametric light generation, which was caused by high nonlinearity of the crystal. Operating characteristics of SPOPO was investigated using output mirrors of different transmission. The maximum output power efficiency was obtained in the cavity with 15 % transmission output coupler and reached >24 % in 1.44 – 1.46 ?m signal spectrum range.

[1] X. P. Zhang, J. Hebling, A. Bartels, D. Nau, J. Kuhl, W. W. Rühle and H. Giessen, "1-GHz-repetition-rate femtosecond optical parametric oscillator", Appl.Phys.Lett. 80, 1873–1875 (2002).

[2] T. Andres, P. Haag, S. Zelt, J.-P. Meyn, A. Borsutzky, R. Beigang, and R. Wallenstein, "Synchronously pumped femtosecond optical parametric oscillator of congruent and stoichiometric MgO-doped periodically poled lithium niobate", Appl. Phys. Lett. B 76, 241–244 (2003).

[3] K.J. Han, D. W. Jang, J. H. Kim, Ch. K. Min, T. H. Joo, Y. S. Lim, D. Lee and K. J. Yee, " Synchronously pumped optical parametric oscillator based on periodically poled MgO-doped lithium niobate", Opt. Expr. 16, 5299–5304 (2008).

9503-35, Session PS

Advances in high-quality factor optical resonators for optoelectronics

Patrice Salzenstein, FEMTO-ST (France); Khaldoun Saleh, CNRS / FEMTO-ST (France)

Optical resonators are useful for making hight stability optoelectronic oscillators (OEO) [1-3] Various resonators are investigated and designed for microwave photonic applications [4]. Their quality factors are characterized by cavity ringdown [5]. Obtained quality factors are in the range Q = 10^8 to Q = 10^10 [6].

References:

[1] Volyanskiy K., Salzenstein P., Tavernier H., Pogurmirskiy M., Chembo Y. K. and Larger L., "Compact Optoelectronic Microwave Oscillators using Ultra-High Q Whispering Gallery Mode Disk-Resonators and Phase Modulation," Optics Express 18(21), 22358-22363 (2010).

[2] Coillet A., Henriet H., Salzenstein P., Phan Huy K., Larger L. and Chembo Y. K., "Time-domain Dynamics and Stability Analysis of Optoelectronic Oscillators based on Whispering-Gallery Mode Resonators," IEEE J of Selected Topics in Quantum Electronics 19(5), 6000112 (2013).

[3] Salzenstein P., Voloshinov V. B. and Trushin A. S., "Investigation in acousto-optic laser stabilization for crystal resonator based optoelectronic oscillators," Optical Engineering 52(2), 024603 (2013)

[4] Tavernier H., Salzenstein P., Volyanskiy K., Chembo Y. K. and Larger L., "Magnesium Fluoride Whispering Gallery Mode Disk-Resonators for Microwave Photonics Applications," IEEE Photonics Technology Letters 22(22), 1629-1631 (2010).

[5] Salzenstein P., Mortier M., Sérier-Brault H., Henriet R., Coillet A., Chembo Y. K., Rasoloniaina A., Dumeige Y., Féron P., "Coupling of high quality factor optical resonators," Physica Scripta T157, 014024 (2013).

[6] Henriet, R., Salzenstein, P., Ristic, D., Coillet, A., Mortier, M., Rasoloniaina, A., Saleh, K., Cibiel, G., Dumeige, Y., Ferrari, M., Chembo, Y. K., Llopis, O., Féron, P., "High quality factor optical resonators," Physica Scripta T162, 014032 (2014).

9503-36, Session PS

Temperature controlled optical resonator process for optoelectronics oscillator application

Patrice Salzenstein, Mikhail Zarubin, FEMTO-ST (France)

Optical resonators are promizing for optoelectronic oscillators (OEO) [1, 2]. The laser needs to be locked on the resonance frequency of the resonator [3] and the quality factor of the optical resonator must be very high. During its process, the resonator must be heat at high temperature to relax stress at its surface. To control the temperature, we use a thermistor especially interesting for its higher sensitivity than thermocouples and resistance temperature detectors. To linearize the characteristic of the thermistor we use a shunt resistance. Oven with high working temperature is made of an aluminium cylinder with valves for Argon gas. Muffle chambers made from clay and nichrome wire hold the optical resonator during the process.

References:

[1] Volyanskiy K., Salzenstein P., Tavernier H., Pogurmirskiy M., Chembo Y. K. and Larger L., "Compact Optoelectronic Microwave Oscillators using Ultra-High Q Whispering Gallery Mode Disk-Resonators and Phase Modulation," Optics Express 18(21), 22358-22363 (2010).

[2] Coillet A., Henriet H., Salzenstein P., Phan Huy K., Larger L. and Chembo Y. K., "Time-domain Dynamics and Stability Analysis of Optoelectronic Oscillators based on Whispering-Gallery Mode Resonators," IEEE J. of Selected Topics in Quantum Electronics 19(5), 6000112 (2013).

[3] Salzenstein P., Voloshinov V. B. and Trushin A. S., "Investigation in acousto-optic laser stabilization for crystal resonator based optoelectronic oscillators," Optical Engineering 52(2), 024603 (2013).

[4] Henriet, R., Salzenstein, P., Ristic, D., Coillet, A., Mortier, M., Rasoloniaina, A., Saleh, K., Cibiel, G., Dumeige, Y., Ferrari, M., Chembo, Y. K., Llopis, O., Féron, P., "High quality factor optical resonators," Physica Scripta T162, 014032 (2014).

9503-37, Session PS

Synchronously pumped femtosecond optical parametric oscillator with broad band chirped mirrors

Karolina Stankeviciute, Vilnius Univ. (Lithuania); Simas Melnikas, Vilnius Univ. (Lithuania) and Ctr. for Physical Sciences and Technology (Lithuania); Simonas Kicas, Ctr. for Physical Sciences and Technology (Lithuania); Mikas Vengris, Mangirdas Malinauskas, Valdas Sirutkaitis, Vilnius Univ. (Lithuania)

Synchronously pumped femtosecond optical parametric oscillators (SPOPOs) provide tunable pulsed radiation at high repetition rate. Tuning range of these devices is determined by nonlinear materials and reflection bandwidth of mirrors used in SPOPO cavity. Dispersion properties of optical elements and especially mirrors placed inside SPOPO cavity play an important role for femtosecond pulse generation. Chirped mirrors are widely used to compensate dispersion; however manufacturing broad band mirrors with controlled dispersion is challenging [1]. Thus a narrow reflection band mirrors are commonly used for SPOPO systems [2]. For our experimental setup a pair of broad band dispersion compensated mirrors was designed and manufactured in such way that their reflection coefficients would be over 99 % in 600-1050 nm spectral range and group delay dispersion (GDD) oscillations would be less than ±10 fs2. GDD properties of mirrors were verified experimentally using homemade white light interferometer (WLI). Measurements have shown a significant experimental GDD spectrum deviation from theoretical in 800-1050 nm spectral region, as GDD oscillations rise up to ±250 fs2. As an outcome of these results, another pair of mirrors was manufactured with some alterations in coatings design. Subsequently, SPOPO cavity was constructed with dispersion compensated mirrors pairs. Radiation of mode-locked Yb:KGW laser providing ~105 fs pulses at 76 MHz repetition rate with average output power of 4 W at 1030 nm wavelength was frequency doubled. Thus up to 2 W at 515 nm was used to pump our SPOPO. We used beta barium borate (BBO) crystal as a nonlinear material for parametric light generation. Phase matching conditions at 515 nm pump allowed us to tune SPOPO signal wavelength in 640-1030 nm spectral region. During this study, GDD impact on SPOPO output pulse duration and wavelength tuning via cavity length detunig were closely examined. During the experiments we observed SPOPO output power as high as 450 mW around 680 nm exhibiting 25 % pump to signal conversion efficiency.

[1] G. Steinmeyer, "Femtosecond dispersion compensation with multilayer coatings: towards the optical octave," Appl. Optics 45, 1484 (2006).

[2] A. Esteban-Martin, V. Ramaih-Badarla, V. Petrov, and M. Ebrahim-Zadeh, "Broadband, rapidly tunable Ti:sapphire-pumped BiB3O6 femtosecond optical parametric oscillator," Optics Lett. 36, 1671 (2011).

9503-39, Session PS

Laser thermal recording on non-homogeneous medium

Ivan V. Gorbov, Anatoly S. Lapchuk, Andriy A. Kryuchyn, Yuriy O. Borodin, Institute for Information Recording (Ukraine)

Laser thermal recording enables to create nanostructured object by using laser radiated in optical waveband. A key feature of such method is the use of non-linear thermoresists as a recording medium. The processes running in thermoresist under laser illumination are very complicated and depend on many structure parameters. A mathematical model and computer program for analysis of laser recording process in a thermoresist layer deposited on multilayer substrate based on finite differences time domain method are elaborated. The program calculates light intensity and temperature distributions in the structure and the phase of thermoresist. The analysis of simulation results showed that sizes of formed structure are mainly determined by such parameters as energy and duration of laser radiation pulses, the level of thermoresist transparency, the ratio of thermal conductivity of thermoresist to multilayer structure on which it is deposited and a latent heat of phase transition. When the thermal conductivity of multilayer structure exceeded the thermal conductivity of thermoresist or when layer of thermoresist is opaque it is practically impossible to create a structure with transverse sizes less than the thickness of the thermoresist layer. Due to the strong heat flow from an area near region of phase transition boundary, the boundary is practically fixed till the complete phase transition at the area. It was shown that properly selected thermal and optical parameters of thermoresist and multilayer structure and short pulses of laser radiation allow creating of the nanoscale structures. The reliable high-density laser thermal recording requires the high accuracy control of thermoresist, multilayer structure and laser pulses parameters.

The method of high-density data thermo-recording by defocused laser beam was proposed. The significant impact on the shape of the laser spot has a selection of the focus point, called the point of constriction. Changing the point of constriction can significantly reduce the diameter of the central peak of the energy distribution of focused laser spot, but this leads to an increase in the intensity of the side peaks. During the traditional photochemical recording can only be used with the constriction point of minimum amplitude of the side peaks. But in case of laser thermo-lithography when recording medium used with non-linear characteristics, it is possible to use other points of constriction. The main condition in this case is that the amplitude of the side peaks should remain below the level at which it will be observed change in the phase state of recording media. Experimental study showed 30% decreasing of central peak diameter of 405 nm laser spot focused by 0.85 NA lens due to shifting of constriction point.

9503-40, Session PS

Analysis of the optoelectronic properties in 1,3-benzoxazole molecule under the effect of electro-acceptor substituent (OH and O2N) and electro-donor (CH3 and NH2) in the ground state and gas phase

Ronal A. Pérez Jimenez, Dairo J. Hernández Páez, Univ. de La Guajira (Colombia); Rafael Jose Carrasquilla Orozco, Oscar Leon Neira Bueno, Maria C. Calderon, Univ. Popular del Cesar (Colombia)

Theoretical calculations were performed on 1,3-benzoxazole and two derivatives structures in the ground state and gas phase using the B3LYP functional and the 6-31+G(d) basis sets. Computational Quantum Chemical calculations were carried out using the Gaussian 03 set of computer programs. Several global molecular descriptors were considered such as the chemical hardness, the electronegativity and the dipole moment for each molecule and was determined the influence that has, about the values of these descriptors, the electro donor and acceptor substituent on the optoelectronic properties of the parent structure (1,3-Benzoxazole).

9503-41, Session PS

Modeling of self-diffraction from the induced aperture in colloidal quantum dots

Kseniia Ezhova, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Alexander M. Smirnov, Lomonosov Moscow State Univ. (Russian Federation)

Modeling of self-diffraction pattern formation from the induced diaphragm, arising in the case of the transparency channel saturation in the case of one-photon resonant non-stationary excitation of the basic exciton transition in colloidal quantum dots (QD) is realized. The simulation results allow to obtain the reference image of self-diffraction pattern and dependence of the intensity transverse distribution of

the output beam from the intensity of the excitation beam, forming a transparency channel. Subsequent comparative analysis with the experimental data (presented in the paper [1] that aimed to study of peculiarities of nonlinear and electro-optical processes occurring in the case of excitation of the exciton transition in colloidal semiconductor QDs CdSe/ZnS) allows to investigate the dependence of the resulting pattern output characteristics on the input parameters that influence to the self-diffraction results formation features. The input parameters are the excitation radiation wavelength, the distance from the source to the cell with the colloidal QD, from the cell to the screen (receiver), aperture radius, which depends on the radiation intensity and the concentration of QD in solution in this case. As a first approximation the two-level system saturation effect is considered as a nonlinear effect responsible for the formation of transparency channel arising in colloidal QD.

Self-diffraction is an effect of self-action of light waves propagating in a nonlinear medium whose properties depend on the intensity of light. The process of self-diffraction from the induced diaphragm is possible due to rapid absorption decrease at the frequency of the basic electron-hole transition. A powerful laser pulse creates a transparency channel, so that it self-diffracts on the induced diaphragm.

The possibility to apply the obtained simulation results for intensity estimation of the laser radiation and for the possible application in the technique (nonlinear-optical limiters of intense laser radiation in the visible and near-infrared region, optical switches) are discussed.

[1] V.S. Dneprovskii, M.V. Kozlova, A.M. Smirnov, Quantum Electronics 43 (10) 927 – 930 (2013)

9503-42, Session PS

DFT study of the electronic structure of 1,3-benzoxazole and derivatives in their neutral, anion and cation forms

Dairo J. Hernández Páez, Samuel E. Zambrano, Rafael Jose Carrasquilla Orozco, Univ. de La Guajira (Colombia); Oscar Leon Neira Bueno, Univ. Popular del Cesar (Colombia)

1,3-Benzoxazole and three derivatives with electron-accepting and electron-donating substituent in their anionic, neutral and cationic charge states are investigated using the density functional theory. The effect of addition and removal of the electron on the bond lengths, atomic charges, frontier orbitals, ionization potential (IP), electron affinity (EA) and reorganization energy is considered. The computed IP, EA and optical gaps are in rather good agreement with available experimental data.

9503-43, Session PS

DFT study of optical and electronic properties of molecule 1,3-benzoxazole under the influence of acceptor substituent (CHO and NO2H2) and donor (NO2H2 and CHO) neutral gas phase and first excited state

Rosa M. Barliza P., Dairo J. Hernández Páez, Martha Kammerer, Univ. de La Guajira (Colombia); Rafael Jose Carrasquilla Orozco, Univ. Popular del Cesar (Colombia); Ronal A. Pérez Jimenez, Univ. de La Guajira (Colombia)

In this paper a comparative theoretical study of the effect of electro-electro-donor and acceptor substituent at the optoelectronic properties of the parent structure of benzoxazole gas phase, both in the ground state and the first singlet excited state was performed. To this end was used as calculation tools computational algorithms containing the Gaussian 09 program package, using chemical model specified by the approach of the theory of density functional (DFT) B3LYP hybrid functional with the set of basis functions 6-31 + G (d). Vertical transition probabilities are estimated from the ground state to the first excited singlet state obtaining electronic transitions that give rise to absorption spectra obtained from TD-B3LYP /6-31+G (d).

9503-44, Session PS

Theoretical study of the solvent effect on the optical absorption and emission properties benzoxazole molecule from the perspective of quantum computational chemistry

Julio Deluque C., Univ. de La Guajira (Colombia); Maria C. Calderon, Univ. Popular del Cesar (Colombia); Dairo J. Hernández Páez, Ronal A. Pérez Jimenez, Univ. de La Guajira (Colombia)

The absorption and emission optical properties of the molecule of 1,benzoxazole on the first excited state have been described theoretically in different solvents by TD-RHF/6-31+G(d) method, using Gaussian 09 and the Polarizable Continuum Model (PCM), to study the solvent effect on these properties. These properties of the benzoxazole are of considerable analytical interest, given that they are related with the search of active medium for tunable lasers. It is found that the solvent to produce both hipsocrómicos and bathochromic effects on the absorption and emission maxima. Generally, the predicted data are in agreement with the experimental data.

9503-45, Session PS

Effect of ambient gases on the characteristics of (Zn,Ga)-doped In2O3 (IZGO) thin films for organic light emitting diodes

KyuMann Lee, MinKyu Lee, Korea Univ. of Technology and Education (Korea, Republic of)

Indium tin oxide (ITO) thin films have been extensively utilized in these devices because of their high transmittance in the visible range and low electrical resistivity. However, indium is a relatively scarce element in the earth's crust, leading to high cost for ITO production. The other drawback of ITO thin films is the unstable chemical stability in a reduced ambient. The indium of ITO layer can diffuse into the organic materials, which leads to significant deterioration of the device reliability. Recently, new transparent conducting oxide such as IZGO ((Zn,Ga)-doped In2O3) thin films have emerged as promising anode materials for OLEDs due to their high work function, low resistivity, and high transmittance over 90% in the visible spectrum range. The properties of IZGO thin films strongly depend on the stoichiometry, microstructure, and the nature of the impurities. Therefore, it is interesting to study the effect of the ambient gas on the structure, the electrical resistivity, and the optical band gap energy of the IZGO thin films. For this purpose, IZGO thin films were deposited by RF magnetron sputtering under various ambient gases (Ar, Ar+O2, and Ar+H2). The electrical resistivity and the optical band gap of the TCO thin films were systematically examined. In order to elucidate the effect of the electrical resistivity and/or the optical band gap on the performance of OLED devices, the organic materials and cathode electrode were sequentially deposited on the TCO thin films. Then, the electrical characteristics such as current density vs. voltage and luminescence vs. voltage of OLED devices were measured.

Conference 9504: Photon Counting Applications

Monday - Tuesday 13–14 April 2015

Part of Proceedings of SPIE Vol. 9504 Photon Counting Applications 2015

9504-1, Session 1

Real-time single-photon imaging with a 64-pixel WSi superconducting nanowire camera *(Invited Paper)*

Varun B. Verma, Michael S. Allman, Martin J. Stevens, Robert D. Horansky, National Institute of Standards and Technology (United States); Francesco Marsili, Matthew D. Shaw, Andrew D. Beyer, Jet Propulsion Lab. (United States); Richard P. Mirin, Sae Woo Nam, National Institute of Standards and Technology (United States)

We have demonstrated a superconducting nanowire camera based on amorphous WSi consisting of 64 individual SNSPD (superconducting nanowire single-photon detector) pixels. Each pixel has an active area of 30 µm x 30 µm, and the 8 x 8 array of pixels are spaced on a 60 µm pitch yielding a fill factor of ~0.25. The camera is biased and read out using a novel row-column readout scheme. Each of the 8 rows is individually biased, and each row and column is individually read out with a chain of room-temperature amplifiers. Output pulses from these amplifier chains are fed into a 16-channel time-tagging unit and to real-time histogramming and coincidence software. Simultaneous voltage pulses on row i and column j indicate that pixel (i,j) has detected a photon.

To test the device, light from a 1550 nm laser is free-space coupled through optical windows to the camera, which is held at a temperature of 800 mK in a closed-cycle cryostat. Because WSi SNSPDs are sensitive to blackbody photons from room temperature, we use two cold bandpass filters inside the cryostat to block most of this background. A computer-controllable image is encoded onto the laser beam with a digital micromirror device, and read out with the superconducting nanowire camera. We have shown that every one of the 64 pixels is sensitive to light, and that the coincidence software can sustain real-time, video-rate imaging with several thousand detected photons per second on each pixel.

9504-2, Session 1

Near-field single photon detection in a scattering SNOM

Qiang Wang, Michiel J. A. de Dood, Leiden Univ. (Netherlands)

If single photons can be detected directly in the optical near-field the investigation of light-matter interaction on the nanoscale will benefit enormously. To this end we perform finite difference simulations to calculate the absorption of a nanometer-sized NbN superconducting single photon detector placed directly in the near-field of a scattering near-field scanning optical microscope (scattering NSOM). By taking into account the position-dependent click probability we finally estimate the overall response of the detector.

We consider a long, 4nm thick NbN wire fabricated on a GaAs substrate and it is constricted to a small, 100?100 nm^2 weak point in the wire. When a current bias is applied to these nanodetectors the superconductivity is weakest at this constriction and absorption of single photons lead to detection events. By reducing the bias current the detector can operate in a higher photon number regime.

In 3D FDTD simulations a sharp metal tip is placed on top of the NbN detector to scatter the incident light to the detector in its optical near-field. The sharp tip acts as an antenna or a point-like source, which localizes the light field around its end. From simulations we find that the absorption of the detector is strongly concentrated and enhanced due to the presence of the tip. The enhancement strongly depends on wavelength, position of the tip and geometry of the tip.

We combine FDTD calculation with a calculation of the position dependent intrinsic click probability. Based on this we will present the complete response of the scattering NSOM as a function of the tip position. Conversely, we expect this direct near-field signal detector can be used as a scanning probe with high spatial resolution and photon number resolving ability.

9504-3, Session 1

Dark counts in superconducting single-photon NbN/NiCu detectors

Loredana Parlato, Umberto Nasti, Univ. degli Studi di Napoli Federico II (Italy); Mikkel Ejrnaes, CNR-SPIN (Italy); Roberto Cristiano, CNR-SPIN (Italy); Hiroaki Myoren, Saitama Univ. (Japan); Roman Sobolewski, Univ. of Rochester (United States); Giovanni Piero Pepe, Univ. degli Studi di Napoli Federico II (Italy) and CNR SPIN UOS Naples (Italy)

Superconducting Single Photon Detectors (SSPDs) are the fastest and most reliable photon counters that became a highly desired technology in recent years. NbN SSPDs demonstrated counting rates exceeding 250 MHz in the wavelength range from UV to mid-IR, high quantum efficiencies at 1550nm, and very low dark-count rates at any operation bias point. In spite of very low values, dark events in a SSPD contribute significantly to noise-equivalent power and the ultimate sensitivity. A complete understanding of their physical nature still remains debated, and generally related to fluctuations occurring in superconducting strips which cause transitions to the normal state from the metastable superconducting state at currents close to the critical value Ic. Several fluctuation sources have been invoked for dark counts from thermal fluctuations of the number of excitations to spontaneous nucleation of the normal state across the strip with 2? –phase slip, from thermal excitation of single vortices near the edge of the strip with a consequent dissipative motion across the strip to the unbinding of vortex-antivortex pairs moving across the strip to opposite edges.

We studied the problem of dark counts in proximitised NbN/NiCu based nanostripes of various dimensions. The presence of a ferromagnetic layer influences the superconducting properties of the superconductor, in particular the critical current density Jc, the critical temperature Tc, the electron relaxation time, and finally the optical response of a SSPD. Accordingly, we focus on the investigation of the dark count rates in the presence of SF proximity effect (up to 6nm of NiCu) with respect to a pure NbN (8nm) SSPD. The observed decrease of the dark counts rate is discussed according to fluctuation models try to identify the leading process influencing dark counts in SSPDs.

9504-4, Session 1

Superconducting and ferromagnetic properties of NbN/NiCu and NbTiN/NiCu bilayer nanostructures for photon detection

Andrii Klimov, Institute of Electron Technology (Poland); Roman Puzniak, Institute of Physics (Poland); Enno Joon, Raivo Stern, National Institute of Chemical Physics and Biophysics (Estonia); Wojtek Slysz, Marek Guziewicz, Marcin Juchniewicz, Institute of Electron Technology (Poland); Jaroslaw Z. Domagala, Institute of Physics (Poland); Michal A. Borysiewicz, Renata Kruszka, Maciej Wegrzecki, Adam Laszcz, Andrzej Czerwinski, Piotr Dziawa, Institute of Electron Technology (Poland); Roman Sobolewski, Univ. of Rochester (United States)

Performance of superconducting single-photon detectors based on resistive hotspot formation in nanostripes upon optical photon absorption depends strongly on the critical current density Jc of the fabricated nanostructure. Utilization of an ultrathin, weak-ferromagnet cap layer on the top of a superconducting film should enhance of the structure's Jc due to an extra flux pinning. We have fabricated a number of both NbN/NiCu and NbTiN/NiCu superconductor/ferromagnet (S/F) ultrathin bilayers and microbridges. NbN and NbTiN underlayers with thicknesses varying from 4 to 7 nm were grown using dc-magnetron sputtering on chemically cleaned sapphire single-crystal substrates. After rapid thermal annealing at high temperatures, the S films were coated with Ni(0.54)Cu(0.46) overlayers with thicknesses about 6 nm, using co-sputtering. Compositions of the deposited films were confirmed by EDX spectroscopy analysis, while TEM studies demonstrated excellent epitaxial quality of our S layers with very sharp F/S and S/substrate interfaces. Magnetic properties of our bilayers were studied using both the SQUID and Vibrating Sample Magnetometer techniques in low and high magnetic fields. Our low-temperature tests confirmed that in all cases NiCu films were ferromagnetic with the Curie temperature of above 30 K. Below the bilayer critical temperature of approx. 12-13 K, the structures were fully proximitized with the strong superconducting signal. For superconducting transport properties characterization, we used bilayers patterned into 40-μm-long microbridges with the width varying from ~2 μm to 0.4 μm. We observed that for NbN/NiCu stripes with the width of above 1 μm, the Jc was slightly enhanced as compared to the reference NbN film, and, e.g., for a 1.6-μm-wide, NiCu(6 nm)/NbN(6 nm) bridge it was equal to 1.3 MA/cm^2 at 5 K (as compared to 1.2 MA/cm2). When the bridge width was reduced to 0.4 μm, Jc of a NiCu(6 nm)/NbN(8 nm) sample was 1 MA/cm2, while for a NiCu(6 nm)/NbTiN(7 nm) it was reduced by a factor of three, to 0.4 MA/cm^2. Patterning using optical lithography and over-etching seems to degrade the superconducting transport properties of the S/F stripes (especially in the case of NiCu/NbTiN samples) and should be substituted for e-beam lithography or, possibly, focused ion beam process.

9504-5, Session 1

YBCO nanowires for optical-photon detection *(Invited Paper)*

Loredana Parlato, Univ. degli Studi di Napoli Federico II (Italy); Giovanni Piero Pepe, Univ. degli Studi di Napoli Federico II (Italy) and CNR-SPIN UOS Naples (Italy); Mikkel Ejrnaes, CNR-SPIN (Italy); Roberto Cristiano, CNR-SPIN (Italy); Riccardo Arpaia, Floriana Lombardi, Chalmers Univ. of Technology (Sweden); Francesco Tafuri, CNR-SPIN (Italy); Roman Sobolewski, Univ. of Rochester (United States)

Recent advances in nano-patterning techniques opened the way for developing advanced applications of superconductors as detectors for single-photon counting with highly improved performances. Superconducting Nanowires Single Photon Detectors (SNSPDs) are currently object of great interest in the field of quantum optics, quantum key distribution and space telecommunication because of their high counting rates, extremely low dark counting rates and high sensitivity for single infrared photons. The best realizations are nowdays based on ultrathin layers of low critical temperature (LTS) superconductors: conditions such as a short coherence length, intrinsic fast quasiparticle recombination time, and, simultaneously, the highest possible transition temperature must be satisfied. Nevertheless, a high-temperature superconductor (HTS), such as YBa2Cu3O7-x (YBCO) meets all of these requirements, and hence it is a good candidate for advanced SNSPDs. Unfortunately, several drawbacks in the YBCO state-of-the-art technology make the realization of YBCO-based SNSPDs a very challenging task. We have successful fabricated 50-nm-thick YBCO and YBCO/LSMO nanowires on LAO substrates. The nanowires widths are in the range 90-500 nm, while the lengths varied up to 10 ?m. We have been able to achieve devices covering areas up to 30?10 ?m2, with a filling factor of 50%. Photo-response measurements have been performed by optical laser pulses at 1550 nm wavelength. A general discussion of experimental results will be presented, focusing also on the perspectives offered by superconducting oxides in the context of photon detection.

9504-6, Session 2

Single photon imaging with superconducting nanowire single photon detectors *(Invited Paper)*

Robert H. Hadfield, Univ. of Glasgow (United Kingdom)

Single nanowire single photon detectors offer single photon sensitivity with free running operation, low timing jitter and low dark counts at infrared wavelengths [1]. Using attenuated laser pulses 1550 nm wavelength, we have employed these devices successfully in time of flight ranging [2] and depth imaging studies in daylight at a range of several kilometres [3]. We are now working to extend this technique to 'ghost imaging' using a source of correlated photon pairs [4]. One photon from the pair at 1550 nm will interrogate an object and be detected via the SNSPD. The second correlated twin (400 nm) will be imaged on a high efficiency CCD. This will allow an image to be rapidly acquired from a large number of modes (>500).

[1] CM Natarajan, MG Tanner, RH Hadfield Superconducting nanowire single-photon detectors: physics and applications Superconductor Science and Technology 25 063001 (2012

[2] RE Warburton, A McCarthy, A Walker, S Hernandez-Marin, RH Hadfield, S Nam, GS Buller Subcentimeter depth resolution using a photon-counting time-of-flight laser ranging system Optics Letters 32 (15) 2266 (2007)

[3] A McCarthy, N Krichel, X Ren, NR Gemmell, MG Tanner, SN Dorenbos, V Zwiller, RH Hadfield, GS Buller Kilometer range time-of-flight depth imaging at 1560 nm wavelength with a superconducting nanowire single-photon detector Optics Express 21 7 8904 (2013)

[4] R Aspden et al EPR based ghost imaging using a single-photon sensitive camera New J Physics 15 073032 (2013)

9504-7, Session 2

Ultrafast superconducting single-photon detector with reduced-size active area coupled to a tapered lensed single-mode fiber

Maria Sidorova, Moscow State Pedagogical Univ. (Russian Federation); Alexander Divochiy, CJSC Superconducting Nanotechnology "SCONTEL" (Russian Federation); Yury B. Vakhtomin, Moscow State Pedagogical Univ. (Russian Federation) and CJSC Superconducting Nanotechnology "SCONTEL" (Russian Federation); Konstantin Smirnov, Moscow State Pedagogical Univ. (Russian Federation)

The Superconducting Single-Photon Detectors (SSPDs) demonstrate very promising performances for a wide area of applications [1] including modern quantum optics and quantum information where single-photons counting is the basic. Since the presentation of the first SSPD more than decade ago [2] these detectors became the subject research of many scientific groups in the whole world.

Here we present the ultrafast NbN SSPD which in contrast to conventional SSPD has record timing jitter <25 ps and ultra short recovery time <2 ns. It is important to note that other key features of SSPD such as extremely low dark counts level and high detection efficiency over a wide spectral range were not worsened at all. The results were obtained thanks to the development of new technique of effective optical coupling between reduced detector active area and a standard single-mode fiber.

Usually the realization of the high efficiency optical coupling to SSPD requires active area size of no less than a core diameter of SM fiber which is about 9 μm. The fabrication of the SSPD with smaller active area 3x3 μm^2 allowed reducing a kinetic inductance of the detector and therefore considerably decreasing the characteristic times of the front and rearing edges of the voltage pulse from detector at registration of a single photon. Such sharpening of the output pulse significantly reduces dead time and improves timing jitter of the receiver.

In order to achieve an effective optical coupling the special tapered lensed fiber was applied. At SMF28e fiber microlens was formed capable to collect light to the spot much smaller than the fiber core. The tapered lensed fiber was fixed inside ferrule so that the focal plane coincides with the flat surface of ferrule. Thus by placing the detector front side to the ferrule surface we achieve the correct position detector's sensitive area relative to the microlens focal plane. To check the robustness of fiber to detector coupling we measured spectral dependence of detection efficiency before and after dozen of thermal cycles. No changes were observed that allows affirming the high stability of such method to multiply thermocycles. The measured quantum efficiency of the detector installed to tapered lensed fiber is about 30% at ?=1.55 μm. It confirms that the efficiency of optical coupling is very close to 100% taking into account absorption ability of radiation by superconducting device.

Also we will present measured pulse shape, timing jitter and dead time of the ultrafast SSPD.

1. C. M. Natarajan, et al., Supercond. Sci. Technol. 25 (2012) 063001.

2. G. N. Gol'tsman, et al., Appl. Phys. Lett. 79, pp. 705, (2001).

9504-8, Session 3

Active quenching and gating circuit of the photon counting detector for laser time transfer with improved timing resolution and stability *(Invited Paper)*

Ivan Prochazka, Josef Blazej, Jan Kodet, Vojtech Michalek, Czech Technical Univ. in Prague (Czech Republic)

We are presenting the results of research and development of a new active quenching and gating electronics for Single Photon Avalanche Detector (SPAD). The goal of the work was to develop a new SPAD detector package for Laser Time Transfer ground to space with improved timing resolution and stability. The first version of a SPAD detector is operational on board of GNSS navigation satellites. It is based on 25 um diameter K14 series SPAD chips. It is providing timing resolution of typically 125 ps and stability of the order of 10 ps. The new control electronics provides timing resolution of 30 ps and timing stability and drifts of the order of one picosecond. The device is constructed on a basis of electronics components for which the space qualified equivalents are commercially available. The device construction, tests and results will be presented in detail.

9504-9, Session 3

High-performance timing electronics for single photon avalanche diode arrays

Giulia Acconcia, Matteo Crotti, Ivan Rech, Massimo Ghioni, Politecnico di Milano (Italy)

The Time Correlated Single Photon Counting (TCSPC) technique is very effective to analyze extremely weak and fast, periodical light signals and then it is increasingly widespread in a large number of fields and in many applications such as fluorescence imaging and laser scanning microscopy.

Nowadays, most of the high-performance TCSPC systems are focused on single channel applications and, to obtain a multidimensional system, the use of multiple acquisition chains is necessary, with very high costs and large occupied areas.

However, the development of Single Photon Avalanche Diode (SPAD) arrays is leading to the design of new multichannel TCSPC systems, that can fit the specifics of even more applications. In this domain, the reduction of occupied area and dissipated power are crucial to develop a densely packed timing array. Nevertheless, available TCSPC systems still suffer from a trade-off between number of channels and performance: the higher the number of channels, the poorer the performance on each channel.

In order to overcome this trade-off, we present the design of the integrated electronics necessary to develop photon timing systems featuring either a large number of channels and high performance.

First of all, a circuit capable of directly reading the SPAD avalanche current is of the utmost importance in order to achieve a very high temporal resolution while minimizing the crosstalk. Thus, a fully integrated trans-impedance stage with a gigahertz bandwidth has been designed and fabricated in 0.18 um featuring a time resolution lower than 40ps and negligible crosstalk.

Secondly, a fully integrated array of high performance time-to-amplitude converters (TAC) has been designed: starting from the very good results obtained with a first prototype consisting of four independent single channel TACs on the same chip, an array of 16 TAC has been designed in 0.35um SiGe technology. The first simulations on the new chip show very high performance on each channel: a time resolution of less than 20 picoseconds on 12.5 ns full scale range, a differential non linearity lower than 1 % peak to peak of the LSB and a conversion frequency of 4MHz.

Finally, an integrated circuit capable of routing the signal coming from the trans-impedance stage towards the TACs has been designed in 0.18 um technology. The routing logic connects the SPAD to one of the TAC converters only if a photon has been detected, thus opening the way to resource sharing: having few TACs in fact allows a larger area and a higher power dissipation for the single converter which contributes to achieve very high performance in terms of time resolution and linearity.

In conclusion, three fully integrated circuits have been designed: a pick-up circuit to read the SPAD current, a routing logic to feed the electrical signal coming from the SPAD to the time measurement blocks and an array of TACs to properly measure the time interval. The development of these building blocks can lead to the design of innovative architectures for TCSPC measurement, featuring both a large number of channels and very high performances on each channel.

9504-10, Session 3

Single photon time transfer link model for GNSS satellites

Michael Vacek, Vojtech Michalek, Marek Peca, Czech Technical Univ. in Prague (Czech Republic) and SERENUM, a.s. (Czech Republic); Ivan Prochazka, Josef Blazej, Czech Technical Univ. in Prague (Czech Republic)

The importance of optical time transfer serving as a complement to traditional microwave links, has been attested for GNSSes and for scientific missions. Single photon time transfer (SPTT) is a process, allowing to compare (subtract) time readings of two distant clocks. Such a comparison may be then used to synchronize less accurate clock to a better reference, to perform clock characterization and calibration, to calculate mean time out of ensemble of several clocks, displaced in space. The single-photon time transfer is well established in field of space geodesy, being supported by passive retro-reflectors within space segment of five known GNSSes. A truly two-way, active terminals work aboard of Jason-2 (T2L2) - multiphoton operation, GNSS Beidou (Compass) - SPTT, and are going to be launched within recent ACES project (ELT) - SPTT, and GNSS GLONASS - multiphoton operation. However, there is still missing comprehensive theoretical model of two-way (using satellite receiver and retro-reflector) SPTT link incorporating all crucial parameters of receiver (both ground and space segment receivers), transmitter, atmosphere effects on uplink and downlink path, influence of retro-reflector. The input to calculation of SPTT link performance will be among others: link budget (distance, power, apertures, beam divergence, attenuation, scattering), propagating medium (atmosphere scintillation, beam wander, etc.), Rx noise factors (white, poissonian, background light), mutual Tx/Rx velocity, wavelength, bandwidth. For a practical applicability, the SPTT model will be evaluated with the properties of typical real components today in operation. The ground-to-space SPTT link performance of typical and worst-case scenarios are modeled and discussed. This work is a part of the ESA study "Comparison of optical time-transfer links".

9504-11, Session 3

Aqueye+: a new ultrafast single photon counter for optical high time resolution astrophysics

Luca Zampieri, INAF - Osservatorio Astronomico di Padova (Italy); Giampiero Naletto, Cesare Barbieri, Enrico Verroi, Univ. degli Studi di Padova (Italy); Mauro Barbieri, INAF - Osservatorio Astronomico di Padova (Italy); Giovanni Ceribella, University of Padova (Italy); Maurizio D'Alessandro, Giancarlo Farisato, INAF-Astronomical Observatory of Padova (Italy); Andrea Di Paola, INAF-Astronomical Observatory of Rome (Italy); Paolo Zoccarato, Trimble Terrasat GmbH (Germany)

Aqueye plus is a new ultrafast single photon counter, based on single photon avalanche photodiodes (SPAD) and a 4-fold split-pupil concept. It is a completely revisited version of its predecessor, Aqueye, successfully mounted at the 182cm Copernicus telescope in Asiago. Here we will present the new technological features implemented on Aqueye plus, namely a state of the art timing system, a dedicated and optimized optical train, a real time acquisition of atmospheric seeing unit and remote control, which will give Aqueye plus much superior performances with respect to its predecessor, unparalleled by any other existing fast photometer. The instrument will host also an optical vorticity module to achieve high performance astronomical coronography. The present paper describes the instrument and its first performances.

9504-12, Session 3

Single-photon level responsivity of asymmetric nanochannel diodes

Yunus E. Akbas, Univ. of Rochester (United States); L. Q. Zhang, Y. Alimi, Aimin M. Song, The Univ. of Manchester (United Kingdom); I. Iñiguez-de-la-Torre, Javier Mateos, Tomás González, Univ. de Salamanca (Spain); Gary W. Wicks, Roman Sobolewski, Univ. of Rochester (United States)

We present our research on fabrication, optical characterization, and physical Monte-Carlo simulations of novel semiconducting asymmetric nano-channel diodes (ANCDs). The ANCD, also called the self-switching diode, is fundamentally a new type of semiconductor nano-device that, contrary to conventional diodes, develops its asymmetric current-voltage (I-V) curve without barriers, relying instead on the asymmetry of the fabricated structure and field-controlled transport in a ballistic nanometer-width channel. Based on Monte Carlo simulations, ANCDs are expected to be powerful, tunable THz generators, as well as sensitive THz detectors. In this presentation, we are focused on not previously pursued, optically-active ANCDs, and demonstrate that they can be operated as very sensitive, single-photon–level, visible-light photodetectors. Our actual test devices exhibited 1.5-μm-long and ~300-nm-wide channels and were fabricated on an InGaAs/InAlAs quantum-well heterostructure mesa, using electron-beam lithography and wet chemical etching. The ANCD I-V curves were collected by measuring the transport current for the voltage-source biasing condition, both in the dark and under light illumination. As an optical excitation we used 800-nm-wavelength continues-wave radiation generated by a commercial, non-mode-locked Ti:sapphire laser. Although the I-V curve measured in the dark was not as strongly nonlinear as theoretically predicted and the nanochannel of our devices remained open even at zero bias, the impact of the light illumination was very clear, and we observed a substantial (several nA) photocurrent for the incident optical power as low as 1 nW. Most interestingly the magnitude of the device optical responsivity, expressed in A/W, increased linearly with the decrease of the optical power over many orders of magnitude, reaching the value of almost 10,000 at the 1-nW excitation. The latter is comparable to the gain of avalanche-type photodetectors. The physics of the photoresponse gain mechanism in ANCD arises from a vast difference between the transient time of electrons travelling in the 2-dimensional gas layer nanochannel and the lifetime of holes pushed towards the substrate. When cooled (to minimize the dark current) our ACNs should be practical photon counters. Especially attractive should be ANCDs implemented in the InAs or InSb material systems, since they will cover the infrared radiation region, including the most important, telecommunication and thermal imaging wavelengths.

9504-13, Session 4

Detectors for counting X- and gamma-rays based on compound semiconductors *(Invited Paper)*

Ralph B. James, Aleksey E. Bolotnikov, Giuseppe S. Camarda, Yonggang Cui, Anwar Hossain, Utpal N. Roy, Ge Yang, Rubi Gul, Brookhaven National Lab. (United States); Wonho Lee, Korea Univ. (Korea, Republic of)

Compound semiconductors are under investigation by many organizations for detecting and imaging X- and gamma-ray radiation based on counting single-photon events. Among the different crystals available today, Cadmium Zinc Telluride (CdZnTe or CZT) is the most extensively studied due to its band-gap, high atomic number, availability of large crystals, and good charge-carrier transport properties. In the past decade, there has been a two-pronged approached approach to advance the technology, (1) Identify defects in the material and fix the material deficiencies therein, and (2) Use the best material available today for fabricating suitable detectors and incorporating them into deployed instruments. Most engineering approaches to develop CZT detectors have focused on designing different configurations of the electrodes and using pulse processing, mainly to minimize the effects of carrier trapping and to improve the spectroscopic and imaging performance. Despite the important progress on developing electron-transport-only detectors and correction algorithms, crystal defects in CZT materials still limit the yield and cost of detector-grade commercial crystals, and they often dominate the detectors' performance, especially for large-volume devices used to detect and image radiation above 200 keV. Over the past years, materials research at BNL was extended to characterizing these CZT materials at the micro-scale level, and correlating the crystal's defects with the detector's performance. We built a set of dedicated tools for this research, including automated infrared (IR) transmission microscopy, X-ray micro-scale mapping using a synchrotron light source, X-ray transmission / refraction tomography, current deep level transient spectroscopy, and photoluminescence measurements. In addition, we used state-of-art instruments to measure some of the electrical, optical and micro-structural properties. This presentation will report some of our recent findings to improve the crystal growth and fabrication processes, improve the methods for purification, distinguish various crystal defects and their effects on carrier trapping, and study the internal electrical field in detectors.

9504-14, Session 4

Large-volume virtual Frisch-grid CdZnTe detectors for X- and gamma-ray sensors

Aleksey E. Bolotnikov, Kim Ackley, Giuseppe S. Cammarda, Carly Cherches, Yonggang Cui, Gianluigi De Geronimo, Jack Fried, Anwar Hossain, Brookhaven National Lab. (United States); Wonho Lee, Korea Univ. (Korea, Republic of); George Mahler, Maxwell Maritato, Brookhaven National Lab. (United States); Matthew Petryk, Binghamton Univ. (United States); Uptal N. Roy, Cynthia Salwen, Ge Yang, Emerson Vernon, Ralph B. James, Brookhaven National Lab. (United States)

We present the results from testing ultra-thick, up to 25 mm, virtual Frisch-grid CdZnTe (CZT) detectors intended for assembling large-effective-area X-ray and gamma-ray sensors. The novel CZT devices provide high-performance spectroscopy and sub-millimeter position

resolution. We employed a data acquisition system based on the newly developed BNL ASIC and data acquisition system for reading the signals from individual detectors and arrays. The performance of the virtual Frisch-grid detectors was enhanced by employing position-sensing strips on the side surfaces of the detectors. The X-Y position information allows for more accurate corrections of charge losses caused by crystal defects. As we will describe in the talk, this feature improves the performance of detectors fabricated from lower-quality CZT material leading to an increase in the production yield and an expected decrease in cost.

The pulse-height spectra obtained with uncollimated radioactive sources validated the operation principles of such devices and how they compensate for non-uniformity of response caused by extended defects in CZT crystals. The results presented here indicated strong correlations between individual sensors' responses and the crystal defects revealed by using several material characterization techniques.

9504-15, Session 4

Study of post-growth annealing of CdMnTe X-ray and gamma-ray detectors in Cd-rich atmosphere

Stephen U. Egarievwe, Alabama A&M Univ. (United States); Utpal N. Roy, Brookhaven National Lab. (United States); David K. Kithinji, Julius O. Jow, John O. Mwathi, Alabama A&M Univ. (United States); Ge Yang, Ralph B. James, Brookhaven National Lab. (United States)

There have been recent interests in the development of Cadmium Manganese Telluride (CdMnTe or CMT) as a semiconductor material for room-temperature X-ray and gamma-ray detection applications. Like Cadmium Zinc Telluride (CZT), CMT has high Z-number (Cd = 48, Mn = 25, Te = 52) that provides high stopping power for these high energy radiations. Bridgman method has been successfully used to grow detector-grade CZT crystals and it is one of the current methods used in the growth of CMT. Due to the growth of CZT and CMT in Te-rich environments, the as-grown crystals are often prone to Te inclusions that limit their performances as X-ray and gamma-ray detectors. This paper will present results of annealing in Cd-rich environment, Bridgman-grown CMT crystals so as to eliminate the Te inclusions and thus improve their charge collection abilities which will in turn lead to better detector performance.

[This work has been supported by the U.S. Department of Homeland Security, Domestic Nuclear Detection Office, under competitively awarded contract/IAA award number 2012-DN-077-ARI065-03. Alabama A&M University researchers were also supported by the U.S. Nuclear Regulatory Commission through award number NRC-27-10-514, and BNL scientists received support from the U.S. Department of Energy Office of Defense Nuclear Nonproliferation R&D. These supports do not constitute an expressed or implied endorsement by the U.S. Government.]

9504-16, Session 4

Defect level analysis of CdZnTe crystals and the related thermal annealing studies

Ge Yang, Aleksey E. Bolotnikov, Yonggang Cui, Giuseppe S. Camarda, Anwar Hossain, Utpal N. Roy, Ralph B. James, Brookhaven National Lab. (United States)

The II-VI compound CdZnTe (CZT) has been considered as one of the leading materials for fabricating room-temperature X-ray and gamma-ray detectors. Different material defects, e.g. Te inclusions/precipitates, sub-grain boundaries, dislocations, etc., can degrade the photon counting capability and associated device performance, lower the yield and affect the deployment of CZT detector technology. These defects play a key role in determining the electrical properties, e.g. resistivity and charge transport properties, of CZT. Thus, it is especially important to study the defect-related energy levels and understand their effect on detector performance. Meanwhile, thermal annealing offers a promising method to reduce these defects and could potentially improve the structural and electrical properties of CZT crystals. Here, we report new analysis results of defect-related energy levels in detector-grade CZT crystals. We will also present our thermal annealing experiments of CZT under suitable Cd, Zn and Te partial pressure control and analyze their effects on CZT's physical properties. In particular, we will focus on the evolution of star-like defects and the electrical properties during annealing process and relate them to the specific annealing conditions such as annealing environment, annealing temperature and annealing time. Test data from low-temperature photoluminescence spectroscopy, infrared (IR) microscopy, white beam X-ray diffraction topography, transmission electron microscopy, and current-voltage measurements will be presented and analyzed. These efforts help to better understand and improve the structural and electrical properties of CZT for photon-counting applications.

9504-17, Session 4

Comparative study of the effects of chemo-mechanical polishing and chemical etching on CdZnTe nuclear radiation detectors

Stephen U. Egarievwe, Alabama A&M Univ. (United States); Anwar Hossain, Brookhaven National Lab. (United States); Julius O. Jow, Alabama A&M Univ. (United States); Utpal N. Roy, Ralph B. James, Brookhaven National Lab. (United States)

Surface defects on cadmium zinc telluride (CdZnTe) crystals for nuclear radiation detection applications are often created during the fabrication process when dicing wafers from the ingot. These defects include surface roughness, dangling bonds, and nonstoichiometric surface. Surface defects reduce the performance of CdZnTe X-ray and gamma-ray detectors, and could also lead to degradation and reduction of the shelf life. To reduce these defects, mechanical polishing, chemical etching and surface passivation are applied to the surfaces of the CdZnTe wafers. This paper will compare the effects of chemo-mechanical polishing and chemical etching on CdZnTe nuclear radiation detectors.

[This work has been supported by the U.S. Department of Homeland Security, Domestic Nuclear Detection Office, under competitively awarded contract/IAA award number 2012-DN-077-ARI065-03. Alabama A&M University researchers were also supported by the U.S. Nuclear Regulatory Commission through award number NRC-27-10-514, and BNL scientists received support from the U.S. Department of Energy Office of Defense Nuclear Nonproliferation R&D. These supports do not constitute an expressed or implied endorsement by the U.S. Government.]

9504-18, Session 5

Enhancing the fill-factor of CMOS SPAD arrays using microlens integration *(Invited Paper)*

Giuseppe Intermite, Ryan E. Warburton, Aongus McCarthy, Ximing Ren, Heriot-Watt Univ. (United Kingdom); Federica A. Villa, Politecnico di Milano (Italy); Andrew J. Waddie, Mohammad R. Taghizadeh, Heriot-Watt Univ. (United Kingdom); Yu Zou, Franco Zappa, Alberto Tosi, Politecnico di Milano (Italy); Gerald S. Buller, Heriot-Watt Univ. (United Kingdom)

Arrays of single-photon avalanche diode (SPAD) detectors were fabricated, using a 0.35 μm CMOS technology process, for use in applications such as time-of-flight 3D ranging and microscopy. Each 150 x 150 μm pixel comprises a 30 μm active area diameter SPAD and its associated circuitry for counting, timing and quenching; resulting in a fill-factor of 3.14%. This paper reports how a higher effective fill-factor was achieved as a result of integrating microlens arrays on top of the 32 x 32 SPAD arrays. Diffractive and refractive microlens arrays were designed to concentrate the incoming light onto the active area of each pixel. A

telecentric imaging system was used to measure the improvement factor (IF) resulting from microlens integration, whilst varying the f-number of incident light from f/2 to f/22 in one-stop increments across a spectral range of 500-900 nm. These measurements have demonstrated an increasing IF with f-number, and a maximum of ~16 at the peak wavelength, showing a good agreement with theoretical values. An IF of 16 represents the highest value reported in the literature for microlenses integrated onto a SPAD detector array. The results from statistical analysis indicated the coefficient of variation of the IF was between 3-10% across the whole f-number range, demonstrating excellent uniformity of the imagers with and without microlenses.

9504-19, Session 5

Occurrence and characteristics of mutual interference between LIDAR scanners

Gunzung Kim, Jeongsook Eom, Yeungnam Univ. (Korea, Republic of); Seonghyeon Park, Yeungnam University (Korea, Republic of); Yongwan Park, Yeungnam Univ. (Korea, Republic of)

LIDAR scanners are key components of intelligent vehicles capable of autonomous travel. Up to now, interference has not been considered as a problem because the percentage of vehicles equipped with LIDAR scanner and therefore the probability of interference was extremely rare, and the scanners were used mainly for comfort functions. On the contrary, obstacle detection functions of autonomous vehicle require very low failure rates. The LIDAR scanner mounted on the top of autonomous vehicle allows the vehicle to generate a detailed 3D map of its environment. So in spite of a predicted higher number of LIDAR scanners, the probability of interference-induced problems has to be reduced considerably. With the increasing autonomous vehicle equipped with LIDAR scanner for obstacle detection and avoidance to navigate safely through environments, the probability of mutual interference becomes an issue. With an increasing number of autonomous vehicle equipped with LIDAR scanner operated close to each other at the same time, LIDAR scanner may receive signals from other LIDAR scanners. The reception of foreign signals can lead to problems such as ghost targets or a reduced signal-to-noise ratio. The reception of unwanted signals from other LIDAR scanners are called mutual interference between LIDAR scanners.

In this paper two experiment are reported, one illustrating training environment and the other is interference testing environment. The mutual interference between LIDAR scanners was tested on two SICK LMS-511 LIDAR scanners currently available off-the-shelf. The experimental area is surrounded by low glossy wood walls. Two LIDAR scanners are located inside of experimental area. One LIDAR scanner - LIDAR scanner V - is acting as victim located at the center and the other LIDAR scanner - LIDAR scanner I - acting as interferer located between LIDAR scanner V and wall. LIDAR scanner I operates only when it is necessary to measure the damage due to mutual interference. LIDAR scanner V operates and records measured data continuously. For 50 hours total scanned lines are 4512061 and total scanned angles are 2892231101. Interfered lines are 199383 and interfered ratio is 4.4 %. Interfered angles of point are 1506741 and interfered ratio is 0.05 %. Longest successive interfered lines are 13 lines and about 0.5sec. Longest successive interfered angles are 102 points and about 25.5 degrees . It states that interference has spatial and temporal locality. If a particular angle is interfered at a particular time, then it is likely that nearby angles will be interfered in the near future. If a particular line is interfered at a particular time, then it is likely that same location will be interfered in the near future. It is difficult to ignore successive mutual interference at the same line or the same angle because it is possible the real object not noise or error.

9504-20, Session 5

Superiorities of time-correlated single-photon counting against standard fluorimetry in exploiting the potential of fluorochromized oligonucleotide probes for biomedical investigation

Marco Lamperti, Univ. degli Studi dell'Insubria (Italy); Luca Nardo, Univ. degli Studi di Milano Bicocca (Italy); Maria Bondani, Consiglio Nazionale delle Ricerche (Italy)

Cytosine methylation is a widespread epigenetic regulation mechanism. Reversible methylation by means of dedicated proteins occurs within gene promoters and it is ascertained that the DNA-binding proteins involved in the initiation of replication and transcription display much reduced chemical affinity for methylated promoters than for the corresponding non-methylated sequences. However, another phenomenon of more biophysical nature has been argued to further reduce the "readability" of methylated promoters. Namely, methylation has been proposed to increase the thermodynamic stability of the double-stranded structure, thus inhibiting DNA breathing, i.e. spontaneous formation of denaturation bubbles in close proximity of promoters and their propagation, with the mediation of motor proteins inducing piconewton traction and torsion stresses on DNA, towards and across the downstream genes. Obviously, local disruption of the double-helical structure is a compelling propaedeutic event for both replication and transcription, and an even modest increase in stability of the double strand might prevent stress-induced bubbles propagation.

In this work, we adopted the melting temperature as indicator of the thermodynamic stability of a synthetic oligonucleotide sequence of 39 bases, dual labelled at its opposite ends with the donor and the acceptor of a fluorescence resonance energy transfer (FRET) pair, which was made to anneal to complementary oligonucleotides methylated at different extents. The melting temperatures of such dual-labelled oligonucleotides could in principle be determined with precision of few tenths of degree by monitoring the FRET efficiency versus temperature, as the single-stranded probe condenses in compact globules in which the donor to acceptor distance notably decreases. Steady-state techniques, however, are unable to discriminate those variations in the fluorescence signal which are induced by denaturation from those due to intrinsic temperature-dependence of the donor quantum yield. This issue can be circumvented by performing time-resolved fluorescence measurements, optimally by means of Time-Correlated Single Photon Counting (TCSPC). In TCSPC, a fluorescence decay time is attributed to each species, and the pre-exponential amplitudes of the different decay components reflect the relative concentrations of the different species. Conversely, temperature-dependent variations in the fluorescence quantum yield are reflected in proportional variations in the decay time values. Another obstacle consists in the fact that commercial samples of fluorochromized oligonucleotides contain aliquots of non-DNA-bound donor fluorophore. Usually, the FRET efficiency is negligible for double-stranded oligonucleotides exceeding few tens of base-pairs. Thus, the fraction of annealed DNA is hardly resolvable from the fraction of unbound donor even with TCSPC. By choosing as the donor a fluorophore, tetramethylrhodamine, which undergoes efficient fluorescence quenching by photoelectron transfer (PET) to guanine bases as far as they are stacked in the ordered double-helical structure, we were able to produce distinct decay times for the donor bound to either double-stranded oligonucleotides or single stranded probe molecules, and for unbound donor, thus obtaining very neat melting curves.

By exploiting the above expedients, we performed a systematic study of the thermodynamic stability of the differently-methylated oligonucleotides. A monotonic increase of the melting temperature upon increasing the degree of methylation was observed.

9504-22, Session PS

Research and Primary Results of SLR Experiment with 1064nm wavelength using Si Detector

Wendong Meng, Shanghai Astronomical Observatory (China)

SLR (Satellite Laser Ranging) is the most common satellite observation technology with the highest single shot measuring precision which usually using 532nm wavelength derived 1064nm laser. 1064nm wavelength has many better properties than 532nm in atmospheric attenuation, photon number, laser power, development and price, and so on, which is benefit to enhance the system detection ability, and carry out the goal of weak signal detection. In this paper, the key technology and difficulties are presented in building up a SLR system with the wavelength of 1064nm, and the corresponding solutions are put forward. With these technologies, the satellite laser ranging based on 1064nm wavelength in China was successfully carried out for the first time and the experimental foundations have been laid for the further development and application in field of space targets observation.

9504-23, Session PS

Thin scintillators for ultrafast hard X-ray imaging

Zhehui Wang, Cris W. Barnes, Jon S. Kapustinsky, Chris L. Morris, Ron O. Nelson, Los Alamos National Lab. (United States); Ren-Yuan Zhu, Liyuan Zhang, Fan Yang, California Institute of Technology (United States)

Ionizations are always accompanied by electronic excitations in atoms when X-rays interact with any medium. Ionizations produce electron and hole pairs in semiconductors. Electron-hole recombination and de-excitations in scintillators produce light at longer wavelengths than that of incident X-rays. In most cases, either the charge pairs or light produced is used for X-ray detection and imaging. Using light has some advantages over using charge pairs in ultrafast X-ray imaging even though photons are slowed down from the speed of light in vacuum by the refractive index of the medium. Photons can still propagate ~ 1000 times faster than the saturated electron speed which is limited to ~ 2x1.0e+7 cm/s and obtainable only when an intense electric field is applied. On the other hand, the spatial resolution of charge-based imaging is typically superior to scintillator-based imaging, since the spatial resolution of charge-based imaging is limited to the electron diffusion length, which can be much smaller than the light attenuation length, one of the limiting factors for the spatial resolution of scintillators. There are some fast scintillators, such as ZnO with various dopants, which have relatively short light attenuation lengths compared with for example LYSO or CLIC. These scintillators are traditionally discounted for applications when a large volume of detector mass is required, since most of the light is self-absorbed. On the other hand, these scintillators can be quite useful for ultrafast hard X-ray imaging because the material thickness needed is comparable to the light attenuation length. We examine the light yield, characteristic light decay time as functions of the thickness for several fast scintillator samples and evaluate their potential uses for ultrafast hard X-ray imaging with a spatial resolution ~ 100 micron, comparable to that in charge-based hard X-ray imaging.

9504-24, Session PS

Modeling of kinetic processes in thermoelectric single photon detectors

Astghik A. Kuzanyan, Armen S Kuzanyan, Vahan R Nikoghosyan, Institute for Physical Research (Armenia)

Intense development of science and engineering requires new generation of devices for precise measurements. Interest in single-photon detectors (SPD) has recently increased dramatically, due to many novel applications in various research fields, such as quantum communication, quantum cryptography, space astronomy, chemical analysis, particle physics, medical applications, traditional and quantum-enabled metrology and others. The most developed SPD are currently based on superconductors. Over the last ten years superconducting nanowire single-photon detectors (SNSPD) are actively investigated because of their high system detection efficiency, low dark count, high counting rate and timing resolution. Following the theory, thermoelectric detectors can compete with superconducting detectors and Thermoelectric Nanowire Single-Photon Detector (TNSPD) with superconducting nanowire single-photon detectors.

Thermoelectric single-photon detectors are one of the emerging techniques for fast single-photon counting . The sensor of the detector is composed of two micron-sized thin pads—photon absorbers, connected by a bridge made of thermoelectric material. The principle of operation of the detector is simple. When one of the pads absorbs a photon, its temperature raises by an amount proportional to the energy of absorbed photon. The resulting temperature difference between the ends of the thermoelectric bridge creates a potential difference ?U. We can measure ?U with high precision and thus register the absorbed photon and determine its energy.

In this work we present the results of computer modeling of the thermoelectric single-photon detector. We observe the processes of heat distribution after absorption of a photon of 0.1-1 keV energy in different parts of the absorber for different geometries of absorbers and bridge. The calculations were carried out by the matrix method for differential equations using parameters for the tungsten absorber and thermoelectric bridge made of (La,Ce)B6.

It is shown that computer simulations may significantly contribute to selection of an optimal geometry of the thermoelectric detector sensor. The results of calculations show that it is realistic to detect photons about 0.1-1 keV energy by accuracy no less than 1% without amplification of the obtained signals for their registration. High count rates up to 200 GHz can be achieved!

9504-25, Session PS

Simultaneous detection of tissue autofluorescence decay distribution and time-gated photo-bleaching rates

Alexey P. Lihachev, Inesa Ferulova, Univ. of Latvia (Latvia); Mindaugas Tamosiunas, Vytautas Magnus Univ. (Lithuania); Janis Spigulis, Univ. of Latvia (Latvia)

Experimental methodology for parallel measurements of in-vivo skin autofluorescence (AF) lifetimes and photo-bleaching dynamic has been developed and tested. The AF lifetime decay distributions were periodically collected from fixed tissue area with subsequent detection of the fluorescence intensity decrease dynamic at different time gates after the pulse excitation. Temporal distributions of skin AF lifetimes and bleaching dynamic were collected and analyzed by means of commercial time-correlated single photon counting system. The main focus of this study is to assess the possibility and potential of a combined time-resolved fluorescence spectroscopy method including parallel analysis of tissue autofluorescence lifetimes and photo-bleaching rates. AF life-times of position stabilized healthy skin were measured during 3 minutes. Skin AF lifetimes were collected every 10 seconds. To-tally during the 3 minute cycle 18 measurements of tissue AF decay distributions were registered. Each meas-urement contained temporal distribution of AF decay and a number of registered photons collected during the 10 seconds. Due to the AF photo-bleaching process, the number of collected photons for each subsequent measurement decreases, thereby giving the opportunity to construct the AF photo-bleaching curves at different time gates after the pulse excitation. The proposed method demonstrates good perspectives for selective analysis and separation of individual tissue fluorophores underlying FLT and bleaching analysis.

9504-26, Session PS

Evaluating the effectiveness of the method extrafocal images when observing low-orbiting space objects

Yury P. Shumilov, V. G. Vygon, Evgeniy A. Grishin, Victor D. Shargorodskii, Precision Systems and Instruments Corp. (Russian Federation)

Observation mode low-orbiting space objects has a number of features. Much energy, high angular velocities, the inability to compensate for the tour turbulent atmosphere throughout the image field (isoplanatic problem), the problem with reference sources, limited time for adaptation, etc. Previously proposed methods do not solve all the problems for the considered space objects.

Method extrafocal images based on obtaining two separated images of the intensity distribution of the object near the aperture. Algorithm for reconstruction of the phase front of these images requires fast computational tools and implemented. Further reduced distorted by turbulent atmosphere image recorded simultaneously with two extrafocal, but in the image plane.

Solved the problem of matching the parameters of the turbulent atmosphere, the speed of the space object, the receiver, backgrounds, read noise and its impact the quality of the implementation of the method.The question of compensation shake the sight line and the residual aberrations in the implementation of the method on a telescope with a large aperture. Analyzed the time variation of these parameters and the time of the implementation of the necessary qualitative and quantitative method of operations. Designed to balance the time due to changes in these parameters. Balance determines the necessary statistics of the signal and permissible statistics and background noise.

Identified an important parameter of the method to be used under the supervision of low-orbiting space objects. This is the minimum number of frames, which is determined, including the movement of a space object.

Analysis is based on a statistical model photoreadout images recorded on a matrix of receivers. Taking into account the characteristics of photoreadout background and receiver noise reading. Calculated threshold ha of characteristic image registration with a given probability.

A comparison with the bispectral method of image processing.

9504-27, Session PS

Single photon detectors based on superconducting NbTiN nanostructures

Wojtek Slysz, Marek Guziewicz, Andrii Klimov, Marcin Juchniewicz, Renata Kruszka, Institute of Electron Technology (Poland); Jaroslaw Z. Domagala, Valery Kolkovsky, Institute of Physics (Poland); Maciej Wegrzecki, Jan Bar, Adam Laszcz, Andrzej Czerwinski, Institute of Electron Technology (Poland); Roman Sobolewski, Univ. of Rochester (United States)

Practical optical quantum systems such as quantum communications or quantum measurement require photon-counting detectors with very high speed, ultrahigh sensitivity and quantum efficiency, along with precise timing characteristics and very low dark counts. Photon number- and energy-resolving capabilities are also very desired features. Presently, only superconducting single photon detectors (SSPDs) based on meander-type, ultrathin and ultra-narrow superconducting nanostripes are able to fulfill the above requirements. We report on characterization of SSPDs based on ultrathin NbTiN films and demonstrate their advantages, as compared to conventional NbN-based devices. Our NbTiN films, deposited on heated Al2O3 single crystal substrates and, subsequently, annealed at 1000 C for 10 min, exhibited excellent epitaxial crystal structure with a very sharp Al2O3/NbTiN interface, what was proven by high-resolution X-ray diffraction (HRXRD) and high-resolution transmission electron microscopy (HRTEM) studies. The films consisted of a single cubic phase with NaCl-type structure and the planes correlated with the Al2O3 crystal orientation. Our 4-nm-thick NbTiN films were characterized by the superconducting transition temperature of 14K and by high critical current densities, reaching 12 MA/cm^2 at 4.2K. These films were, subsequently, patterned using electron-beam lithography to form 8x10 µm ^2 meanders, consisting of 100-nm-wide stripes and ~50% fill factor. The meander structures were successfully operated as single photon quantum detectors with very low dark counts. Their photon counting efficiency and other performance parameters will be presented.

Conference 9505: Quantum Optics and Quantum Information Transfer and Processing

Wednesday - Thursday 15–16 April 2015

Part of Proceedings of SPIE Vol. 9505 Quantum Optics and Quantum Information Transfer and Processing 2015

9505-5, Session 1

A protocol of quantum key distribution without relying on information-disturbance trade off *(Invited Paper)*

Masato KOASHI, Univ. of Tokyo (Japan)

Since the proposal of the Bennett-Brassard 1984 (BB84) protocol, the basic idea behind quantum key distribution (QKD) has widely been understood as the property that any attempt to distinguish quantum states should cause disturbance, as dictated in the original version of Heisenberg's uncertainty principle. Here we propose a new scheme of QKD called round-robin differential-phase-shift (RRDPS) protocol, which is based on an entirely different principle. In the RRDPS protocol, the amount of privacy amplification is essentially constant and there is no need to change it according to the observed amount of disturbance. This means that it is hard for an eavesdropper to guess the bit value regardless of the amount of disturbance she has caused.

The RRDPS protocol is simply implemented by binary phase coding on a laser pulse train at the sender, and a variable-delay interferometer followed by photon detectors at the receiver. Detection of a photon tells the receiver the phase difference (a bit value) between a pair of pulses in the received pulse train. He then publicly announces the positions of the pair, enabling the sender to look up her record to learn the same phase difference, namely, the same bit value. The crux in this procedure is the randomness of the positions of the pair from which the bit value is defined. They are partly determined by the randomness in the position of the received photon, and partly by the randomness in the receiver's choice of the delay. This prevents the eavesdropper from fully controlling the choice of the pulse pair, and she would have to leave it up to chance to learn the bit value.

The new scheme has a better tolerance on bit errors and is free from the cost of monitoring eavesdropping attempts. In contrast to the conventional QKD schemes, the amount of privacy amplification is the same even if the quality of the transmission channel becomes poorer and the bit error rate increases. This leads to a higher bit error threshold, typically over 30% and with no theoretical bound less than 50%. The fact that the protocol does not require the precise estimation of the amount of signal disturbance is advantageous when the finite-key-size effect is taken into account; the RRDPS protocol can produce a key even when the total number of transmitted bits is small.

9505-6, Session 1

Quantum key distribution in optical access networks *(Invited Paper)*

Bernd Fröhlich, James F. Dynes, Marco Lucamarini, Andrew W. Sharpe, Simon W. B. Tam, Zhiliang L. Yuan, Andrew J. Shields, Toshiba Research Europe Ltd. (United Kingdom)

Optical access networks provide the connection to a multitude of users in the final span of the network. Realization of a quantum equivalent of conventional optical access networks, a Quantum Access Network (QAN), is an appealing idea as it opens up a route to make quantum networks scalable. We have recently demonstrated Quantum Key Distribution (QKD) in an access network permitting up to 64 users to connect to a network node to exchange secret keys [B. Fröhlich et al., Nature 501, 69]. A remaining question is whether this QAN can coexist with conventional access network traffic in the same optical network.

Transmission of the fragile quantum states used to distil secret encryption keys is challenging in the harsh environment of live telecom networks. The many orders of magnitude stronger data signals generate additional noise in the quantum channel which can be a significant impairment to quantum communication. Recently, a range of experiments have shown that quantum signals can indeed coexist with conventional telecom traffic. Most notably a field experiment has shown coexistence with data rates as high as 40 Gbps [I. Choi et al., Optics Express 22, 23121].

Optical access networks based on passive splitters provide an even more challenging environment for coexistence with telecom signals due to the high loss in the fiber distribution network. Here, we discuss new results demonstrating successful integration of QKD in a conventional Gigabit-capable Passive Optical Network (GPON). We transmit quantum keys alongside network traffic of 8 active users in a range of network configurations. Our results demonstrate that noise generated in the feeder fiber connecting the network node with the passive optical splitter is especially detrimental to quantum communication and we discuss methods to overcome this restriction.

9505-7, Session 1

Faked state attack on realistic round robin DPS quantum key distribution systems and countermeasure

Takehisa Iwakoshi, Tamagawa Univ. (Japan)

In May 2014, a new quantum key distribution protocol named "Round Robin Differential-Phase- Shift Quantum Key Distribution (RR DPS QKD)" was proposed [1]. It has a special feature that the key consumption via privacy amplification is a small constant because RR DPS QKD guarantees its security by information causality, not by information-disturbance trade-off like typical QKD protocols [2]. Therefore, the literature claims that RR DPS QKD does not need to monitor the disturbance in the quantum channel by an attacker. However, this study shows that a modified Faked-State Attack can hack a realistic RR DPS QKD systems almost perfectly, even the security was guaranteed by information causality [3].

A RR DPS QKD system employs a variable delay rB ? {1, 2, 3,..., L-1} at Bob's side, while a normal DPS QKD system has a fixed delay rB = 1. Therefore, a Faked-State Attack was possible by sending phase-modulated blinding pulses to Bob's side. In a normal DPS QKD system, it is well known that Faked-State Attacks works perfectly [4] when the QKD system employs Avalanche-Photo-Diodes (APDs) or Superconducting-Nanowire-Single-Photon-Detectors (SNSPDs), therefore here we assume that a target RR DPS QKD system also employs SNSPDs. A similar scheme can be applied to even when APDs are employed.

The attacking scheme is as follows. The attacker Eve in the middle of the quantum channel sends phase modulated laser pulses |exp[iϖ/L]>1 |exp[i2ϖ/L]>2 |exp[i3ϖ/L]>3 ...|exp[i(L-1)ϖ/L]>L-1 to blind Bob's detectors. While blinding, Eve intercepts Alice's photon by a copy of Bob's system where her variable delay is rE ? {1, 2, 3,..., L-1}. Then, she resends a pair of brighter pulses |0>1 |0>2 ... |0>k-1 |?>k |0>k+1 ...|0>k+rE-1 |(-1)^sE ?>k+rE |0>k+rE+1 ...|0>L-1 when Eve needs to cause a detection event on Bob's side at her will. If rE = rB, then Eve can force Bob to get her bit sE and call the correct pair of pulses she resends to let Alice to obtain a key bit sA = sE. If rE ≠ rB, Bob detects nothing. This implies that Eve can steal the secret key from Alice and Bob almost perfectly no matter the physical principle of the protocol is.

Therefore, this study also modify RR DPS QKD protocol as a possible type of Measurement- Device-Independent QKD to avoid the Faked-State Attack.

References

[1] T. Sasaki, Y. Yamamoto, and M. Koashi, "Practical quantum key distribution protocol without monitoring signal disturbance," Nature, 509(7501), 475-478 (2014)

[2] C. H. Bennett and G. Brassard, "Quantum cryptography: public

key distribution and coin tossing," Proceedings of IEEE International Conference on Computers, Systems and Signal Processing, Vol. 175. No. 0. (1984)

[3] M. Pawlowski, et al., "Information causality as a physical principle," Nature, 461(7267), 1101-1104 (2009).

[4] M. G. Tanner, et al., "Optimised quantum hacking of superconducting nanowire single-photon detectors," Optics express, 22(6), 6734-6748 (2013).

9505-8, Session 1

Bidirectional quantum communication in presence of noise

Anirban Pathak, Kishore Thapliyal, Jaypee Institute of Information Technology (India)

Several schemes of bidirectional and controlled bidirectional quantum communication have been introduced in the recent past [[1, 2, 3, 4] and references therein]. For example, schemes for quantum key agreement [1], quantum dialogue [2], controlled bidirectional state teleportation [3], etc. are proposed by some of the present authors. However, except in the case of bidirectional remote state preparation [4], the effect of noise is not rigorously studied. Keeping this fact in mind, the effects of different types of noise models (e.g., amplitude damping, phase damping, generalized amplitude damping and squeezed generalized amplitude damping noise) on the bidirectional quantum communication schemes are studied using the relevant Kraus operators. Here we have considered that the noise only affects the travel qubits of the quantum channel used for the particular quantum communication process. The effect of noise is illustrated by plotting the fidelity of the expected quantum state and the produced quantum state vs decoherence time and other relevant parameters. In most of the cases, we have observed that the effect of phase damping noise is more than that of the amplitude damping noise for the same decoherence rate. Very interestingly, it is shown that the Kak's three step QKD protocol [5] fails in the presence of any of the above noise models.

This is so because the Kraus operators of the noise models do not commute with unitary operators used by Alice and Bob in Kak's three step protocol.

References

[1] C. Shukla, N. Alam and A. Pathak, "Protocols of quantum key agreement solely using Bell states and Bell measurement", Quant. Info. Process. 13 (2014) 2391.

[2] C. Shukla, V. Kothari, A. Banerjee and A. Pathak, "On the group-theoretic structure of a class of quantum dialogue protocols", Phys. Lett. A, 377 (2013) 518.

[3] C. Shukla, A. Banerjee and A. Pathak, "Bidirectional controlled teleportation by using 5-Qubit states: A generalized view", Int. J. Theor. Phys, 52 (2013) 3790.

[4] V. Sharma, C, Shukla, S. Banerjee and A.Pathak, "Controlled bidirectional remote state preparation in noisy environment: A generalized view", arXiv: 1409.0833 (2014).

[5] S. Kak, "A three-stage quantum cryptography protocol." Foundations of Physics Letters 19, (2006) 293.

9505-9, Session 2

Giant twin-beam generation along the pump energy propagation *(Invited Paper)*

Maria V Chekhova, Max-Planck Institute for the Science of Light (Germany) and M.V. Lomonosov Moscow State University (Russian Federation)

Walk-off effects, originating from the difference between the group and phase velocities, limit the efficiency of nonlinear optical interactions. While transverse walk-off can be eliminated by proper medium engineering, longitudinal walk-off is harder to avoid. In particular, ultrafast twin-beam generation via pulsed parametric down-conversion and four-wave mixing is only possible in short crystals or fibres or in double-path schemes. In our recent experiments, we have shown that in high-gain parametric down-conversion, one can overcome the destructive role of both effects and even turn them into useful tools for shaping the emission. In one of our experiments, the signal beam is emitted along the pump Poynting vector; in another one, group velocity of the signal beam matches that of the pump. The result is dramatically enhanced generation of both signal and idler twin beams, with the simultaneous narrowing of angular and frequency spectrum. The effect will enable efficient generation of ultrafast twin photons and beams in cavities, waveguides, and whispering-gallery mode resonators. It also provides a source of tunable broadband radiation with high directivity, which can be considered as an OPO without a cavity.

9505-10, Session 2

Breaking the mirror symmetry of spontaneous emission via spin-orbit interaction of light *(Invited Paper)*

Arno Rauschenbeutel, Vienna University of Technology (Austria)

The fundamental guided mode in an optical nanofiber exhibits a significant polarization component that points in the direction of propagation of the light. In contrast to paraxial light fields, the corresponding intrinsic angular momentum of the light field is position-dependent - an effect referred to as spin-orbit interaction of light. Remarkably, the light's spin can even be perpendicular to the propagation direction. I will show that the interaction of emitters with such light fields leads to new and surprising effects. In particular, the intrinsic mirror symmetry of the emission of light by gold nanoparticles as well as by atoms near a silica nanophotonic waveguide is broken. This allowed us to realize chiral nanophotonic interfaces in which the emission direction of light into the waveguide is controlled by the polarization of the excitation light [1] or by the internal state of the atoms [2].

[1] J. Petersen et al., Science 346, 67 (2014).

[2] R. Mitsch et al., arXiv:1406.0896 (2014).

9505-11, Session 2

Quantum detector tomography on superconducting single photon detectors

Jelmer Renema, Leiden Univ. (Netherlands); Rosalinda Gaudio, Technische Univ. Eindhoven (Netherlands); Qiang Wang, Leiden Univ. (Netherlands); Zili Zhou, Technische Univ. Eindhoven (Netherlands); Andreas Engel, Univ. of Zürich (Switzerland); Andrea Fiore, Technische Univ. Eindhoven (Netherlands); Martin P. van Exter, Michiel J. A. de Dood, Leiden Univ. (Netherlands)

Superconducting single photon detectors (SSPDs) [1] are single-photon detectors consisting of a thin superconducting wire biased close to the critical current. With 93% efficiency [2], negligible dark counts, and multi-pixel detectors at telecommunication wavelengths, these detectors will find substantial use in quantum optics and quantum communications applications. However, the working mechanism of SSPDs is badly understood.

Over the last few years, we have tackled some of the open problems in this topic via quantum detector tomography (QDT) [3-6]. Detector tomography is the inverse process of state tomography: we use a set of known states to probe an unknown detector. We use coherent states, as these are easily available in the lab. We deconvolute the response of the detector from the probability distribution of photon numbers in the coherent state.

Unlike semiconductor-based detectors, QDT on an SSPD is a nontrivial process. In a semiconductor-based detector each absorbed photon individually forms an electron-hole pair which either triggers the detector or doesn't, which means that the detector is entirely described by a dark count rate and a single-photon efficiency. In SSPDs however, there are multiphoton detection modes at different bias currents, where several absorbed photons cause a joint detection event. Quantum detector tomography, which takes into account all multiphoton detection probabilities, is therefore the natural way of investigating the SSPD detection mechanism.

These results represent the first application of QDT to an unknown system. I will present an overview of our results regarding the role of the normal (non-superconducting) state in the detection process of magnetic vortices, which were achieved by investigating the multiphoton detection regime. Moreover, I will present our latest results, which probe the intrinsic localized response of the detector with a 10 nm resolution. These results provide important insight on the microscopic principles underlying the detection process and have applications in quantum optics, nanophotonics and in the solid-state physics of thin films.

[1] G.N. Goltsman et al, Applied Physics Letters 79 (6), 705-707 (2001)

[2] F. Marsili et al, Nature Photonics 7 (3), 210-214

[3] Renema et al, Optics Express 20 (3), 2806-2813

[4] Renema et al, Physical Review A 85 (4), 043837

[5] Renema et al, Physical Review B 87 (17), 174526

[6] Renema et al, Physical Review letters 112 (11), 117604

9505-12, Session 2

Effects of pump depletion on spatial and spectral properties of parametric down-conversion

Alessia Allevi, Marco Lamperti, Univ. degli Studi dell'Insubria (Italy); Radek Machulka, Palacky Univ. Olomouc (Czech Republic); Ottavia Jedrkiewicz, Consiglio Nazionale delle Ricerche (Italy); Enrico Brambilla, Univ. degli Studi dell'Insubria (Italy); Alessandra Gatti, Consiglio Nazionale delle Ricerche (Italy); Jan Perina Jr., Ondrej Haderka, Palacky Univ. Olomouc (Czech Republic); Maria Bondani, Consiglio Nazionale delle Ricerche (Italy)

It is well known that optical twin-beam states (TWB) generated by spontaneous parametric down-conversion (PDC) exhibit spatial and spectral correlations.

The first experimental measurements of spatial correlations in TWB, aimed at determining the size of the coherence areas in a transverse plane, were performed in the single-photon regime on twin-beam states containing one photon at most by using scanned single-photon detectors. The experimental results can be compared to a well-established theory properly working in this regime, in which, for instance, the pump beam can be considered as non-evolving during the interaction (undepleted-pump approximation). On the other hand, TWB can also be generated in a much higher intensity regime, in which coherence areas become visible in single-shot images at the output of the nonlinear crystal, and the evolution of the pump field cannot be neglected.

By using an EMCCD camera, we recorded far-field single-shot images obtained by using an imaging spectrometer that resolves emission angles and wavelengths simultaneously.

We analyzed series of single-shot images at different powers of the pump beam to study the evolution of several quantities characterizing the generated TWB for different (from low to high) values of the parametric gain. Such values could be experimentally obtained by exploiting the third-harmonics (349 nm) of a ps-pulsed mode-locked Nd:YLF laser amplified at 500 Hz (High-Q Laser) to pump a 8-mm-long (cut angle 37 deg) BBO crystal.

In particular, we demonstrated that correlation widths in spectrum and space increase monotonically at low pump powers and then start decreasing at high pump powers due to the onset of pump depletion. At the same time, we demonstrated that the number of modes evaluated from photon statistics follows a complementary behavior with respect to correlation widths. This effect can be interpreted in terms of the evolution of the number of Schmidt modes in the radiation field.

The occurrence of pump depletion can be shown by monitoring the spatial and spectral profile of the pump in the different experimental conditions: a progressively deeper hole sets up in the pump profile at increasing powers. In the pump-depletion regime the evolution of the pump field must be taken into account together with the evolution of the PDC. In particular, we observed that the pump spectrum widens in the depletion regime, and this implies a widening of the overall spectrum of the PDC.

9505-13, Session 2

Generation of discrete spatial entanglement in multimode nonlinear waveguides

Michal Jachura, Univ. of Warsaw (Poland); Michal Karpinski, Univ. of Oxford (United Kingdom); Jasleen Lugani, Divya Bharadwaj, Krishna Thyagarajan, Indian Institute of Technology Delhi (India); Konrad Banaszek, Univ. of Warsaw (Poland)

We propose and discuss theoretically two schemes for generating spatially entangled photon pairs using type-II spontaneous parametric down-conversion (SPDC) process in a periodically poled potassium titanyl phosphate (PPKTP) multimode nonlinear waveguide. Both schemes exploit intermodal dispersion in the waveguide which recently has been successfully employed to control the spatial characteristics of light generated in the SPDC process [1,2]. They enable creation of discrete entanglement in the basis of transverse spatial modes of the waveguide. In the first approach, two simultaneously driven SPDC processes into different pairs of spatial modes are phase matched for the same degenerate wavelength, whereas in the second approach we consider the regime of short waveguide lengths where due to the proximity of phase matching bandwidths, spectral distinguishability between photons originating from different processes can be suppressed by using a narrowband interference filter. We have performed numerical simulations based on the finite difference method to find the optimal properties of the waveguide for the experimental realization of proposed schemes. Significantly, the optimized waveguide parameters do not exceed current technological limitations of sample manufacturing. Finally we present and analyze an experimental method for detecting entanglement based on measuring displaced spatial parity [3] with the help of inverting Sagnac interferometers and photon counting. Using the simulated mode profiles we calculated the maximum attainable value of the Clauser-Horne-Shimony-Holt combination for each experimental scheme. In both cases CHSH inequality has been violated with the CHSH combination reaching -2.1647 and -2.1650 respectively, which illustrates the feasibility of observing non-classical features of the generated states.

[1] M. Karpi?ski, C. Radzewicz, and K. Banaszek, Opt. Lett. 37, 878 (2012)

[2] M. Jachura, M. Karpi?ski, C. Radzewicz, and K. Banaszek, Opt. Express 22, 8624 (2014)

[3] E. Mukamel, K. Banaszek, I. A. Walmsley, and C. Dorrer, Optics Lett. 28, 1317 (2003)

9505-14, Session 3

Quantum memories with cold neutral atoms: from free-space to all-fibered implementations *(Invited Paper)*

Julien Laurat, Laboratoire Kastler Brossel (France)

Optical memories are critical building blocks for the development of quantum networks. In this context, I will present recent results based on large ensemble of cold neutral atoms, in two different settings. The first example will be the storage of multimode structured light, including twisted light and vector vortex beams, in a free-space implementation based on a magneto-optical trap. The full structuration of light in the transverse plane holds the promise of unprecedented capabilities for applications in classical optics as well as in quantum optics and information sciences. To extend their use to quantum networks,

multimode memories have to be realized. By combining an ensemble-based memory implementation and an additional dual-rail multiplexing of the storing medium, we demonstrated a multiple-degree-of-freedom register able to store and retrieve on-demand such states. Specifically, we generated a set of vectorial modes via liquid crystal cell with topological charge in the optic axis distribution and demonstrated the preservation of the phase and polarization singularities, at the single-photon level. As an example of application in quantum information scenario, we show the conservation of rotational invariance for qubits encoded for misalignment-immune quantum communications. In a second part of the talk, I will then report progresses towards a novel physical implementation based on an optical tapered nanofiber. By interfacing a nanofiber with a laser-cooled ensemble of atoms, we recently observed electromagnetically-induced transparency and stored light pulses at the single-photon level. This result based on subdiffraction-limited optical mode interacting with atoms via the strong evanescent field demonstrates a promising alternative to free-space focusing and a new capability for information storage in an all-fibered quantum network.

9505-15, Session 3

Restoring broken entanglement by separable correlations *(Invited Paper)*

Gaetana Spedalieri, Stefano Pirandola, The Univ. of York (United Kingdom)

We consider a quantum repeater which is used by two remote parties to perform several continuous variable protocols: Entanglement swapping, quantum teleportation, entanglement distillation, and quantum key distribution. In general, we assume that these protocols are operated under non-Markovian conditions, considering an environment with correlated Gaussian noise. We then show that, even if entanglement is completely lost at the repeater, all these protocols can progressively be reactivated by the separable (i.e., local) correlations of the environment. Our theoretical findings are confirmed by a proof-of-principle experiment and provide new perspectives for harnessing correlated errors and non-Markovian decoherence inside quantum computers and quantum networks.

9505-16, Session 3

An integrated source of filtered photon pairs for large scale quantum photonic systems

Nicholas C. Harris, Massachusetts Institute of Technology (United States); Davide Grassani, Angelica Simbula, Matteo Galli, Univ. degli Studi di Pavia (Italy); Mihir Pant, Dirk R. Englund, Massachusetts Institute of Technology (United States); Daniele Bajoni, Univ. degli Studi di Pavia (Italy); Christophe Galland, Univ. Stuttgart (Germany)

We demonstrate the first on-chip spectral filtering of quantum-correlated photons generated by spontaneous four-wave mixing in a silicon ring resonator. Pump rejection by more than 95 dB in a single chip and demultiplexing of signal and idler photons transferred via a fiber to another identical chip are achieved with a reconfigurable CMOS silicon photonic integrated circuits based on Bragg reflectors and tunable ring resonators [1]. Non-classical two-photon temporal correlations are measured at the output of the second chip without further off-chip filtering. Our system paves the way toward large-scale quantum photonic circuits by allowing photon sources and detectors to be integrated on the same chip.

[1] N. Harris et al., arXiv:1409.8215 (2014)

9505-17, Session 3

Building a room temperature quantum processor

Eden Figueroa, Stony Brook Univ. (United States)

Given the recent experimental success in regard to the advancement of quantum devices, we are now at the point where we must interconnect many of them in order to bring about the first generation of quantum processing machines.

In this elementary quantum processor, individual nodes must be equipped with the functionality to perform several key tasks in order to meet the criteria necessary for quantum information processing. Namely, some nodes need to be able to receive, store and retrieve photonic qubits (quantum memories), while other nodes must be geared toward the manipulation of qubits (quantum gates).

In this work we will present our recent results regarding the construction of a room temperature quantum processor capable of storing and processing photonic polarization qubits. First, we will show the storage of single photon level polarization qubits in warm rubidium vapor [1]. Secondly, we will discuss our recent experiments in which we have performed quantum process tomography of an EIT Kerr non-linearity. Lastly, we will present our new data showing the cascading of two room temperature single-photon level memories.

[1] Scientific Reports 5, 7658 (2014).

9505-26, Session PS

Spatial resolution dependence on light polarization in direct laser writing 3D lithography

Sima Rekštyte, Tomas Jonavicius, Mangirdas Malinauskas, Vilnius Univ. (Lithuania)

Direct laser writing lithography is widely used for materials processing in scientific research and industrial applications [1]. However, still not all of the physical mechanisms occurring during light-matter interaction using ultra-short laser pulses are fully understood and exploited, for instance - the light polarization dependence on the laser polymerization.

Here we present a systematic study on influence of polarization of laser pulse on exposure and a feature size (spatial resolution and shape of the produced voxel) in photosensitized and pure SZ2080 photopolymer. Vectorial Debye's theory predicts that using a high numerical aperture focusing (NA>0.7) causes light depolarization at the focal region [2] with preferentially elongated focal spot along direction of linearly polarized light. Here we show that polarization and scan direction affect resolution of direct laser writing which is essential to optimize for high sub-diffraction resolution reproducable nanostructures [3]. Structures consisting of components oriented at various angles in respect to the laser light polarization were fabricated on a well–leveled glass substrate as well as were suspended in air in between support structures. SZ2080 hybrid was doped with 1% w.t. of 4,4'-Bis (ethyl-amino)-benzophenon photoinitiator used as a photopolymer. In comparison pure SZ2080 material was applied. Fabrication parameters were: laser wavelength ? = 1030 nm, pulse repetition rate varied from f = 1 to 200 kHz, pulse duration ? = 300 fs, laser intensity of the order of ~0.1 TW/cm2 intensity/irradiance in the sample at the focus of a 100x 1.4 numerical aperture (NA) objective lens at a 100 ?m/s sample linear translation velocity. For the comparison, the same structures were fabricated using circular polarized light for reference; also, experiments were repeated at a 90-deg-rotated polarization to eliminate stage related uncertainty. All of the samples were examined using scanning electron microscope and widths of the formed lines were measured.

It is shown that using a linearly polarized femtosecond pulsed light focused to diffraction limited spot width of photopolymerized lines increases when the angle between light polarization and sample translation directions increases and reaches maximum at 90 degrees. Variation of ~5,8 % in line-width was observed. As expected, using circularly polarized light and altering the sample scanning direction such effect is not noticeable. Additionally, a slight increase in lined-width

resolution is achieved (~10%). This observation cannot be explained by Debye theory of elongated focus only. Heat localization and diffusion from the focal volume and possible influence of transient nano-structures such as observed in bulk silica at pre-breakdown conditions are discussed as possible explanation of the mechanism. Differences of the produced voxels aspect ratios' and granulations employing 1 kHz and 200 kHz pulse repetition rate irradiation was noticed as well as pure and photosensitized SZ2080 corresponded to different generated feature shapes and dimensions.

[1] M. Malinauskas, et al., "Nanophotonics lithography: a versatile tool for manufacturing functional three-dimensional micro-/nano-objects", Lith. J. Physics, 52(4), 312-326 (2012).

[2] M. Gu, Advanced optical imaging Theory (Springer), 6, (1999).

[3] H.B. Sun and S. Kawata, Two-Photon Photopolymerization and 3D Lithographic Microfabrication (Springer-Verlag), 4, (2004).

9505-27, Session PS

Design of 1.2m telescope for space-to-ground quantum communication

Bo Qi, Institute of Optics and Electronics (China)

Due to low absorption and negligible non-birefringent character in atmosphere, optical free space therefore serves as the most promising channel for large-scale quantum communication by use of satellites and optical ground stations. Quantum communication in space has become a new technological challenge in the evolving field of quantum communications. Its main goal is to achieve the distribution of single photons or entangled photon pairs from satellites to implement both quantum technologies such as quantum cryptography and fundamental quantum physics experiments. This article describes the equipment and features of the 1.2m telescope which will perform experiments with quantum experiment satellite of China. The optical ground station uses 1.2m gimbaled telescope to collect the photons, the strategy of the system is slightly developed to meet the need of tracking LEO satellite?which has coarse and fine loop, and it can control a transmitting and receiving laser beam within a few micro radians jitter. This telescope with multiple functions will play an important role in space-to-ground quantum communication.

9505-28, Session PS

Spectral coherence of twin beams by single-shot measurements with a fiber spectrometer

Alessia Allevi, Univ. degli Studi dell'Insubria (Italy); Justinas Galinis, Vilnius Univ. (Lithuania); Marco Lamperti, Univ. degli Studi dell'Insubria (Italy); Radek Machulka, Jan Perina Jr., Ondrej Haderka, Palacky Univ. Olomouc (Czech Republic); Maria Bondani, Consiglio Nazionale delle Ricerche (Italy)

Spectral and spatial coherence properties of twin beam states (TWB) generated by spontaneous parametric down-conversion (PDC) can be measured in different intensity regimes from single-photon up to very high values of parametric gain. Coherence properties emerge from coincidence or correlation measurements performed by using single-photon detectors (APDs, ICCDs...) or mesoscopic and macroscopic detectors (HPDs, pin photodiodes, EMCCD and CCD cameras...) within optical setups exploiting imaging systems and imaging spectrometers.

Here we consider TWB states generated by pumping a 8-mm-long (??=37o) BBO crystal with the third-harmonics (349 nm) of a ps-pulsed mode-locked Nd:YLF laser amplified at 500 Hz (High-Q Laser) at different values of pump powers.

The measurements were performed by selecting a portion of the PDC light by a variable-size iris located at different distances from the BBO and measuring the light passing the iris with a fiber spectrometer (AvaSpec-ULS2048L, Avantes, 0.6 nm resolution). The intensity of the down-converted light was high enough to allow the recording of single-shot spectra.

Single-shot spectra exhibit a well-defined peak structure, where the peak wavelengths change value from shot to shot but the overall number of peaks in the spectrum is rather constant. This can be interpreted as the existence of coherence structure in the PDC output.

We study the number and the width of the peaks as a function of the different parameters in the experimental setup (pump power, iris size, iris distance from the BBO crystal). Moreover we evaluated the number of modes in the intensity distribution of the light in different portions of the spectrum.

The experimental results indicate that the behavior of the number of modes from statistics and the number and size of peaks evolve differently with the parameters. In particular, given a selection of a wavelength interval, the number and size of peaks in the detected spectrum are quite independent of all the parameters, while the number of modes in the intensity statistics in the same intervals changes as a function of all of them. More in detail, at fixed distance, the number of modes increases at increasing iris size up to a value of iris larger than the entire downconverted cone. This result is expected from the geometry of the PDC interaction and propagation. Less obvious is the behavior as a function of pump power: the number of modes decreases at increasing pump power down to a minimum value and then it increases again, as the effect of pump depletion.

9505-29, Session PS

Evolution of spatio-spectral coherence properties of twin beam states in the high-gain regime

Alessia Allevi, Univ. degli Studi dell'Insubria (Italy); Ottavia Jedrkiewicz, Consiglio Nazionale delle Ricerche (Italy); Ondrej Haderka, Jan Perina Jr., Palacky Univ. Olomouc (Czech Republic); Maria Bondani, Consiglio Nazionale delle Ricerche (Italy)

Parametric down conversion (PDC) is a well-known nonlinear process extensively investigated and exploited for the production of entangled states of light, which can be useful for many applications in quantum state engineering, quantum information and quantum communication protocols.

During the last few decades, most of the work has been performed at the single photon level, whereas more intense regimes have been less explored due to the lack either of suitable detectors or of proper laser sources.

In this work we present the results of some recent experimental investigations performed in the macroscopic domain, also including pump depletion. We achieved such a condition by pumping either a 4-mm-long or a 8-mm-long nonlinear crystal with the third-harmonic pulses of a ps-Nd:YLF laser amplified at 500 Hz.

The spatio-spectral properties of the generated twin beam (TWB) states were studied by sending the far-field pattern of PDC radiation to an imaging spectrometer, at whose output an electron-multiplying CCD (EMCCD) camera was used to register single-shot images. In particular, we investigated the widths of spatial and spectral profiles as well as the number of modes close to frequency degeneracy and collinear-interaction geometry. In order to directly compare the results obtained in the two crystals, we determined the value of parametric gain from the evolution of the mean number of photons as a function of pump mean power. In this way we could verify that, even if pump depletion occurs at different absolute values of pump power, the corresponding PDC gain is the same in both. Nevertheless, from the analysis of spatio-spectral coherence areas and of the number of modes some differences emerge in the absolute values, thus testifying the key role of crystal length in the realization of the nonlinear process.

If on the one hand this sort of investigation is useful for better understanding the evolution of coherence properties as a function of the different parameters governing the PDC process (pump mean power and nonlinear crystal length), on the other hand it opens the way towards the tailoring of TWB states for the implementation of quantum protocols.

9505-30, Session PS

Coupling of spin and orbital degrees of freedom in tunable Hong-Ou-Mandel interference involving photons in hybrid spin-orbit modes

Cody C. Leary, Maggie Lankford, Deepika Sundarraman, The College of Wooster (United States)

Hong-Ou-Mandel interference (HOMI) is an important component of many optical quantum information processing schemes. Although entangled photons utilizing the polarization and path degrees of freedom have been the subject of much study in this context, the extension of HOMI to photons involving nontrivial transverse spatial (orbital) modes or hybrid spatial-polarization modes has yet to be systematically explored. Here we investigate the connection between two-photon states involving photons in product modes of their spin and orbital degrees of freedom and those involving photons in hybrid spin-orbit modes, as mediated by HOMI in an asymmetric Mach-Zehnder interferometer with an extra mirror in one arm.

We predict that two input photons in balanced superposition states of both their spin and orbital degrees of freedom will exhibit HOMI while undergoing a simultaneous mode conversion from product spin-orbit input modes to hybrid output modes bearing orbital angular momentum. These hybrid outputs contain a nontrivial polarization structure, which is radially symmetric but continuously varies along the azimuthal direction in the plane perpendicular to propagation. Furthermore, this spatially varying polarization profile may be controllably rotated about the photonic beam axis by varying the relative phase between the vertical and horizontal components of the input polarization state of each photon. In this way, a type of coupling of the spin and orbital degrees of freedom is exhibited: the transverse spatial profile of each polarization component of both photons may be continuously manipulated by tuning each photon's polarization degree of freedom, in such as way that the HOMI between the photons remains stable.

We present experimental evidence in support of the above predictions by manipulating classical spin-orbit beams originating from few-mode optical fibers in an asymmetric interferometer in order to produce and manipulate the hybrid modes described above, which we observe interfere in such a way as to be consistent with our predictions involving HOMI.

An interesting corollary to this work is the possibility of demonstrating in a simple experimental system that Hong-Ou-Mandel interference may occur between distinguishable input modes in the context of interferometric systems of the above kind, in contrast to the more common requirement that the input modes must be indistinguishable. Identical input modes are not a prerequisite for HOMI, it is the indistinguishability of the outputs that matters.

9505-31, Session PS

Effects of surface ligands and solvents on quantum dot photostability under pulsed UV laser irradiation

Victor A. Krivenkov, Pavel S. Samokhvalov, National Research Nuclear Univ. MEPhI (Russian Federation); Pavel A Linkov, National Research Nuclear University MEPhI (Russian Federation) and Université de Reims Champagne-Ardenne (France); Sergey D. Prokhorov, Igor L. Martynov, Alexander A. Chistyakov, National Research Nuclear Univ. MEPhI (Russian Federation); Igor R. Nabiev, National Research Nuclear Univ. MEPhI (Russian Federation) and Univ. de Reims Champagne-Ardenne (France)

Semiconductor quantum dots (QDs) play an important role in nanotechnology. Colloidal QDs are known as efficient, cheap and reproducible components of many nano-optoelectronic devices (LEDs, solar cells, sensors, etc.), and recently they have been shown as prospective single photon sources for quantum communications [1]. In this field QDs operate under strong photon flux, and their stability under high and constant excitation may strongly affect the quantum device properties.

In this work we have studied the key parameters which determine the photostability of colloidal solutions of CdSe/ZnS QDs under pulsed UV laser irradiation. We have found that variation of the organic ligands which passivate the nanocrystal surface, or the solvent, can lead to dramatic changes in photophysical properties of QD solutions. Thus, we have found that the thoroughly purified solutions of QDs in chloroform degrade upon pulsed UV irradiation irrespectively of the type of surface ligand (tri-n-octylphosphine, TOPO; n-hexadecylamine, HDA or n-octanethiol, OT), in contrast to our previous investigations where small amount of free ligand molecules was present in QD solutions [2]. Yet, solutions in more photochemically inert n-octane showed a clear dependence of photostability of QDs on the choice of ligand system. In particular, HDA-coated CdSe/ZnS quantum dots showed a complete absence of photochemical response to laser irradiation and no signs of photoinduced aggregation, while the same QDs coated with TOPO immediately started to form aggregates followed by sustainable photobrightening with photoluminescence (PL) quantum yield increase of up to 1.9 times when the irradiation dose reaches 9.6 x 10^-15 J per particle. OT-capped QDs solution exhibited a smooth decrease of PL intensity, finally reaching PL quantum yield 2 times lower than the initial value under the same irradiation dose used for TOPO-coated QDs. To verify our results, we have investigated the thermodynamically induced degradation of luminescent properties of QDs, which is the consequence of ligand loss by QD due to desorption of them in highly dilute solutions. We found that this process becomes significant only when the concentration of QDs solution is lower than 10^-7 – 10^-8 M, what is orders of magnitude lower than the dilutions used in this work. Thus, we can conclude that the studied effects have a purely photochemical nature.

We presume that the reason of difference in photochemical response of QDs solutions is caused by the specific alignment of band levels of QDs and HOMO energies of ligand molecules, what, in turn, determines the rate of hole transfer from inorganic part of QD to surface bound ligands. Thus, low HOMO energy of HDA molecule inhibits such hole transfer, what makes HDA-capped CdSe/ZnS QDs most stable. OT and TOPO have their HOMO levels higher than that of QDs valence band, what leads to pronounced photoresponse.

Our findings show that the proper choice of ligand system is crucial for long-term stability of photophysical properties of QDs. The results presented here may pave the way for rational design of organic capping layer of QDs intended for use in optoelectronic devices or preparation of light conversion composite materials.

[1] P. Michler, A. Kiraz, C. Becher, W. V. Schoenfeld, P. M. Petroff, Lidong Zhang, E. Hu, and A. Imamoglu, "A Quantum Dot Single-Photon Turnstile Device", Science, 2000, 290, 2282-2285.

[2] Krivenkov, V., Samokhvalov, P. S., Linkov, P., Solovyeva, D. O., Kotkovskii, G. E., Chistyakov, A., Nabiev, I., "Surface ligands affect photoinduced modulation of the quantum dots optical performance," Procs. SPIE., 2014, 9126, D. L. Andrews, J.-M. Nunzi, and A. Ostendorf, Eds., 91263N.

9505-32, Session PS

Creating Sagnac-type source of entangled photons: technical aspects

Alexander P. Shurupov, Miloslav Dusek, Palacky Univ. Olomouc (Czech Republic)

Sources of photonic entanglement are integral parts of quantum optics experiments implementing quantum information protocols. The most frequent method to create polarization entangled photon pairs is spontaneous parametric down-conversion (SPDC) in nonlinear media. Recently sources based on SPDC in bidirectionally pumped periodically polled non-linear crystals has become a popular choice for the experiments where high efficiency of entangled pairs is required like in quantum teleportation, quantum information processing, or loophole free Bell tests.

In this work we address technical aspects of building such a source. We discuss all the stages of experimental implementation of the source including selection of the crystal, optimization of focusing parameters for a pump and down-conversion beams, and measurement of source performance. We focus on typical problems and their solutions. In particular we describe a source of frequency degenerate polarization entangled photons based on type-II PP-KTP crystal pumped at 405 nm.

Though the experiment realization is under construction at the moment of submission, we have performed first measurement of coincidence count rate, which gave us 30 kHz for 20 mW laser pump. This value will be optimized by the time of presentation and other parameters of the source will be measured.

9505-33, Session PS

Theoretical description of spatial multiphoton correlations in bright squeezed vacuum states of light

Polina R. Sharapova, O. V. Tikhonova, Lomonosov Moscow State Univ. (Russian Federation); Angela Marcela Perez Castaneda, Max-Planck-Institut für die Physik des Lichts (Germany); Maria V. Chekhova, Lomonosov Moscow State Univ. (Russian Federation); Gerd Leuchs, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Bright squeezed vacuum (BSV) is a macroscopic non-classical state of light that attracts much interest because of its important features such as high degree of entanglement [1] and noise reduction below the standard quantum limit [2]. These reasons give rise to the wide range of applications of BSV, for example, in quantum imaging [3], metrology [4], quantum optomechanics, etc. Moreover, due to the very broad photon-number probability distribution the entanglement arising in such states is more rich and pronounced in comparison to biphoton light emitted via spontaneous parametric down conversion (PDC).

In contrast to the low-gain PDC, to develop fully consistent theoretical description of the strongly pumped (high-gain) BSV seems to be a rather difficult problem due to the contribution of correlated high-order Fock components and non-applicability of the perturbation theory. In a high-gain regime it is much more convenient to find the time dependence of physical operators and calculate the observables in the Heisenberg picture. In this case the Schmidt-mode formalism used in the Schrodinger picture for the description of multimode two-photon light [5] is replaced by a similar procedure, called Bloch-Messiah reduction [6]. There are several papers describing BSV correlations in terms of the so-called broadband modes [7, 8]. However the results mainly concern correlations in the frequency domain and can be obtained only numerically from the set of integro-differential equations.

In our work we present fully analytical description of the angular spectrum and correlations of BSV. The theoretical approach is based on the Bloch-Messiah reduction and allows one to obtain the analytical solution for the evolution of the photon-creation operators for the collective spatial Schmidt modes. Moreover we obtain the explicit analytical expressions for the non-linear signal and for all required correlation characteristics. The obtained theoretical results are compared with the experimental data on spatial correlations in BSV and are found to be in a good agreement. The physics of the found entanglement is explained in terms of collective Schmidt modes of the system.

References:

1. T.Sh.Iskhakov, I.N.Agafonov, M.V.Chekhova, and G. Leuchs, PRL 109, 150502 (2012).

2. I.N. Agafonov, M.V. Chekhova, and G. Leuchs, PRA 82, 011801 (2010).

3. G. Brida, M. Genovese, and I. Ruo Berchera, Nature Photonics 4, 227 (2010).

4. G. Brida, I.P. Degiovanni, M. Genovese, M.L. Rastello, and I. Ruo Berchera, Optics Express 18, 20572 (2010).

5. M.V. Fedorov, M.A. Efremov, A.E. Kazakov, K.W. Chan, C.K. Law, and J.H. Eberly, PRA 69, 052117 (2004).

6. S.L. Braunstein, PRA 71, 055801 (2005).

7. A.Christ, B.Brecht, W.Mauerer and Christine Silberhorn, New Journ. of Phys. 15, 053038 (2013)

8. W. Wasilewski, A. I. Lvovsky, K. Banaszek, and Czes?aw Radzewicz, PRA 73, 063819 (2006).

9. E. Brambilla, A.Gatti, M.Bache and L.A. Lugiato, Phys Rev A 69, 023802 (2004)

9505-34, Session PS

Experimental observation of transition between strong and weak non-Markovianity

Alvaro Cuevas, Sapienza Univ. di Roma (Italy)

We experimentally observed in an optical setup and using full tomography process the so-called weak non-Markovian dynamics of a qubit [1], implementing the collisional model proposed in [2] to investigate the non-Markovian dynamics of an open quantum system. Through careful control of the environment state of our open system, we also also observed the transition from weakly to strong (essentially) non-Markovianity.

In our all-optical setup, a single photon system, initially entangled in polarization with an ancilla, is made to sequentially interact with a sequence of liquid crystal retarders driven by proper electric pulses and simulating the environment. Depending on how the voltage is applied on each liquid crystal, it will work as a half-wave plate with different orientations. By properly the parameters of the qubit-environment interactions, the system dynamics can suffer a transition from weak to strong non-Markovianity.

In the strong regime, the full reconstruction of the entangled state was made by single entanglement witness between system and ancilla, showing a backow of information, while, in the weak regime, given the contractive unital map feature, we can only measure the dynamics by a full process tomography analysis, searching for the violation of the divisibility map criterion.

References:

[1] D. Chruscinski and S. Maniscalco, Phys. Rev. Lett. 112, 120404 (2014).

[2] B. Bylicka, D. Chruscinski, and S. Maniscalco, Scientific Reports 4, 5720 (2014).

9505-1, Session 4

New directions in quantum processing with optical systems *(Invited Paper)*

Timothy C Ralph, Univ of Queensland (Australia)

Quantum information can be encoded and processed by optical systems with high fidelity. However, as for all other potential quantum computing architectures, major hurdles stand in the way of scale-up for optical processors. In this talk I will discuss two interesting new directions in quantum processing with optical systems. The first is the recent realization that single purpose optical quantum processors of surprisingly low complexity and modest size can solve sampling problems that are believed to be intractable for classical computers. I will discuss extensions of the original Boson Sampling scenario to Gaussian input states that still lead to outputs that cannot be efficiently simulated by classical computation. I will also discuss what quantum optics can tell us about the computational complexity classes of certain problems. The second is new ideas on how to implement deterministic quantum logic gates using non-linear optical interactions. The power of such interactions have long been known in principle, but more recently noise issues associated with the multi-frequency-mode nature of the fields have been found to plague many schemes. I will discuss a scheme that combines passive and active Gaussian optics with non-linear interactions in order to avoid these noise problems.

9505-2, Session 4

Optimal entanglement-assisted discrimination of quantum measurements *(Invited Paper)*

Jaromír Fiurásek, Martina Mikova, Michal Sedlák, Ivo Straka, Michal Micuda, Palacky Univ. Olomouc (Czech Republic); Mario Ziman, Slovak Academy of Sciences (Slovakia) and Masaryk Univ. (Czech Republic); Miloslav Dusek, Miroslav Jezek, Palacky Univ. Olomouc (Czech Republic)

We investigate optimal discrimination between two projective single-qubit measurements in a scenario where the measurement can be performed only once. We consider general setting involving a tunable fraction of inconclusive outcomes and we prove that the optimal discrimination strategy requires an entangled probe state for any nonzero rate of inconclusive outcomes. We experimentally implement this optimal discrimination strategy for projective measurements on polarization states of single photons. Our setup involves a real-time electrooptical feed-forward loop which allows us to fully harness the benefits of entanglement in discrimination of quantum measurements. The experimental data clearly demonstrate the advantage of entanglement-based discrimination strategy as compared to unentangled single-qubit probes.

9505-3, Session 4

Discrete time quantum walks with adjustable coin and step operation

Fabian Katzschmann, Sonja Barkhofen, Thomas Nitsche, Univ. Paderborn (Germany); Jaroslav Novotny, Czech Technical Univ. Prague (Czech Republic); Aurél Gábris, Igor Jex, Czech Technical Univ. in Prague (Czech Republic); Christine Silberhorn, Univ. Paderborn (Germany)

Linear optical networks which comprise a large number of optical modes have been investigated intensively over the last decades in various theoretical proposals.

Most recently their relevance for studies of photonic quantum walk systems has attracted attention, because they can be considered as a standard model to describe the dynamics of quantum particles in a discretized environment and serve as a simulator for complex quantum systems, which are not as readily accessible.

Introducing randomness into the network on which the walker evolves is essential for capturing various effects known from observations in biological, statistical and condensed matter physics.

Breaking links in the underlying graph structures leads to the concept of percolation, addressed in recent theoretical studies.

In its generalization the graph topology can even change in time, modelling a randomly evolving, fluctuating medium.

However, their experimental realization requires setups with increasing complexity and control of the system parameters.

Here, we present an experiment with precise dynamical control of the underlying graph structure, facilitating the blending of percolation with a genuine quantum process while exploiting the high intrinsic coherence and versatility of a time-multiplexed quantum walk architecture. Our approach allows for the simulation of subtle decoherence phenomena.

Our system makes use of a coherent light pulse as the walker, its polarisation as quantum coin state and they map its position information into the time domain.

First we employ a half-wave plate acting on the polarization to implement the coin operation.

The information about links being absent must then be encoded in a dynamical step operation dependent on position and step.

Since a direct modification of the step operator remains a challenging task in experimental realisations, we combine three auxiliary operations to generate it.

By making use of the double loop structure originally introduced for a 2d walk each pulse performs a half-step according to its polarisation after the coin operation in the first loop and exits into the second loop that contains an electro-optic modulator (EOM), fast enough for single position selectivity and able to either flip the polarisation of a pulse or to transmit it unchanged.

Each pulse trying to traverse a broken link get its polarisation flipped by the EOM and will accordingly be back reflected.

Thus the walker effectively stayed where it was and did not transgress the gap.

An existing link will simply transmit the pulse unchanged between the half-steps and thus perform a step onto a neighbouring site.

Based on this elaborate scheme we first present a finite walk limited to 3 positions by choice and not by static geometry.

By averaging over 64 percolation patterns we simulate a 3 sited graph with both edges being present with a 50% probability. Intuitively an increase of decoherence leads to a monotonous evolution into a totally mixed state would be expected.

However, the observation of the walker's internal degree of freedom exhibits an oscillatory dynamic of the Stokes parameters and the corresponding density matrix with time reaching the completely mixed state and moving away again proving the versatility and broad applicability of the presented quantum simulator.

9505-4, Session 4

Pulse-controlled quantum gate sequences on a strongly coupled qubit chain

Holger Frydrych, Technische Univ. Darmstadt (Germany); Michael Marthaler, Karlsruher Institut für Technologie (Germany); Gernot Alber, Technische Univ. Darmstadt (Germany)

Qubits are the foundation of quantum computation. Current implementations of qubits are typically either well isolated, but difficult to couple for the purpose of implementing multi-qubit gates, or strongly coupled, but difficult to decouple when necessary.

We investigate a possible approach to do controlled quantum computation on a linear qubit chain with static always-on nearest-neighbor couplings which cannot be modified. The qubits in the chain are individually controllable by a pulse generator. This pulse control can be used to perform rotation operations on individual qubits and, as a special case, allows the implementation of Pauli X and Y pulses.

With the help of the Pauli pulses we propose a simple dynamical decoupling [1] scheme that is capable of eliminating to first order any of the qubit couplings in the chain, allowing us to isolate any two neighboring qubits in the chain. We can then leverage the natural coupling between these two qubits to implement a two-qubit gate operation. In our model, we use an XX-type interaction, which naturally implements the so-called iSWAP gate that can be combined with additional single-qubit gates to perform the CNS gate, a combination of a CNOT and a SWAP operation on the two qubits [2]. Since our decoupling scheme allows us to suppress only specific couplings, we can even implement parallel gate operations.

With the help of the CNS gate, we demonstrate how to implement a quantum circuit on the qubit chain which entangles all of the qubits in a GHZ state. To entangle an N-qubit chain, the circuit requires N-1 applications of the CNS gate, where at each step, two CNS gates can be applied in parallel. Numerical simulation results are presented for the achievable GHZ state fidelity, depending on the number N of qubits and the achievable pulse width, where shorter pulses with stronger amplitudes generally lead to higher fidelities.

Our model is based on superconducting flux qubits controlled by a microwave emitter. For this scenario, we briefly discuss physical limits of the achievable pulse amplitudes. However, the presented control method is not restricted to this particular qubit chain implementation.

[1] L. Viola, E. Knill, and S. Lloyd, Phys. Rev. Lett. 82, 2417 (1999)

[2] N. Schuch and J. Siewert, Phys. Rev. A. 67, 032301 (2003)

9505-18, Session 5

Gaussian optimization conjectures: new results and proofs *(Invited Paper)*

Vittorio Giovannetti, Scuola Normale Superiore (United States)

Optical channels, such as fibers or free-space links, are ubiquitous in today's telecommunication networks. They rely on the electromagnetic field associated with photons to carry information from one point to another in space [1]. As a re- sult, a complete physical model of these channels must neces- sarily take quantum effects into account in order to determine their ultimate performances. Specifically, Gaussian photonic (or bosonic) quantum channels have been extensively studied over the past decades given their importance for practical pur- poses [2]. In spite of this, a longstanding conjecture on the op- timality of Gaussian encodings has yet prevented finding their communication capacity. In my talk I will report the solution of this conjecture by proving that the vacuum state achieves the minimum output entropy of a generic Gaussian bosonic channel [3]. This establishes the ultimate achievable bit rate under an energy constraint, as well as the long awaited proof that the single-letter classical capacity of these channels is ad- ditive [4]. Beyond capacities, it also has broad consequences in quantum information sciences allowing one to compute the entanglement of formation [5] for some non-symmetric Gaus- sian states.

I will also present a proof of the stronger version of the conjecture [6] which establish the optimality of Gaus- sian encoding in terms of majorization. Finally I will briefly mention on a generalization [7] of the entropy power inequal- ity [8].

Part of the research was funded by the EC-Framework Projects (Framework 7) under the project Thermodynamics of Mesoscopic Quantum Systems (THERMIQ).

[1] C. M. Caves and P. B. Drummond, Quantum limits on bosonic communication rates, Rev. Mod. Phys. 66, 481 (1994).

[2] A. S. Holevo and R. F. Werner, Evaluating capacities of bosonic Gaussian channels, Phys. Rev. A 63, 032312 (2001).

[3] V. Giovannetti, A. S. Holevo, and R. Garc ?ıa-Patro ?n, arXiv:1312.2251 [quant-ph].

[4] V. Giovannetti, R. Garc ?ıa-Patro ?n, N. J. Cerf, and A. S. Holevo, arXiv:1312.6225 [quant-ph].

[5] C. H. Bennett, D. P. DiVincenzo, J. A. Smolin, and W. K. Woot- ters, Mixed-state entanglement and quantum error correction Phys. Rev. A 54, 3824 (1996).

[6] A. Mari, V. Giovannetti, and A. S. Holevo, arXiv:1312.3545 [quant-ph].

[7] G. De Palma, A. Mari, and V. Giovannetti, arXiv:1402.0404 [quant-ph].

[8] R. Ko ?nig and G. Smith, arXiv:1205.3409.

9505-19, Session 5

Path entangled quantum networks *(Invited Paper)*

Rob Thew, Univ. de Genève (Switzerland)

Optical path entanglement - entanglement between several optical paths sharing a single photon - is one of the simplest forms of entanglement to produce. It is also a promising resource for long-distance quantum communication and has the potential to extend known point-to-point quantum repeaters to richer topologies for quantum networks.

However, the problem has been to detect entanglement between multiple optical paths sharing a single photon. We present a scalable protocol for detecting entanglement, which uses only local measurements, in which photon counting is combined with displacement operations. The resulting entanglement witness does not require post-selection, or assumptions about the photon number in each path. Furthermore, it guarantees that entanglement lies in a subspace with at most one photon per optical path and reveals genuine entanglement. We demonstrate its scalability and resistance to loss by performing various experiments for bipartite and tripartite entangled systems.

Transmission loss in quantum networks also presents a problem in the case of device independent protocols, such as QKD, that require a detection-loophole-free Bell test to ensure security. We present recent results on heralded qubit amplification, for both time-bin and path-entangled schemes.

We anticipate interesting applications of our results to certify the functioning of future quantum networks.

9505-20, Session 5

Real-time phase-reference monitoring in a quasi-optimal coherent-state receiver

Alessia Allevi, Univ. degli Studi dell'Insubria (Italy); Matteo Bina, Univ. degli Studi di Milano (Italy); Maria Bondani, Consiglio Nazionale delle Ricerche (Italy); Stefano Olivares, Univ. degli Studi di Milano (Italy)

Communication channels based on coherent signals are of great interest for the scientific community in view of their technological applications when quantum resources, such as entanglement, cannot be exploited. From a more fundamental point of view, they require facing the problem to discriminate among non-orthogonal states. Usually, in the case of a binary phase-shift-keyed channel, the detection/discrimination stage includes a quasi-optimal receiver, in which, in the simplest case, a local oscillator (LO) is mixed at a beam splitter with the states to be discriminated. The main limitation in the reliability of such systems is given by the need of knowing the relative phase between signal and LO. Indeed, this is only one example of the more general task of phase estimation in Physics.

Here we propose, and experimentally test, a real-time monitoring of the phase by considering one of the best known phase-shift-keyed communication receivers, namely the Kennedy-like receiver. Its traditional scheme is based on interfering the two signals encoding the message with a reference LO and detecting the output with an ON/OFF photodetector. In our work, we demonstrate that, without interrupting the communication, the Bayesian processing of a small amount of data samples, corresponding to a statistical mixture of the states to be discriminated, allows the achievement of the minimum uncertainty in phase estimation, given by the inverse of the Fisher information associated with the statistics of the collected data.

The performances of our phase-estimation method are also investigated, both numerically and experimentally, in the presence of a uniform phase noise, whereas considerations about the phenomenon of phase diffusion are discussed from the theoretical point of view.

Finally, we also show that the use of photon-number resolving detectors in the receiver represents the best phase-estimation strategy, especially with respect to the usually employed ON/OFF detectors. From the experimental point of view, this comparison is realized by employing hybrid photodetectors as the detectors. In fact, they are endowed with partial photon-number capability, and can be used to reconstruct the statistics of detected photons.

Our investigation not only opens new perspectives in the field of Quantum Communication, but, by creating a link between state discrimination and phase estimation in quantum systems, it can in principle find applications also in other contexts, in which the estimation of the phase represents an unavoidable requirement.

9505-21, Session 5

Incoherent on-off keying with classical and nonclassical light

Marcin Jarzyna, Piotr Kuszaj, Konrad Banaszek, Univ. of Warsaw (Poland)

Optical transmission has become the backbone of modern high-throughput fiber-based information infrastructures. It is also studied in the context of more specialized applications, such as deep-space communication. Transfer rates attainable over optical channels are fundamentally limited by the available signal power, spectral range, and noise effects in the medium transmitting signals, which altogether determine the ultimate channel capacity implied by the laws of quantum physics. One of the basic models of optical communication is a lossy narrowband channel, where a single bosonic mode transmitted in each use undergoes linear amplitude damping. A natural physical constraint in this scenario is a bound on the average power. Among common modulation schemes, on-off keying (OOK) and its restricted version pulse position modulation (PPM), which use just two states: an empty vacuum bin and a non-zero light pulse, are known to approach the capacity of the narrowband channel at very low average energy levels even if incoherent, direct photodetection is used. In this paper, we present a systematic study of the effects of the photon statistics on the transmission rate in the incoherent scenario with direct detection. Using the quantum theory of photodetection, we identify the well-known g(2) normalized intensity correlation function at zero delay as the relevant characteristics that explicitly enters the expression for Shannon mutual information. This provides a simple scaling formula for photon information efficiency. The analysis is extended into the non-classical region of sub-Poissonian photon statistics, quantifying how much the transmission rate can be enhanced by the use of non-classical states of light.

9505-22, Session 6

Practical secure quantum communications *(Invited Paper)*

Eleni Diamanti, Télécom ParisTech (France)

The ability to distribute secret keys with information-theoretic security is undoubtedly one of the most important achievements of the field of quantum information processing and communications. Quantum key distribution (QKD) protocols in which the key information is encoded on quantum continuous variables, such as the values of quadrature components of coherent states of light, present the major advantage that they only require standard telecommunication technology, and in particular, that they do not use photon counters. After introducing such protocols, we present the state-of-the-art in long-distance fiber optic experiments for continuous-variable quantum key distribution (CV-QKD). Furthermore, we discuss the resistance of CV-QKD systems to eavesdropping attacks based on auxiliary information channels that are typically not taken into account in security proofs, as well as avenues to exploit the standard components employed in such systems with the goal of developing silicon photonic chips for quantum key distribution. This can open the way to the widespread use of this technology for high-security applications.

In addition to quantum key distribution, the security of future quantum information networks will also rely on other cryptographic protocols executed between potentially distrustful parties with access to resources of variable complexity. We discuss in this context theoretical protocols and practical photonic implementations of quantum coin flipping and multiparty entangled state verification, which are at the heart of several advanced communication and computation tasks. As with QKD, imperfections and limitations of practical systems affect the security of these protocols, nevertheless it is still possible to achieve high performance and demonstrate strong security guarantees – superior to what classical resources alone could ever provide.

These developments offer a powerful toolbox for practical applications of secure communications within future quantum networks.

References

P. Jouguet, S. Kunz-Jacques, A. Leverrier, P. Grangier, E. Diamanti, Nature Photon. 7, 378 (2013).

P. Jouguet, S. Kunz-Jacques, E. Diamanti, Phys. Rev. A 87, 062313 (2013).

A. Pappa, P. Jouguet, T. Lawson, A. Chailloux, M. Legré, P. Trinkler, I. Kerenidis, E. Diamanti, Nature Commun. 5, 3717 (2014).

A. Pappa, A. Chailloux, S. Wehner, E. Diamanti, I. Kerenidis, Phys. Rev. Lett. 108, 260502 (2012).

9505-23, Session 6

Coherent spectral manipulation of nonclassical light *(Invited Paper)*

Michal Karpinski, Laura Wright, Alex O. C. Davis, Brian J. Smith, Univ. of Oxford (United Kingdom)

Spectral manipulation of non-classical states of light is critical for realistic implementations of photonic quantum technologies [1]. Efficient encoding of quantum information in the spectral degree of freedom of a single photon as well as interfacing different nodes of future hybrid quantum networks both rely upon this capability. To date spectral manipulation of quantum light has been addressed by means of nonlinear optical frequency conversion [2]. This technique enables realization of large frequency shifts at a cost of high power of pump fields necessary to achieve deterministic conversion, which ultimately limits the achievable conversion rates. Here we experimentally demonstrate an approach to spectral manipulation of few-photon level optical fields that is free from this limitation, because it does not involve all-optical nonlinearities. We employ fast electro-optic modulation [3] to perform deterministic frequency shifts and bandwidth manipulation of few-picosecond pulses of light at the single-photon level.

Coherent manipulation of optical pulses is achieved by subjecting individual wave packets to electro-optic phase modulation in a regime where the optical pulse duration is shorter than variations in the phase modulation. This enables us to imprint a variety of deterministic temporally varying phases on the pulse, e.g. a linear temporal phase that implements a spectral shear of the wave packet [3]. To achieve a spectral shear of significant magnitude requires use of state-of-the-art electro-optic modulation operating at high frequency (40 GHz). We demonstrate deterministic frequency shifts of near infrared (830 nm central wavelength), heralded single photon pulses in wave packets of approximately 1 ps duration by more than 1 nm. We confirm preservation of non-classical photon number statistics through the process and demonstrate the photon wave-packet is left undisturbed by verifying non-classical two-photon interference with spectrally shifted single-photon wave packets.

We discuss applications of our technique to spectral-temporal quantum state tomography, quantum networking, quantum key distribution, and spectral multiplexing of heralded single-photon sources, stressing the importance of the fast switching capability of the technique.

References:

[1] P. P. Rohde et al., Phys. Rev. A 72, 052332 (2005).

[2] J. Huang and P. Kumar, Phys. Rev. Lett. 68, 2153 (1992).

[3] C. Dorrer and I. Kang, Opt. Lett. 28, 477 (2003); I. Kang et al., ibid., 2264 (2003).

9505-24, Session 6

Temporal shaping of single-photon pulses

Gaston Hornecker, Emanuel Peinke, Institut NÉEL (France); Julien Claudon, Commissariat à l'Énergie Atomique (France); Alexia Auffèves, Institut NÉEL (France); Jean-Michel Gérard, Commissariat à l'Énergie Atomique (France)

The ability to control the temporal shape of single photon pulses is highly desirable in quantum information processing. For instance, it has been shown that Gaussian pulses are best suited for linear optics quantum computing [1]. By mimicking the time reversal of a spontaneous emission, it also allows to optimize the absorption of the prepared photons by a quantum emitter. In this work we investigate the potential of using fast modifications of the detuning between an atomic system and a cavity during photon emission to reach this goal. We compare two approaches consisting of varying the atomic or cavity frequency. The latter, achievable by a fast modification of the refractive index of a solid state cavity, will be shown to have negligible influence on the photon spectrum. It allows to create gaussian pulses interacting with target photons with a visibility of 99%, as well as time reversed photons absorbed by an atom in a cavity with a probability of 93%.

[1] Peter P. Rohde, Timothy C. Ralph and Michael A. Nielsen, "Optimal photons for quantum-information processing" Phys. Rev. A 72, 052332 (2005).

9505-25, Session 6

Spatial-mode-selective quantum frequency conversion in nonlinear waveguides

Young Bong Kwon, Michael Vasilyev, The Univ. of Texas at Arlington (United States)

Following the current trends of classical long-distance communications, the future quantum communication links will aim to maximize their capacities / rates by utilizing multiple wavelengths, polarizations, and spatial modes of the fiber. Hence, there is a need for spatial-mode-selective frequency up-converters of quantum states from infrared to visible region, which will be useful not only for interfacing the optical fiber links with quantum memories and for increasing the photon detection efficiency (both are well known applications), but also for demultiplexing of spatial modes that are otherwise difficult to discriminate in both spatial and spatial-frequency domains. The key to the quantum use of this device is its ability to up-convert the desired mode with 100% efficiency without affecting any other spatially overlapping modes.

In this paper we present two such spatial-mode-selective quantum frequency converters. The first one is based on sum-frequency generation (SFG) in 2D free space (slab waveguide with one-dimensional confinement) and represents a straightforward extension of temporal-mode-selective SFG. The eigenmodes of this 2D process can be found by performing singular-value decomposition (SVD) of its Green's function, and the resulting SVD spectrum (conversion efficiencies for different modes) can be controlled by properly adjusting the pump spatial profile. The second spatial-mode-selective frequency up-converter is based on a multimode waveguide with two-dimensional confinement and is experimentally implemented. Here, the waveguide geometry defines the dispersion and, consequently, the phase-matching conditions for various combinations of signal, pump, and sum-frequency modes. With proper quasi-phase-matching, one can approach 100% up-conversion of any mode superposition from a sub-space of several lowest waveguide modes, without affecting any orthogonal mode superpositions, by properly choosing the pump mode profile.

Conference 9506: Optical Sensors

Monday - Thursday 13–16 April 2015

Part of Proceedings of SPIE Vol. 9506 Optical Sensors 2015

9506-1, Session 1

Dilute nitride resonant cavity enhanced photodetector with internal gain for operation at ?=1.286 μm

Naci Balkan, Univ. of Essex (United Kingdom); Ayse Erol, Fahrettin Sarcan, Istanbul Univ. (Turkey); Mohammad S. B. Nordin, Leena F. F. Al-Ghuraibawi, Univ. of Essex (United Kingdom)

RCEPDs have been widely investigated for applications in the 1.3 and 1.55 μm windows of optical communication systems, for their high speed and wavelength-selective capabilities [1] [2]. They consist of a thin narrow multiple quantum well absorbing region sandwiched between two mirrors, commonly, Distributed Bragg Reflector (DBR) stacks [3]. Light that cannot be absorbed in the first pass is reflected back into the absorption region, therefore, the high efficiencies are achieved with high-reflectivity mirrors. Traditionally, InP-based materials such as InGaAsP have been used for the telecommunication wavelengths[4]. However, InP-based material is not lattice matched to GaAs wafers. Therefore, the formation of high reflectivity DBR mirrors is a major problem because of the small contrast between the refractive indices of the alternating layers of the InGaAsP-InP Bragg mirrors, which are commonly used in these structures. In order to overcome this problem either wafer-fusing on to GaAs/GaAlAs is employed, or some esoteric dielectric mirror pairs are used as reflectors. These options have long term reliability issues, necessitate complex fabrication process and are also costly [5][6]. Here we report on a novel-design dilute nitride resonant cavity enhanced photodedector (RCEPD) operating at the telecom wavelengths. The active region of the device contains GaAs/Ga0.65In0.35N0.02 As0.98 quantum wells. The cavity is formed using GaAs/AlGaAs top and bottom DBRs. At T=300K, dark current values are 1.7 nA and 6.5 nA, at reverse bias voltages of 1V and 2V respectively. The external quantum efficiency is 45.6% at 1.286 ?m. The full-width at half-maximum is 1.7 nm.. Furthermore, the device has significant internal gain following the photocurrent saturation, associated with impact ionisation at bias voltages of V ≥2V.

[1] M. S. U?nlu? and S. Strite, “Resonant cavity enhanced photonic devices,” J. Appl. Phys., vol. 78, no. 2, p. 607, 1995.

[2] S. Substrates, M. K. Emsley, O. Dosunmu, and M. S. Ünlü, “High-Speed Resonant-Cavity-Enhanced Silicon Photodetectors on Reflecting,” vol. 14, no. 4, pp. 519–521, 2002.

[3] K. Kishino, J. Chyi, and H. Morkoq, “Resonant Cavity -Enhanced (RCE) Photodetectors,” vol. 21, no. 8, 1991.

[4] H. G. Front-end, K. Yang, A. L. Gutierrez-aitken, X. Zhang, G. I. Haddad, and P. Bhattacharya, “Design, Modeling, and Characterization of Monolithically Integrated InP-Based (1.55 pm) High-speed (24 Gbh) p-i-dHBT Front-End Photoreceivers,” vol. 14, no. 8, pp. 1831–1839, 1996.

[5] S. O. Wafer-fused, A. Syrbu, S. Member, A. Mircea, A. Mereuta, A. Caliman, C. Berseth, G. Suruceanu, V. Iakovlev, M. Achtenhagen, A. Rudra, E. Kapon, and A. We, “1.5-mW Single-Mode Operation of Wafer-Fused 1550-nm VCSELs,” vol. 16, no. 5, pp. 1230–1232, 2004.

[6] G. Boehm, M. Grau, O. Dier, K. Windhorn, E. Roenneberg, J. Rosskopf, R. Shau, R. Meyer, M. Ortsiefer, and M.-C. Amann, “Growth of InAs-containing quantum wells for InP-based VCSELs emitting at 2.3?m,” J. Cryst. Growth, vol. 301–302, pp. 941–944, Apr. 2007.

9506-3, Session 1

Modeling of CMOS image sensors for time-of-flight applications

Adrian Driewer, Bedrich J. Hosticka, Andreas Spickermann, Holger Vogt, Fraunhofer-Institut für Mikroelektronische Schaltungen und Systeme (Germany)

This contribution describes the modeling of CMOS image sensors employed in time-of-flight (ToF) sensor systems for 3D ranging applications. The system under consideration is based on the pulse modulated (PM) ToF principle which measures the elapsed time between the emission of a light pulse and the detection of the reflected light. In indirect ToF measurements the detected signal is integrated at two different short time integrators featuring distinct integration times. The actual distance information can then be determined from the comparison of their output signals.

The employed approach allows elimination of undesired reflectance effects, and the influence of ambient light through an in-pixel background measurement. Since the sensor is operated with very short integration times it is crucial to accomplish a fast transfer of the generated charge from the photodetector to the sense node, and speedy conversion into an electrical signal at its output. In our case, we employed a lateral drift field photodetector (LDPD), which is basically a pinned photodiode with a built-in drift field formed by a doping gradient.

Our model relies on the theoretical description of photo-generation, charge transfer including diffusion, fringing field, self-induced drift (SID), and charge-to-voltage conversion at a floating diffusion. The resulting nonlinear parabolic differential equation, which describes the time-dependent charge carrier distribution in the photoactive area, has been partially solved analytically, and a comparison to numerical calculations proved the consistency of the results.

In addition, the model has been verified using measurements on various 3D ToF range sensors developed in 0.35 μm CMOS technology and featuring different geometry arrangements and various doping profiles. In these measurements the sensors have been irradiated by a pulsed infrared laser with the irradiance ranging from 15 W/m? to 8000 W/m? for different integration times. It shows an excellent accordance with the results predicted by the model.

From the calculated time-dependent charge carrier distribution the expected transfer speed can be obtained. This enables two application scenarios of the model.

At first, the effects resulting from the doping gradient can be quantified, allowing optimization of the LDPD design on early stages, and maximize charge transfer velocity. The concept of a novel pixel architecture based on these optimizations will be presented.

The measurement results show clear dependence of the charge transfer speed on irradiance. As a second application, the model delivers a theoretical explanation of this behavior and makes possible the correction of the measured time-of-flight and enhancement of the distance information without extensive calibration procedures.

9506-4, Session 1

Radiometric calibration of digital cameras using gaussian processes

Martin Schall, Michael Grunwald, Hochschule Konstanz (Germany); Georg Umlauf, Institut for Optical System, University of Applied Sciences Konstanz (Germany); Matthias O. Franz, Hochschule Konstanz (Germany)

Digital cameras are subject to physical, electronic and optic effects that result in errors and noise in the image. These effects include for example a temperature dependent dark current, read noise, optical vignetting or different sensitivities of individual pixels. The task of a radiometric calibration is to reduce these errors in the image and thus improve the quality of the overall application. A classical approach to do a radiometric calibration is the application of flat fields and dark frames. In this work we present an algorithm for radiometric calibration based on Gaussian Processes. Gaussian Processes are a regression method widely used in machine learning that is particularly useful in our context due to its efficient model selection process. Then Gaussian Process regression is used to learn a temperature and exposure time dependent mapping from observed gray-scale values to true light intensities for each

pixel. Regression models based on the characteristics of single pixels suffer from excessively high runtime and thus are unsuitable for many practical applications. In contrast, a single regression model for an entire image with high spatial resolution leads to a low quality radiometric calibration, which also limits its practical use. The proposed algorithm is predicated on a clustering of the pixels such that each pixel cluster can be represented by one single regression model without quality loss. Partitioning is done by extracting features from the characteristic of each pixel and using them for lexicographic sorting. Splitting the sorted data into partitions with equal size yields the final clusters, each of which is represented by the cluster centers. An individual Gaussian Process regression and model selection is done for each cluster. Calibration is performed by interpolating the gray-scale value of each pixel with the regression model of the respective cluster. The experimental comparison of the proposed approach to classical flat field calibration shows a consistently higher reconstruction quality for the same overall number of calibration frames.

9506-5, Session 1

Hyperspectral light field imaging

Raimund Leitner, Andreas Kenda, Andreas Tortschanoff, Carinthian Tech Research AG (Austria); Josef Atzler, Molecular Devices LLC (Austria)

Light-field imaging acquires light intensity and direction usually described using a 4D-representation L(x,y,u,v). After light field acquisition, this allows to change the view-point and re-focus partially blurred regions, an important feature for many applications in imaging and microscopy. The combination with hyper-spectral imaging provides the additional advantage that objects (beads, cells, cell parts) can be categorised using their spectroscopic signatures or concentrations can be estimated using spectral unmixing techniques. Using a fluorescence microscope, a LCTF tuneable filter and a light-field setup as a test-bed, fluorescence-marked beads have been imaged and reconstructed into a 4D hyper-spectral image cube. The results demonstrate the advantages of the approach for fluorescence microscopy providing extended DoF and the fidelity of hyper-spectral imaging. The presented approach allows hyper-spectral unmixing and spatial separation of close objects due to the angular information available from the light field. Thus, this represents a novel solution for the classical ambiguity currently a problem in fluorescence microscopy.

9506-6, Session 2

Φ-OTDR signal amplification

Petr Münster, Brno Univ. of Technology (Czech Republic); Josef Vojtech, CESNET z.s.p.o. (Czech Republic); Petr Sysel, Radim Sifta, Vít Novotny, Tomás Horváth, Brno Univ. of Technology (Czech Republic); Stanislav Sima, CESNET z.s.p.o. (Czech Republic); Miloslav Filka, Brno Univ. of Technology (Czech Republic)

Phase-sensitive optical time-domain reflectometry (?-OTDR) seems to be the most appropriate solution for acoustic vibration along standard optical fiber detection. In general the sensing system measures phase changes of the received Rayleigh back-scattered signal in the fiber. Since the back-scattered signal intensity is decreased about tens of decibels in comparison to the forward propagating pulse power level, the received signal power level is very low. That is why the main limiting parameter of the system is the power level of the back-scattered signal, which limits maximum achievable distance. For long reach sensing it is necessary to create high power optical pulses with short time-duration. Direct pulse amplification by erbium doped fiber amplifier (EDFA) is an issue because of the pulses low repetition rate. We have designed and verified simple method using a holding beam for amplifying of pulses with low repetition rate by standard telecommunication EDFA booster instead of deployment of an expensive optical shutter. A second CW laser with a different wavelength for EDFA stabilization is used in our setup. Because a pulse loses its energy during propagation in the fiber and with longer distances the received signal power is lower. We have performed measurement using distributed amplification by 1st order Raman amplifier (RA). In telecommunications this amplifier is used to compensate for fiber loses. The second setup uses remote amplification by remotely pumped erbium doped fiber (EDF) placed after a few tens of kilometers of sensing fiber. A pump laser is placed in the transmitter part of the system from where EDF is pumped. In this paper, we present an overview of few techniques for ?-ODTR signals amplification and their verification by measurement.

9506-7, Session 2

Real time polarization sensor image processing on an embedded FPGA/multi-core DSP system

Marcus Bednara, Katarzyna Chuchacz-Kowalczyk, Fraunhofer-Institut für Integrierte Schaltungen (IIS) (Germany)

A polarization sensor with per-pixel nanowire grid polarizers using the available CMOS metal layers enables capturing relevant polarization parameters of light (i.e. angle and degree of polarization) in one single shot, with the high frame rate of up to 80 fps. The algorithm for extracting the polarization state of light from sensor raw data and representing it in a form of a synthetically generated color map is computationally complex and can hardly be implemented on embedded image processing systems optimized for consumer applications. To overcome the limitations of state of the art systems, the algorithm was implemented on a high performance embedded image processing platform that was developed as a replacement for PC in mobile or power constrained applications, as well as a basis for custom and application specific platform development. The system is based on a multi-core DSP and a high-performance FPGA and can be applied in typical non-consumer environments, e.g., polarization based image analysis for industrial or medical applications. In this paper, the proposed strategy for algorithm optimization towards embedded implementation is presented in detail, including its efficient parallelization, minimization of inter-process communication overhead, efficient use of FPGA and overcoming cache coherence issues. Furthermore, a framework for the parallelization of image processing functions on a multi-core DSP is presented. Performance evaluation of the complete embedded system includes the comparison with a state of the art PC implementation, which clearly indicates that a similar processing speed can be achieved in both cases. However, significantly lower power consumption makes the presented platform highly attractive for non-PC based applications.

9506-8, Session 2

Integrated optics on Lithium Niobate for sensing applications

Annamaria Zaltron, Giacomo Bettella, Univ. degli Studi di Padova (Italy); Gianluca Pozza, Riccardo Zamboni, Univ degli Studi di Padova (Italy); Sebastian Kroesen, Michael Esseling, Cornelia Denz, Westfälische Wilhelms-Univ. Münster (Germany); Cinzia Sada, Univ. degli Studi di Padova (Italy)

Lithium Niobate (LiNbO3) is an electro-optic material well known in the field of integrated optical devices, thanks to its unique combination of optical and structural properties. Its remarkable optical coefficients and significant photorefractive response have allowed to exploit this material for the realization of various optical systems, such as second-harmonic generation, holographic gratings, optical modulator and waveguides, particles manipulation and so on [1-3]. Moreover, the recent development of techniques able to modify this material at a micro- and nanometer scale has led to a progressive increasing interest in it by the side of both the scientific and the industrial communities, thus promoting theoretical and experimental studies on pure and doped LiNbO3 crystals.

Recently lithium niobate has been also proposed as candidate for application in opto-microfluidic technology [4,5], thus combining the tools typical of microfluidics with the potentialities offered by this material. The idea is to realize in a LiNbO3 substrate a T-shaped droplet

generator where optical stages are integrated, in order to obtain a system able to perform on-site optical sensing processes such as those required in chemical and biological analyses.

The realization of such a device requires different preparation steps, from the creation of the microfluidic droplet generation by means of femtosecond laser ablation to the implementation of channel waveguides and wavelength filters for the optical sensing of the droplets. Moreover, a stage for droplet manipulation can be integrated inside the microfluidic channels, in order to route the droplet towards the desired outlet door accordingly to their optical properties.

In this work, by a step-by-step logic, we will describe the recent results on the realisation of each of the mentioned stages and, consequently, the future perspectives and challenges in understanding the physical phenomena behind. Finally the potential realization of optical sensing platforms will be discussed.

References

[1] L. Arizmendi, phys. stat. sol. (a) 201 (2), 253, 2004

[2] T. Volk and M. Wöhlecke, Lithium nionate: defects, photorefraction and ferroelectric switching, Springer Series in Material Science, 2008

[3] M. Esseling et al., Appl Phys Lett 103, 061115, 2013

[4] G. Pozza et al., T-junction droplet generator realised in lithium niobate crystals by laser ablation, Optofluid. Microfluid. Nanofluid., accepted, 2014

[5] M. Sridhar et al., Biomicrofluidics 6 (1), 12819, 2012

9506-9, Session 2

Onboard compensation technique for misalignment of satellite sensor telescope for Earth observation

Norihide Miyamura, Meisei Univ. (Japan)

We are developing an adaptive optics system (AOS) for earth observing remote sensing sensor. In this system, high spatial resolution has to be achieved by a lightweight sensor system due to the launcher's requirements. Moreover, simple hardware architecture has to be selected to achieve high reliability. Optical surface deformation and misalignment of the optical elements become too large to ignore for large aperture optical system. For conventional system, optical alignment is adjusted in laboratory before launch to achieve desired imaging performance. However, it is difficult to adjust the alignment for large sized optics in high accuracy. Furthermore, thermal environment in orbit and vibration in launch vehicle cause the misalignments of the optics. Image based AOS compensate that misalignments using deformable mirror and observed images. In remote sensing, it is difficult to use a reference point source unless the satellite controls its attitude toward a star. We propose the control algorithm of the deformable mirror on the basis of the extended scene instead of the point source.

9506-11, Session 2

Infrared moving target detection algorithm based on multiscale codebook model

Lei Liu, Yayun Zhou, Nanjing Univ. of Science and Technology (China)

With the continuous development of science and technology, infrared sensor technology has played an important role in national defense, medical, transportation and other areas. The tracking technology of small infrared target is an important branch of infrared imaging technology, which has not only very important scientific research value, but also has broad application prospect in the military and civil area.

Nowadays, different algorithms have been proposed for infrared target tracking. However, under complex backgrounds, such as clutter, varying illumination, and occlusion, the traditional tracking method often loses the real infrared small target.

To cope with these problems, in this paper we have present a novel infrared moving target detection algorithm based on multiscale codebook model according to the characteristics of small target in infrared images. The basic principles and the implementing procedure of these algorithms for target tracking are described. Firstly, the infrared video is stratified by Gauss Pyramid. Secondly, codebook model is built for each layer image and the moving target in infrared video is detected according to model. Finally, each layer results are combined and the final detection result is get. The experimental results show that, compared with traditional detection algorithms, the result of multiscale codebook model has better detection effects, richer target information and lower false detection rate. This algorithm can not only be used in the field of image fusion, in order to improve the fusion effect, but also be used in security surveillance, night vision surveillance and other civil and military fields.

9506-12, Session 3

A suite of optical fibre sensors for structural condition monitoring *(Invited Paper)*

Tong Sun, City Univ. London (United Kingdom)

No Abstract Available

9506-13, Session 3

Photoluminescent temperature sensor based on borate and phosphate glasses doped with copper clusters

Anastasiia N. Babkina, Pavel S. Shirshnev, Nikolay V. Nikonorov, Aleksandr I. Sidorov, Elena V. Kolobkova, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

By operating principle luminescent temperature sensors can be divided into several types: the first one functions by means of thermal shifting of the maximum of the luminescent band, the second one is based on thermal energy redistribution in the closely spaced luminescent bands and the third one works per thermal changing of the luminescence decay time. The first type of sensors is not widespread now because of its low temperature measurement accuracy (±5K) and great persistence (units of seconds) [1]. This happened as there is no appropriate active material with excellent thermal sensitivity. Recently [2] glassy material with a suitable sensitivity for usage in fluorescent temperature sensors based on optical fibers has been first demonstrated. It was found out [2], that potassium-alumina-borate glass with following composition: K2O(20)-Al2O3(25)-B2O3(55)-Cu2O(5)-NaCl(7,5) (mol%) - has a luminescent thermochromism - reversible change in the position of maximum of the luminescent band with temperature changes in the range from 77K up to 523K. While heating of glass sample from room temperature up to 523K and cooling down to 77K the luminescent band shift measures as 95nm to the short wavelengths and to the long wavelengths respectively. The luminescent centers in borate glass excited by 405nm were determined as molecular clusters (Cu2O)n [2]. The present investigation revealed the presence of luminescent thermochromism in copper doped glass with another matrix, namely fluorophosphates with following composition: NaPO3(12)-Ba(PO3)2(17)-AlF3(5,3)-CuCl(1) (wt%). Irradiation of these glasses by 405nm excites the same luminescence as in borate ones. As it can be seen fluorophosphate glass has less components than borates, and its synthesizing process technologically is less complicated: 1273K and 30 minutes comparing with 1623K and 90 minutes for borate glass. However, during temperature investigations in the indicated temperature range the luminescent band shift of fluorophosphate glass was only 20nm.

It is well known that the luminescence of molecular clusters depends on the surrounding amorphous matrix. With temperature changing boron, a large amount of which is included in the borate glasses, changes its valence state, which may well affect the luminescence of molecular clusters with copper. It can be concluded that the copper doped borate glasses can be used as a new active materials in the fluorescent fiber temperature sensors. In the worst case the temperature measurement accuracy of these sensors with standard detector were predicted

to be 1K. These sensor will have advanced features: in addition to a simple determination of the temperature at one point, it will be able to determine the temperature gradient along the extended samples and to compare the temperatures of two or more objects.

1. G. Brambilla, H.H. Kee, V. Pruneri, T.P. Newson. Optical fibre sensors for earth sciences: from basic concepts to optimising glass composition for high temperature applications // Optics and Lasers in Engineering, 2002, Vol. 37, pp. 215–232.

2. A.N. Babkina, N.V. Nikonorov, T.A. Shakhverdov, P.S. Shirshnev, A.I. Sidorov. Luminescent thermochromism in potassium-alumina-borate glass with copper-containing molecular clusters at elevated temperatures // Optical Materials, 2014, Vol. 36, pp. 773–777.

9506-14, Session 3

FBG-based Novel Sensor for High-temperature Measurement and Its Low-cost Interrogation

Venkata Reddy Mamidi, Srimannarayana Kamineni, R. L. N. Sai Prasad, Venkatappa Rao Thumu, Vengal Rao Pachava, National Institute of Technology, Warangal (India)

In this paper we present a fiber Bragg grating (FBG)-based novel sensor accompanied with low cost interrogation system, which measures the temperature from 20°C to 1000°C with the resolution of 1°C.

FBGs are the most attractive sensing elements for temperature and strain owing to their all advantages of fiber optics, high sensitivity, accuracy and multiplexing capability. For many years, a large quantity of development and research in the field of FBG-based low-temperature sensing have been reported, but the area of high-temperature sensing is comparatively immature. The standard Type-I FBGs imprinted by weak and strong excimer laser survive up to 450°C and 700°C respectively, beyond the limit the gratings get erased if they are directly subjected to the temperature. However, Fs-IR laser induced Type-II gratings and regenerated gratings are proved to withstand higher-temperature, they were observed to have short term stability at high temperature. So there is a necessity to having an alternative technique to go for high-temperature measurement using FBG sensors.

The designed FBG temperature sensor works based on measurement of the shift in Bragg wavelength that corresponds to the temperature induced strain by making use of a mechanical transducer. The transducing element provides temperature dependent strain on FBG by means of differential linear thermal expansion of two different materials. The shift in Bragg wavelength due to strain is given as

$\Delta\lambda B = \lambda B$ (1-pe) ε,

where pe is effective strain-optic constant, ε is applied strain that can be given as $\alpha = (\alpha 1-\alpha 2)\Delta t$, $\alpha 1$, $\alpha 2$ are linear thermal expansion coefficients of both the materials, Δt is change in temperature..

A bimetallic strip of stainless steel (SS) and mild steel (MS) measures 24cm and 6cm in length, respectively, is welded at one end inside a rectangular metallic frame made of SS. Since the difference in thermal expansion coefficients of SS and MS is ~5 ?/°C, the free end of bimetallic strip get shifted 300 ?m away from the rectangular frame at the maximum applied temperature of 1000 °C. A Type-I FBG of resonance wavelength, 1552.98 nm is glued between free end of the bimetallic strip and outer frame by fixing the fiber of length 10 cm. The FBG is illuminated by a broad band light source, and its reflected output is directed to an optical spectrum analyser (OSA). When the sensor probe is subjected to the temperature over the range of 20-1000 °C, the FBG get strained axially. The shift in Bragg wavelength of FBG due to this temperature induced strain is measured by using OSA. Further the bulk and expensive OSA is replaced by a low cost interrogation system that employed an LPG, a photodiode, a transimpedance amplifier, and a digital multimeter. The LPG converts the wavelength information of FBG into its equivalent intensity modulated signal which can be captured by a simple photodiode and then converted into voltage signal using a transimpedance amplifier. The achieved resolution of the sensor is 1°C with time constant, 80 sec. However, the betterment of the sensor is in full pace.

The important aspects that are involved in this design are; (i) design of an FBG-based rigid sensor probe for high-temperature measurement, (ii) making the sensor output independent of length of the probe subjected to the temperature, and (iii) making the measurement system cost effective by replacing the OSA with low cost interrogation system.

9506-15, Session 3

Polarimetric and fiber Bragg grating reflective hybrid sensor for simultaneous measurement of strain and temperature in composite material

Marcin S. Bieda, Piotr Lesiak, Mateusz Szel?g, Micha? Kuczkowski, Andrzej W. Domanski, Tomasz R. Woli?ski, Warsaw Univ. of Technology (Poland); Gerald Farrell, Dublin Institute of Technology (Ireland)

Fiber optic sensors are often used to measure strain in different materials [1]. They are especially convenient to use with composite materials because of their similar mechanical properties. With some effort, optical fiber can be embedded into such material, acting as an internal sensor [2]. In most cases such sensor is used to monitor internal strain, therefore influence of other factors such as temperature should be minimized.

It is possible to design polarimetric or Fiber Brag Grating (FBG) sensor which is not sensitive for the temperature change. However, sensor embedded in composite material behave in different way than in open-air. Composite material elongates with temperature, and this causes strain of the embedded sensing fiber [3]. Even if the fiber optic sensor is temperature insensitive, sensor readout changes with temperature variations due to change in sensor length transferred from the composite.

In order to measure strain independently from temperature, hybrid solution based on polarimetric and FBG sensors is proposed. This sensor is designed in reflective configuration, where FBG act as a mirror. Reflective sensors are easier to implement in composite materials, because only one end of the fiber needs to be transferred out from the material. This configuration has other advantages:the same fiber is used to measure strain and temperature, so the measurement is taken exactly in the same place and, sensor uses only one light source [4].

In the proposed sensor, light is inserted into the fiber from edge-emitting LED with 50:50 splitter. Other arms of the splitter are used to monitor light power at sensor input and output. By monitoring polarization and wavelength of reflected light, output signals form polarimetric and FBG part of the sensor can be determined. Relation between strain and temperature sensitivity is different in the FBG than in the polarimetric sensor. With the information from those two sensors, both temperature and strain can be determined.

[1] G. Hegde, A. Asundi, “Performance analysis of all-fiber polarimetric strain sensor for composites structural health monitoring,” NDT&E International 39, 320–327 (2006).

[2] A. W. Domanski, M. Bieda, P. Lesiak, P. Makowski, M. Szelag, T. Pocz?sny, K. Prokopczuk, P. Sobotka, M. Chych?owski, M. Sierakowski, T. R. Woli?ski, “Polarimetric optical fiber sensors for dynamic strain measurement in composite materials,” Acta Physica Polonica A. 124, 399-401 (2013).

[3] P. Lesiak, M. Szel?g, D. Budaszewski, R. Plaga, K. Mile?ko, G. Rajan, Y. Semenova, G. Farrell, A. Boczkowska, A. Doma?ski, T. Woli?ski, “Influence of lamination process on optical fiber sensors embedded in composite material,” Measurement, Vol. 45, Is. 9, 2275-2280, (2012).

[4] K. Chah, C. Caucheteur, P. Mégret, S. Sulejmani, T. Geernaert, H. Thienpont, F. Berghmans, M. Wuilpart, “ Reflective polarimetric vibration sensor based on temperature-independent FBG in HiBi microstructured optical fiber,” Proceedings of SPIE, Vol. 9141, (2014).

9506-16, Session 3

Reflection-type compact photonic displacement sensor tapping into a projected beam

Yong-Geon Lee, Hak-Soon Lee, Sang-Shin Lee, Kwangwoon Univ. (Korea, Republic of)

A photonic displacement sensor is perceived to be of tremendous importance for various applications, including robotic manipulators for automatic systems, medical equipment, printers, motion sensing systems. A photonic sensor is usually comprised of a code scale, a light source, a receiver such as a photodetectors (PDs) and a signal processing circuit. Depending on the arrangement of the constituent components, the sensor is classified into reflection and transmission types. As opposed to the transmission type sensor where the light source and PDs are disposed on the opposite sides of the codescale thereby giving rise to bulky size and difficulty in poor integration, a reflection type sensor is advantagoeous in terms of miniaturization as it facilitates the integration of light source and the PDs on the same side of the codescale. The resolution of the reflection type sensors based on a collimated beam may be enhanced via the reduction of the codescale pitch, but this would require the simulataneous reduction of the PD cells accordingly, which would be challenging from the perspective of manufacturing. In this aspect, the utilization of a projected beam instead of a collimated beam serves as a promising scheme, so as to substantially alleviate unavoidable stringent restrictions, including the sophisticated tailoring of the receiver grating originating from a reduction in the codescale pitch.

In this work, A reflection-type compact photonic displacement sensor incorporating a projected beam was embodied featuring high structural tolerance. The projected beam, which is established by imaging a collimated beam from a VCSEL via an aspheric lens, is selectively reflected by a code scale grating, to propagate in the form of a spatially modulated pattern, which is progressively increasing. The encoded beam is ultimately accepted and analyzed by a receiver empolying four of serially concatenated identical PD cells. The original signals from the PD cells undergo a signal processing to produce two quadrature sensor signals Sig-A and Sig-B which may be effectively utilized to acquire a resolution equivalent to one quater of the pitch of the code scale, while the direction of displacement is discerned. The proposed sensor has been thoroughly designed by virtue of ray-optic based simulations and passively constructed by plastic injection molding technique. The fabricated displacement sensor was evaluated by observing output signals, when the code scale was motor-driven in either the clockwise or counter-clockwise direction. Then, the quadrature output signals, Sig-A and B, exhibit a phase difference of 90°, where Sig-A lags behind Sig-B in case of the clockwise displacement. Based on either Sig-A or Sig-B, we could realize a positional resolution of ~10 ?m and an angular resolution ~0.04°. Finally, the dependence of the sensor performance on the positional tolerance of the constituent components has been confirmed to be of ±100 ?m.

9506-17, Session 4

Compact optical displacement sensing by detection of microwave signals generated from a monolithic passively mode-locked laser under feedback

Christos Simos, Technological Educational Institute of Lamia (Sterea Ellada) (Greece) and National and Kapodistrian Univ. of Athens (Greece); Hercules A. Simos, Technological Educational Institute of Piraeus (Greece) and National and Kapodistrian Univ. of Athens (Greece); Thomas Nikas, Dimitris Syvridis, National and Kapodistrian Univ. of Athens (Greece)

A monolithic passively mode-locked laser is proposed as a compact optical sensor for displacements and vibrations of a reflecting object. The sensing principle relies on the pulling of the laser repetition frequency that is induced by optical feedback from the object under measurement. It has been previously observed that, when a semiconductor passively mode locked laser receives a sufficient level of optical feedback from an external reflecting surface exhibits a repetition frequency that is no more determined by the mode-locking rule of the free-running operation but is imposed by the length of the external cavity. Therefore measurement of the resulting laser repetition frequency under self-injection permits the accurate determination of the relative position of the reflecting object. In a first step, the sensing principle has been numerically investigated in order to identify the feedback levels that were necessary to stimulate the pulling phenomenon and evaluate the resulting dynamic range of operation. Next, the technique was experimentally validated using a pigtailed mode-locked laser and a fiber based feedback-cavity. Finally an alternative implementation based on a very simple free-space setup was also investigated. In all cases the repetition rate of the laser was wirelessly detected by means of a simple dipole antenna which captures the microwave signal generated by the saturable absorber and the wiring of the laser. . The required setup is very simple requiring few optical component besides the laser itself. Furthermore, the deduction of the relative position of the reflecting object is straightforward and does not require any processing of the detected signal. The proposed sensor has sub-wavelength resolution and its performance depends on the RF linewidth of the laser and the resolution of the repetition frequency measurement.

9506-18, Session 4

A compact semiconductor digital interferometer and its applications

Ivan V. Gorbov, Oleksander I. Britsky, Viacheslav V. Petrov, Institute for Information Recording (Ukraine); Iryna V. Balagura, Institute for Information Recording of NAS of Ukraine (Ukraine)

Laser interferometers are widespread at nano-measurements in various fields of science and technology. It should be noted that there is a significant number of applications where movement is measured with high accuracy but in the range of 500 mm. This touches upon microscopy, ultra-dense optical recording and the research of nano-processes in materials. Thus, for such applications we developed a miniature semiconductor digital Michelson interferometer. Designing of the precision temperature stability system for miniature low-cost semiconductor laser with 0.01 º? accuracy enabled to use it for creation of compact interferometer rather than a helium-neon one. It allowed a using of a single 5 V power supply unit and possibility to make the interferometer in volume less than 1 dm^3 too. Proper firmware and software was designed for the interferometer signals real-time processing and conversion in to respective shifts. In the result the relative displacement between 0-500 mm was measured with a resolution of better than 1 nm.

Practical use of the compact semiconductor digital interferometer in seismometers showed its advantages in the measurement of displacement, rather than its speed. For example, it enabled to expand a frequency range diapason down to near zero frequencies restricting only by seismometer mechanical system. In the infralow frequencies outside the frequency characteristic of seismometer, it can be used as delta gravimeter. In this frequency diapason mechanical seismometer functions as a spring balance. Based on the seismometer SL-210 was experimentally confirmed the possibility of measuring the effect of the Moon, the Sun and its planets to Earth's gravity.

At the same time practical use of the interferometer showed its shortcomings, which didn't appear in the theoretical descriptions. This refers to the parasitic effects of electrical noises on the quadrature signals of the interferometer. This interferences lead to distortion of the uniqueness of reference for the relative shift transition through the value of ? / 2, where ? - wavelength of the laser. The algorithmic solution of this problem was proposed and experimentally confirmed.

It should be noted that with the help of the interferometer can be studied both a slowly changing and relatively high-frequency processes. The first includes, for example, the processes of thermal expansions of the materials and gravitation changing. Studies of the Earth's surface vibrations can be referred to the second. The maximum speed of the

measured movement is determined by the laser wavelength and the frequency of ADC conversion. The advanced processing algorithm for the interferometer quadrature signals was designed. It enabled to reduce restrictions on speed of measured movements.

9506-20, Session 4

Effective application of optical sensing technology for sustainable liquid level sensing and rainfall measurement

Muhammad Hassan Bin Afzal, Univ. of Dhaka (Bangladesh)

Rainfall measurement is performed on regular basis to facilitate effectively the weather stations and local inhabitants. Different types of rain gauges are available with different measuring principle for rainfall measurement. In this research work, a novel optical rain sensor is designed, which precisely calculate the rainfall level according to rainfall intensity. This proposed optical rain sensor model introduced in this paper, which is basically designed for remote sensing of rainfall and it designated as R-ORMS (Remote Optical Rainfall Measurement sensor). This sensor is combination of some improved method of tipping bucket rain gauge and most of the optical hydreon rain sensor's principle. This optical sensor can detect the starting time and ending time of rain, rain intensity and rainfall level. An infrared beam from Light Emitting Diode (LED) through powerful convex lens can accurately determines the diameter of each rain drops by total internal reflection principle. Calculations of these accumulative results determine the rain intensity and rainfall level. Accurate rainfall level is determined by internal optical LED based sensor which is embedded in bucket wall. This internal sensor is also following the total internal reflection (TIR) principle and the Fresnel's law. This specific optical rain gauge is designed based on combined principle of RG-11 and tipping bucket. But most of the drawbacks of tipping bucket some of RG-11 can be avoided by this proposed new design. It has same outlook as optical tipping bucket but this one is much smaller in size and light-weight and easier to move around. Upper portion of this rain gauge has a rain water collector funnel with a filter. The Hydreon or RG-11 placed above the filter at one side on a small stand. A washer is set below the filter holder to wash the filter with high speed water flow. The water collected from drain tube rain water through a narrow pipe to a collector for washing the filter. Two buckets are attached with each other and placed below the funnel and on a rotator. The funnel's end or narrow cylindrical portion is place in one of two buckets. This is an entirely novel design of optical sensing principle based rain sensor and also suitable for remote sensing rainfall level. The performance of this proposed sensor has been comprehensively compared with other sensors with similar attributes and it showed better and sustainable result. Future related works have been proposed at the end of this paper, to provide improved and enhanced performance of proposed novel rain sensor.

9506-21, Session 4

Microstructure encryption and decryption techniques in optical variable and invariable devices in printed documents for security and forensic applications

Radhakrishna Prabhu, The Robert Gordon Univ. (United Kingdom); Sajan Ambadiyil, Jayan K. G., Ctr. For Development of Imaging Technology (India); Vellara Pappukutty Mahadevan Pillai, Univ. of Kerala (India)

Today, document counterfeiting is a global menace because of the advanced technologies available at ever decreasing prices. Instead of eschew the paper documents; applying efficient cost effective security methodologies are the feasible solutions. This paper reports a novel cost effective and simple optical technique using micro text encrypted optical variable devices (OVD) threads, Ultra violet based optical invariable devices (UV-OID) patterns and Artistic fonts for secure preparation of the documents and its forensic application. Applying any one of the technique or together can effectively enhance the level of security of the most valuable document. The genuineness of the documents can be verified using simple decryption techniques.

This paper will discuss the design, development and implementation of a simple cost effective secure methodology. This will involve the features like (i) the development of micro text encrypted OVD threads instead of security window thread (ii) the development of microstructure embedded UV based OID patterns as an alternative to the security fibres (iii) encryption of micro letters in the core heading made up of artistic fonts. Further, this paper reports the microstructure encryption and decryption techniques in optical variable and invariable devices in printed documents for security and forensic applications.

The OVD has been demonstrated by encrypting the micro texts 'CDIT' and 'GOK' in Arial type font (height <100 μ), in consecutive layers using Kinemax dot matrix OVD origination machine having 6000dpi resolution. In order to verify the security features, the image of decrypted information encrypted in the OVD pattern was first captured microscopically and then digitally zoomed. The final decrypted image was obtained after image processing using MATLAB software.

In the case of UV-OID, embedding an authenticating fluorescent pattern on document security has been demonstrated in a novel way. This has been achieved by incorporating microstructure/text to the authenticated fluorescent pattern in a specific manner in the whole area. The detail of the encryption will be visible to the naked eye only if it is exposed to UV light along with a microscope and the processing software. In this method it is possible to embed any text in any shape and dimension and in any orientation along with any available colours to the paper documents.

Embedding micro letter into the core heading font of the documents is another method for enhancing the security of the document in a cost effective manner. Legible artistic font is the best option for the encryption of the micro letters in the same. Stylistic effect of the artistic font makes the encryption unnoticed and the legible nature makes quick reading of the core heading. The balance between legibility and style is one of the important factors to be considered when choosing a font for the micro letter encryption.

9506-22, Session 5

Advanced materials for optical gas and biosensing application by using propagating and localized plasmonic and magneto-plasmonic transduction *(Invited Paper)*

Roberto Rella, Istituto per la Microelettronica e Microsistemi (Italy)

Among all transduction methodologies reported in the field of solid state optical chemical sensors, the attention has been focused onto the optical sensing and biosensing characterization by using propagating and localized surface plasmon resonance (SPR) technique and its evolution towards active plasmonics. The research in this field is always oriented in the improvement of the sensing features in terms of sensitivity and limits of detection although quite smart results have been reached. To this purpose different strategies have been proposed to realize advanced materials for high sensitive plasmonic devices, as an example:

- Highly disordered system of silica nanowires (NWs) decorated with Au NPs present unique light trapping properties due to the combination of the highly diffusivity of transparent silica NWs, with the selective absorption resonances given by Au NPs.

- Activation of the transducer by the application of an oscillating magnetic field in a transversal configuration to improve the gas sensing performance of classical SPR sensors. In this case magneto-plasmonic nanostructures are used as transductors in which the combination of the magneto-optic (MO) effects of a magnetic material and the surface plasmon resonance (SPR) of metallic give rise to a new sensing probe. Since the MO effects are much localized, a very sharp curve can be obtained; as a consequence, small variations of the refractive index will induce large changes in the MO response, allowing to greatly improving the sensitivity of the MOSPR sensor.

[1]Convertino, A ; Cuscuna, M ; Martelli, F.; Manera, MG; Rella, R., Journal

of Physical chemistry C, 118 (2014) 685-690

[2] Schuck, P.,1997, Annu. Rev. Biophys. Biomol. Struct. 26, 541-566.

[3] González-Díaz, J. B., García-Martín, A., Armelles, G., García-Martín, J. M., Clavero, C., Cebollada, A., Lukaszew, R. A., Skuza, J. R., Kumah, D. P., Clarke, R., 2007, Phys. Rev. B 76, 153402.

[4] Manera, M. G., Montagna, G., Ferreiro-Vila, E., Gonza?lez-García, L., Sa?nchez-Valencia, J. R., Gonza?lez-Elipe, A. R., Cebollada, A., Garcia-Martin, J. M., Garcia-Martin, A., Armelles, G., Rella R., 2011, J. Mater. Chem., 21, 16049?16056

9506-23, Session 5

Label-free optical affinity biosensors for medical applications: fouling problems

Eduard Brynda, Cesar Rodriguez-Emmenegger, Andrés de los Santos Pereira, Tomas Riedel, Institute of Macromolecular Chemistry of the ASCR, v.v.i. (Czech Republic)

The fouling from body fluids, particularly, from blood plasma or serum, is still an essential barrier to applications of label-free optical biosensors in medical diagnostics. A potential construction of the biosensors consists in coating the optical transducer with an antifouling polymer brush on which bioreceptors are immobilized.

Polymer brushes, which provide the best currently available antifouling surfaces, were characterized by the fouling of undiluted human blood plasma. Mean values [ng/cm2] of pooled plasma fouling were 35 on poly(oligo (ethylene glycol) methacrylate)) (pHOEGMA), 27 on poly(oligo(ethylene glycol) methyl ether methacrylate) (pMeOEGMA), 20 on poly(2-hydroxyethyl methacrylate) (pHEMA), 1.8 on poly(carboxybetaine acrylamide) (pCBAA), and below the detection limit of our surface plasmon resonance SPR measurement ,0.03, on poly(N-(2-hydroxypropyl) methacrylamide)) (pHPMA), Except for pHPMA, differences were observed in pooled plasma fouling purchased from different companies The fouling of plasma samples collected from different individual donors was between 0-11 ng/cm2 on pCBAA, 13-28 on pMeOEGMA, 5-63 on pHOEGMA, and 7-193 on pHPMA. Evidently the diagnostics of a plasma sample from an individual cannot be referenced to measurements in plasma from another source.

Chemical activation of –COOH groups present in zwitterionic side chains of pCBAA or –OH groups terminating side chains of pHOEGMA, pHEMA, and pHPMA brushes is required for subsequent procedures leading to bioreceptor immobilization. The activation usually impairs antifouling properties of the brushes. Owing to a spontaneous hydrolysis of reactive intermediates, which remain on pCBAA after the bioreceptor attachment, back to –COOH, the fouling increases only to 13 ng/cm2.The fouling increases much more on the other polymer brushes due to changes in their structure associated with the transformation of activated –OH to some non reactive carbamates.

The big differences in the fouling of plasma from different sources and a high increase in fouling after bioreceptor attachment disqualify pHEMA brush from application in medical diagnostics. A lower increase in fouling after the functionalization with bioreceptor places pCBAA before pHOEGMA, pHEMA, and pHPMA. On the other hand, well controlled and living character of pHOEGMA polymerization makes it possible to prepare easily and reproducibly brushes with precisely adjusted thickness, which places them before pHPMA and pCBAA. A recently developed functionalization of pMeOEGMA end-groups is expected to allow the bioreceptor immobilization without impairing the antifouling brush structure.

Acknowledgement: This research was supported by the Czech Science Foundation under Contract No P205/12/G118

9506-24, Session 5

Diameter control of carbon nanotubes using argon-acetylene mixture and their application as IR sensor

Rana A. Afzal, Umair Manzoor, King Saud Univ. (Saudi Arabia); Arshad S. Bhatti, COMSATS Institute of Information Technology (Pakistan); Abdulrahman A. Alazba, Muhammad T. Amin, King Saud Univ. (Saudi Arabia)

Multi-walled carbon nanotubes (CNTs) were grown via pyrolytic chemical vapor deposition technique and explored for their infrared sensing behavior. CNT synthesis was carried out over cobalt zinc ferrite ($Co_{0.5}Zn_{0.5}Fe_2O_4$) catalyst nanoparticles under different gas flow conditions to control outside diameter of the nanotubes. It was found that a progressive decrease in the carbon precursor gas (acetylene in this case) from 5:1 to 9:1 (v/v) causes reduction of average CNT diameter from 85 to 635 nm. Growth conditions involving higher temperatures yield nanotubes/nanofibers with outer diameter of >500 nm, presumably due to surface aggregation of nanoparticles or increased flux of carbonaceous species at the catalyst surface or both. Current-voltage characteristics of the nanotubes depending on the CNT diameter, revealed linear or non-linear behavior. When incorporated as sensing layer, the sensitivity of ~5.3 was noticed with response time of ~4.1 s. It is believed that IR sensing characteristics of such CNT based detectors can be further enhanced through post-synthesis purification and chemical functionalization treatments.

9506-25, Session 5

UV sensors based on Mg doped ZnO nanoparticles synthesized by water-based chemical method

Mirza S. Alam, COMSATS Institute of Information Technology (Pakistan); Umair Manzoor, Abdulrahman A. Alazba, King Saud Univ. (Saudi Arabia)

ZnO (II-VI) compound semiconductor, a direct band gap material of band gap 3.4eV proves to be an interesting material for UV devices. Doped samples are synthesized by using additional Mg ions, which are then embedded in ZnO during particle formation in water based co-precipitation. XRD analysis is used to study phase purity and crystal structure in different doping concentrations. Particle size and decease in lattice constants is observed. The identification of ZnO and doping concentration of Mg is determined by FTIR spectroscopy. Increase in band gap of doped nanoparticles is calculated by UV-vis spectroscopy. Finally the sensing of UV is tested by observing the response of nanoparticles by giving them exposure to UV light and measures the resistance in presence and absence of UV light.

9506-26, Session 6

Plasmonically Amplified Fluorescence Bioassay with Microarray Format *(Invited Paper)*

Jakub Dostalek, Selma Gogalic, Simone Hageneder, Claudia Ctortecka, Martin Bauch, Imran Khan, Claudia Preininger, Ursula Sauer, AIT Austrian Institute of Technology GmbH (Austria)

Recent rapid advancements in plasmonics – a branch of nanophotonics that investigates tightly confined electromagnetic fields in vicinity to metallic films and metallic nanostructures – offer efficient means for advancing performance characteristics of various fluorescence–based analytical technologies [1]. This paper will discuss implementations of surface plasmon-enhanced fluorescence for detection of biomolecular

analytes by using fluorescence immunoassays. These assays utilize fluorophore labels and their near-field coupling with surface plasmons allows for increasing the signal-to-noise ratio of detected fluorescence signal by the combination of increased excitation rate, improved quantum yield of emitter, and directional fluorescence emission. Strategies on tuning the depth probed by surface plasmon field in order to maximize sensitivity of biosensors for the analysis of species that vary in size from several nanometers (e.g. biomolecules) to around hundred nanometers (exosome vesicles) and even several micrometers (bacterial pathogens) will be presented. In particular, design of plasmonic structures for the fluorescence amplification of assays with epi-fluorescence readout geometry will be discussed as these can be exploited in regularly used microarray scanners and fluorescence microscopes. Structures providing the enhancement factor of around 100 [2] and possible routes for even stronger enhancement >1000 [3] will be shown. New applications of surface plasmon-enhanced fluorescence biosensor detection schemes for the analysis of trace amounts of biomarkers will be presented: the analysis of auto-antibodies in saliva matrix and detection of exosomes in the context of cancer diagnostics will be discussed. Approaches relying on plasmonic nanostructures that can be prepared by mass production-compatible methods such as nanoimprint lithography will be addressed.

Acknowledgments: This work was partially supported by the Austrian Science Fund (FWF), project ACTIPLAS (P 244920-N20).

References:

[1] M. Bauch, et al., Plasmonics (2014), 9 (4), 781-799.

[2] M. Bauch, et al., Optics Express (2014), submitted.

[3] M. Bauch, et al., Optics Express (2013) 21(17) pp 20470-20483.

9506-27, Session 6

Morphological studies of resonances in plasmonic metasurfaces for SPR sensing

Jakub Lelek, Pavel Kwiecien, Ivan Richter, Czech Technical Univ. in Prague (Czech Republic); Jiri Homola, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

We investigate selected periodic arrays of nanostructures inspired by metasurfaces originally used in metamaterial structures and evaluate their potential for surface plasmon resonance. Building blocks including rectangles, cut wires, crosses, fishnets, split ring resonators (SRR) were ordered on suitable substrates and , their reflection (R), transmission (T), and loss energy (L) spectra were calculated. The numerical studies were performed using our efficient in-house two-dimensional rigorous coupled-wave analysis (2D RCWA) technique. Our technique incorporates all the key improvements of the method available, taking into account both proper Fourier factorization rules, adaptive spatial resolution techniques, as well as structural symmetries. Using the R, T, and L spectra, we investigated spectral sensitivity of SPR and calculated the respective SPR sensor characteristics, such as figures of merit (FOM), enabling direct comparison of various structural morphologies for potential sensing applications. Also, optimization of the structures in terms of FOM has been performed to identify the most promising candidates. Various materials were evaluated as substrates for these metasurfaces, including refractive index-matching substrate (Cytop). In addition to ideal building block boundaries, more realistic shapes of surfaces have been investigated (e.g., step-wise tilted boundaries, instead of ideally vertical smooth boundaries). To allow for interpretation of spectral resonant features and the interplay of individual and surface lattice resonances, we were gradually changing the morphology of individual building blocks from one type of element to another one. We believe that this study will bring insight into plasmonic behavior of nanostructured surfaces and will benefit research into SPR biosensors.

9506-28, Session 6

Novel plasmonic sensors using particle-film interactions

Alexander W. Powell, Univ. of Oxford (United Kingdom)

The effect of a thin film environment on the plasmonic modes and scattering behaviour of silver nanoparticles is explored and exploited to create a novel sensor architecture. Finite-difference time-domain simulations, scattering spectroscopy and a dark-field Fourier microscope are used to investigate the parameter space.

The addition of a polymer film above silver nanoparticles (NP's) on a silica substrate was found to have a strong effect on the angular scattering behaviour of a particle due to an interference effect, which is highly sensitive to the parameters of the film. The plasmonic modes excited within a NP depend strongly on wavelength, particle shape and the surrounding environment. For particles with flat faces, the modes are especially sensitive to surface interactions and the addition of even a very thin (< 5 nm) spacer layer between a NP and a high-index or metallic substrate can radically alter the resonance conditions. By utilising polymer films that respond to changes in their environment, it is possible to create highly sensitive, sub-wavelength sensor components.

We are developing such a sensor using a moisture sensitive polymer film as a spacer layer between a Ag nanocube and a silver film. A change in the thickness of a spacer layer between the cube and the substrate in response to a change in humidity alters the mode excited in the gap and results in a shift in the resonance wavelength. This type of device demonstrates the exciting possibility of operation at exclusively sub-wavelength scales and the potential for integration into plasmonic circuits. Here we present some initial results, demonstrating the succesful utilisation of these nanostructures to detect a change in humidity, along with a theoretical investigation revealing routes to increased performance.

9506-29, Session 6

Optical biosensor based on a propagating mode supported by a sparse array of metal nanoparticles

Barbora Spackova, Maria Lara Ermini, Ji?í Slab?, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Pavel Kwiecien, Ivan Richter, Czech Technical Univ. in Prague (Czech Republic); Jiri Homola, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

Plasmonic biosensors present a powerful technology that allows for the direct observation of molecular interactions in real-time. Plasmonic biosensors employ either propagating surface plasmons supported by a thin metal film or localized surface plasmons excited on metal nanoparticles. Here we present an alternative approach employing a waveguide mode supported by a weakly absorbing dielectric film formed by a sparse plasmonic nanoparticle array embedded in dielectric medium. Due to the low inherent losses of the waveguide, coupling of light into a waveguide mode gives rise to sharp features in the spectrum of light. We demonstrate that this sensor can attain high surface sensitivity due to the substantial overlap between the electromagnetic field of the propagating mode and sensing area containing biorecognition elements. In order to achieve efficient coupling of light into this waveguide interfaced with aqueous sample, refractive index-matching substrate (Cytop) is used. In addition to the improved optical performance, the proposed biosensor also provides enhanced mass-transport of the analyte due to smaller footprint of the sensing area. Theoretical analysis of the waveguiding structure is carried out using the rigorous coupled-wave analysis and analytical theory based on effective medium approximation. The parameters of the structure are optimized to achieve the best sensing performance. Laboratory samples of the sensor are fabricated and evaluated in a model immunosensing experiment. Results of the experiments show that the proposed sensor provides a limit of detection better by an order of magnitude than the conventional plasmonic biosensor.

9506-30, Session 6

The development of a multi incident angles and multi points measurement phase image interrogation surface plasmon resonance system

Jyun Liao, Shu-Sheng Lee, National Taiwan Ocean Univ. (Taiwan); Shih-Yuan Lin, National Taiwan Ocean Univ (Taiwan)

The bio-medical detection technology is still in rapid progress along with the growing awareness of health of human beings. The information about the health condition is quite helpful to early treatment and disease prevention and also plays a very important role in facilitate the improvement of the medical treatment. Surface plasmon resonance (SPR) is one of the recent applied technology in bio-medical detection, and it is gradually accepted by the researchers. However, it is still not adopted widely and needs more efforts to improve. In our research work, a previous developed phase interrogation SPR detection system is modified and the concept of multi-incident angles of detecting light is used for obtaining more data. Besides, only one detecting focal point optical setup is replaced by a focusing line light to have more than one measuring areas, and this can provide a control reaction accompanied with the experimental reaction on the chip at the same time. To realize the idea, the light beam is enlarged by a beam expander and then focused by a cylindrical elliptic reflective mirror in our system. The phase variation of the sample variation with different detecting incident angle can provide more data and can reduce the errors, increase the resolution, and raise the detection ability. To acquire the inference fringes images of the phase, the time-stepped quadrature phase shifting method has been introduced. The images needed to retrieve the phase by this method is much less than the five-stepped phase shifting method. The data processing time can be reduced and this provides the opportunity to measure the reaction in real-time. Finally, sodium chloride-water solution and Ethanol-water solution in different concentration has been measured to verify our system is workable.

9506-31, Session 7

Nano slot-antenna array refractive index sensors: Approaching the conventional theoretical limit of the figure of merit

Michal Eitan-Wiener, Tel Aviv Univ. (Israel); Zeev Iluz, CST AG (Germany); Yuval Yifat, Yael Hanein, Amir Boag, Jacob Scheuer, Tel Aviv Univ. (Israel)

Surface plasmon resonance (SPR) phenomena are among the most promising approaches for the realization of label-free biosensors based on refractive index (RI) sensing, with applications ranging from medical diagnosis to environmental monitoring. Such sensors can be roughly classified as either localized or propagating SPR devices, where the latter typically exhibit substantially higher sensitivities (1-2 orders of magnitude) compared to the former ones. Nevertheless, the simplicity, low-cost, compact dimensions and suitability for integration, which render localized SPR sensors highly attractive for practical devices, triggered substantial research efforts attempting to enhance their performance. Here we demonstrate an RI sensor utilizing an array of nanometer scale slot-antennas milled in a thin gold layer using a single lithographic step. The slot-antenna RI sensor exhibits a figure of merit (FOM) of 140-210, thus exceeding the theoretically estimated bound for standard propagating SPR sensors in Kretschmann configuration (~108). The underlying mechanism enabling this high FOM is symmetry breaking which lifts the geometrical degeneracy of Wood's anomaly. The measured sensitivity (>1000 nm/RIU) and FOM render the presented device a highly attractive approach for label-free biochemical sensing.

9506-32, Session 7

Multiple beam interference lithography for preparation of periodic plasmonic arrays

Milan Vala, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

Periodic plasmonic arrays have been intensively studied and utilized in applications such as surface enhanced Raman scattering (SERS) or affinity plasmonic biosensing for more than a decade [1]. The interference lithography (IL) is a well-established method for the production of 2D periodic arrays. By proper selection of the polarization and orientation of the incident beams, various lattice symmetries and shapes of nano-features can be obtained [2, 3]. However, fabrication of sparse plasmonic arrays is still challenging. The addition of four coherent beams to original four-beam IL in order to suppress every second interference maxima of the original pattern, yielding an array with a doubled period yet having the same size of the nano-features has been reported [4]. The drawback of such approach is the extreme sensitivity to the adjustment of the mutual positions and orientation of large number of interfering beams.

In this contribution, we will present a novel approach to a multiple-beam interference lithography that enables production of macroscopic areas of perfectly periodic sparse plasmonic arrays. This method is based on the interference of a large number of coherent beams originating from diffraction of large-diameter collimated beam on a single transmission phase mask. The geometry (periods and profile depth) of the phase mask is designed to provide optimum diffraction efficiencies to all (up to 21) diffracted orders to yield an interference pattern with high contrast. This approach enables multiple-beam interference lithography without the need of laborious adjustment of individual interfering beams, as their mutual positions and directions are given only by the properties of the phase mask. Moreover, the small ratio of feature size to the period of the interference pattern enables production of nano-features of complex shapes (e.g. rods, dimers) by performing several consecutive exposures with slightly shifted interference pattern.

The design and optimization of the transmission diffractive mask will be discussed and verified by the preparation of the sparse periodic plasmonic arrays. Prepared plasmonic arrays will be characterized both morphologically and optically.

REFERENCES:

1. Valsecchi, C. and A.G. Brolo, Periodic Metallic Nanostructures as Plasmonic Chemical Sensors. Langmuir, 2013. 29(19): p. 5638-5649.

2. Vala, M. and J. Homola, Flexible method based on four-beam interference lithography for fabrication of large areas of perfectly periodic plasmonic arrays. Optics Express, 2014. 22(15): p. 18778-18789.

3. Rodriguez, A., et al., Laser interference lithography for nanoscale structuring of materials: From laboratory to industry. Microelectronic Engineering, 2009. 86(4-6): p. 937-940.

4. Solak, H.H., et al., Multiple-beam interference lithography with electron beam written gratings. Journal of Vacuum Science & Technology B, 2002. 20(6): p. 2844-2848.

9506-33, Session 7

Ultrasensitive graphene coated SPR sensor for biosensing applications

Radhakrishna Prabhu, Kaushalkumar Bhavsar, Patricia M. Pollard, The Robert Gordon Univ. (United Kingdom)

Surface plasmon resonance (SPR) is a well-known, rapid and sensitive technique used for probing the biomolecular interactions in real time. Several new approaches have been suggested to improve the sensitivity of SPR sensors over the last two decades. Most of them are based on creating nanoparticles and nanoholes on the metal surface to enhance the localized E-field and therefore, quite challenging to have control over their optical properties.

Graphene, a single layer of carbon atoms arranged in honeycomb structure, is emerging as the most popular material of the decade which

is under intense research. Graphene has very high surface to volume ratio and strong binding/adsorption affinity towards biomolecules due to its carbon ring structure from ϖ-ϖ stacking interactions. Recently, there have been few reports on using the graphene on thin metal film based SPR sensor in order to improve the sensitivity. Herein, we propose a new dual wavelength based approach for graphene based SPR sensing to further enhance the sensitivity. Reflectivity of the p-polarized incident light has been calculated using the N-layer model for the most common Kretschmann configuration. Sensitivity of the SPR with and without graphene layer has been calculated for a single and dual wavelength based approaches. Also, the effect of graphene layers on the sensitivity of single and dual wavelength based approaches have been calculated. Computational results show that the proposed graphene SPR sensor using dual wavelength approach has $(1 + 0.1 L)\ \eta$ times higher sensitivity than the conventional gold thin film based SPR sensors. Further, increase in the number of graphene layers, L, improves the sensitivity. Where, η represents the enhanced sensitivity due to increased binding/adsorption of biomolecules on graphene over a gold thin film. Also, the dual wavelength based approach is almost four times more sensitive than the results reported earlier for a single wavelength based graphene SPR. The improved sensitivity is due to the new approach of using differential signals with different wavelengths. Sensitivity analysis has been carried out for a refractive index (Δn) = 0.005 with L = 1 to 10.

9506-34, Session 7

New biosensing platform combining label-free and labelled analysis using Bloch surface-waves

Norbert Danz, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Riccardo Rizzo, Univ. degli Studi di Roma La Sapienza (Italy); Peter Munzert, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Frank Sonntag, Stefan Schmieder, Fraunhofer IWS Dresden (Germany); Alberto Sinibaldi, Oleksiy Anopchenko, Francesco Michelotti, Univ. degli Studi di Roma La Sapienza (Italy)

Sensors utilizing surface plasmon resonance (SPR) are established as the method of choice in label-free optical biosensing [1] and a variety of optical approaches including imaging, angularly and spectrally resolved resonance tracking are applied to read the transducers information. Previously, surface waves propagating at the boundary of truncated one dimensional photonic crystals (1D-PC) have been suggested [2] to be applied in SPR configurations. Due to the decreased losses in state-of-the-art dielectric thin film stacks, BSW feature very low resonance widths compared to the SPR case.

Bloch surface wave (BSW) sensors feature the possibility to optimize the resonance, i.e., to tune its position and width as the most important parameters. We performed such optimization [3] for the case of angularly resolved resonance analysis based upon previously derived merit functions [4]. Besides label-free operation, the large field enhancement and the absence of quenching allow utilizing BSW coupled fluorescence excitation and emission to additionally detect the presence of fluorescent labels [5]. This approach can be adapted to the case of angularly resolved resonance detection, thus giving rise to a combined labelled / label-free biosensor platform.

We report on the development and initial results of such combined biosensing platform and disposable chips. Based upon previous work on angularly resolved SPR analysis [6, 7] a new optical system has been designed and set-up. It features the combination of SPR-like angularly resolved resonance tracking with the detection of fluorescent labels. All analysis can be performed in a parallel manner for multiple spots that are arranged as a one-dimensional array inside a microfluidic channel. In order to enable for later on disposable use, both injection molded polymer and glass substrates have been prepared and coated with 1D-PC.

The authors acknowledge funding by the European Commission through the project BILOBA (Grant agreement 318035).

[1] J. Homola, Chem. Rev. 108 (2008) 462

[2] M. Shinn, W.M. Robertson, Sens. Act.B 105 (2005) 360

[3] R. Rizzo, N. Danz, F. Michelottiet al., Optics Express 22 (2014) 23202

[4] A. Sinibaldi, R. Rizzo, G. Figliozzi, et al., Optics Express, 21, 23331 (2013)

[5] A. Sinibaldi, A. Fieramosca, R. Rizzo et al., Optics Letters 15 (2014) 2947

[6] N. Danz, A. Kick, F. Sonntag et al., Eng. Life Sci. 11 (2011) 566

[7] A. Sinibaldi, N. Danz, E Descrovi et al., Sens. Act. B 174 (2012) 292

9506-35, Session 7

Quantitative detection of bovine and porcine gelatin difference using surface plasmon resonance based biosensor

Devy P. Wardani, Kamsul Abraha, Univ. Gadjah Mada (Indonesia)

Gelatin is a biopolymer derived from collagen that is widely used in food and pharmaceutical products. Due to some religion restrictions and health issues regarding the gelatin consumption which is extracted from certain species, it is necessary to establish a robust, reliable, sensitive and simple quantitative method to detect gelatin from different parent collagen species. To the best of our knowledge, there has not been a gelatin differentiation method based on optical sensor that could detect gelatin from different species quantitatively.

Surface plasmon resonance (SPR) based biosensor is known to be a sensitive, simple and label free optical method for detecting biomaterials that is able to do quantitative detection. Therefore, we have utilized SPR-based biosensor to detect the differentiation between bovine and porcine gelatin in various concentration, from 0% to 10% (w/w). The gelatin solutions were deposited onto a thin (0.15 mm) glass substrates and then attached to the sensor chip (gold coated BK7 prism) for the detection. The reflected intensity of p-polarized He-Ne laser was measured to find the SPR angle at where the maximum absorbance occured. We plotted the SPR-angle data from each gelatin against its concentration to find the sensitivity and the limit of detection. All measurements were done in triplicate to ensure the sensor's reliability. Further observation was to relate the gelatin concentrations with refractive indices and SPR angles of each gelatin. By using the least square curve fitting, we built a model of SPR sensor response in gelatin measurement to develop the quantitative detection of both gelatins.

Here, we report the ability of SPR-based biosensor to detect difference between both gelatins, its sensitivity toward the gelatin concentration change, its reliability and limit of detection of the sensor. The results show that SPR-based biosensor is a promising tool for detecting gelatin from different raw materials quantitatively.

9506-19, Session PS

Monitoring of high refractive index edible oils using coated long period fiber grating sensors

Luis Coelho, Diana Viegas, INESC Porto (Portugal); José Luís Campos Oliveira Santos, Univ. do Porto (Portugal); Jose Manuel M. M. de Almeida, Univ. de Trás-os-Montes e Alto Douro (Portugal) and Univ. do Porto (Portugal)

Edible oils in general, and olive oil in particular, are recognised as healthy foodstuff due to its capacity to prevent pathologies, such as cancer and cardiovascular diseases. In Mediterranean countries olive oil is a significant source of mono- and polyunsaturated fatty acids, tocopherols and phytosterols.

Uncooked olive oil keeps all its nutritional components, such as vitamins, essential fatty acids and antioxidants. However, olive oil is frequently used for baking and cooking in Mediterranean countries where deep frying is a popular method for food preparation.

Olive oil is an edible oil made from fruits of the olive tree (Olea europaea L.) by mechanical processes (crushing, malaxation and centrifugation)

and can be consumed by humans without additional treatments. However, once the mechanical extraction of olive oil is complete, up to 10% of the oil remains in the olive pulp and in the mill wastewater, which can be extracted using organic solvents, often hexane.

Optical fibre sensors based on long period fibre gratings have been extensively studied and applied as strain, bending and temperature sensors, in the detection of organic and inorganic compounds and as an immobilized antibody biosensor. It has been demonstrated that the highest wavelength and transmission sensitivity of the long period fibre gratings occurs for surround refractive index values slightly lower than the cladding refractive index. However, for surround refractive index higher than the cladding refractive index, which is the case of the most edible oils, there is very low wavelength sensitivity to surround refractive index variations and a considerable reduction in transmission sensitivity is observed. This drawback can be overlapped by coating the bare long period fibre grating with a thin film of a material that has a refractive index higher than the cladding, such as titanium dioxide. The response of the long period fibre grating is modified according to the thickness of the film and could lead to the realization of a chemical sensor for the food industry with high sensitivity.

In this work long period fibre gratings coated with a titanium dioxide thin film were successfully used for real time monitoring the thermal deterioration of olive oil and to detect the small levels of hexane diluted in olive oil. For a titanium dioxide coating of 30 nm a detection limit in deterioration of about 5 minutes at 180 ºC and of about 2 minutes at 225 ºC was observed for the sensing system. And using the same long period fibre grating a wavelength sensitivity of 1.28 nm / % (V/V) was achieved in the range 0 to 10% of hexane in olive oil.

9506-50, Session PS

A new method to measure low-order aberrations based on wavefront slope

Qiong Zhou, Wenguang Liu, Zongfu Jiang, National Univ. of Defense Technology (China)

With the increase of laser power, thermally induced wavefront distortions have reduced the beam quality, which is one of the main technical challenges in the development of high power laser. Generally, thermally induced wavefront distortions include a large proportion of low-order aberrations with large PV value, mainly constituted by defocus and astigmatism. Shack–Hartmann Wavefront Sensor(SHWS) is widely used to measure wavefront distortions, but it is very expensive and complex (maybe need a 64?64 microlens array), and usually designed to detect the higher-order aberrations with small PV value. In this paper we discuss a new method to detect low-order aberration with large PV value.
This method also depends on wavefront slope measurements but only need measurements of 6 spots, which means that only 6 lens are used in detective process, and the mathematical algorithm involved in the calculation process is different from zonal or modal estimation used in SHWS. To evaluate the accuracy of this method we simulate this optical measurement process by using the Zemax simulation software and Matlab calculation software. Simulation results show that the calculation error of aberration can be keep lower than 1% for aberrations with different combinations of defocus, 0 degree astigmatism, 45 degree astigmatism and some high-order terms. Based on simulation results two possible configurations for low-order aberration measuring instruments are described and are studied respectively. Compared with classic SHWS the new measurement instruments can be used to direct measure low-order aberrations for laser beam with large transverse area and do not need beam contracting system.

9506-52, Session PS

Plasmonic nanostructures for affinity biosensing and SERS

Jirí Slaby, Jiri Homola, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

Surface plasmons (SPs) on gold nanostructures present a promising approach to the development of new biosensors [1]. Due to subwavelength localization of light, SPs are sensitive to the refractive index changes in the close vicinity of the nanostructured surface, where the electromagnetic field is highly enhanced. Nanostructures supporting localized SPs thus can be used for affinity biosensing as well as for surface-enhanced spectroscopies such as SERS (Surface-Enhanced Raman Scattering), offering both high sensitivity and the ability to identify molecules [2].

In the presented work, plasmonic resonances on selected nanostructures (e.g. arranged nanoparticle clusters) are studied both theoretically and experimentally. Extinction spectra of selected nanostructures are simulated using Boundary Element Method and sharp plasmonic resonances are identified. The simulations provide distribution of electric field in the vicinity of the nanostructure, refractive-index sensitivities and figures of merit of the resonances. Arrays of selected nanostructures are fabricated by electron-beam lithography and characterized using the scanning electron microscopy, atomic force microscopy and optical spectroscopy. The potential of the fabricated plasmonic nanostructures for refractive index sensing and surface-enhanced Raman scattering is validate in model experiments.

References:

[1] A. Dmitriev, Nanoplasmonic Sensors, 1st ed. New York: Springer, 2012.

[2] C. Cao, J. Zhang, X. Wen, S. L. Dodson, N. T. Dao, L. M. Wong, S. Wang, S. Li, A. T. Phan, and Q. Xiong, "Metamaterials-Based Label-Free Nanosensor for Conformation and Affinity Biosensing," ACS Nano, vol. 7, no. 9, pp. 7583–7591, Sep. 2013.

9506-53, Session PS

Flexible SPR system able to switch between Kretschmann and SPRi

Alain J. Corso, Univ. degli Studi di Padova (Italy); Sara Zuccon, Paola Zuppella, Maria G. Pelizzo, IFN-CNR LUXOR Lab. (Italy)

Tunable surface-plasmon resonance system able to switch between imaging and Kretschmann angular resolved systems by exploiting an tunable optical module is presented. This set up allows to perform complementary measurements (SPR angular resolve and SPR imaging) on the same setup with no moving parts. Furthermore, this switching capability can be used to calibrate the imaging with the angular resolved measurements, to enhance the quality of the image and SPR curve and to change/optimize the penetration depth of the evanescent wave probe at the interface metal/target.

9506-54, Session PS

High efficiency SERS test strips

Ran Zhang, Yan He, Hong-Bo Sun, Jilin Univ. (China)

As a convenient analysis and detection medium, test strips such as pH test strips, glucose test strips, urine test strips and lipolysis test strips are widely used in both research fields and daily life because of their distinct convenience and high efficiency. Especially in various biological and chemical detections, test strips also demonstrate many unique advantages including low-cost, easy handling, portability, high sensitivity and less analyte consumption. However, for SERS spectroscopy, there is still a lack of generally available and highly efficient substrates, just like test strips, which significantly limits its wide applications and makes SERS analysis an 'in-lab-only' technique. At present, to prepare and use a high-performance SERS substrate in a similar manner to test strips, is still not only a dream but also a scientific challenge.

Paper, which is widely used in our daily life, is considered to be a cheap and flexible substrate. In this talk we propose convenient and e?cient SERS test strips by simple physical vapor deposition (PVD) coating of a silver layer on paper. With the help of our SERS test strips, sensitive and reproducible SERS tests are realized in a low cost and facile fashion. Taking advantage of the connatural hierarchical micro/nanostructures of paper constructed from irregular stacking of cellulose microfibers which have abundant nanofibrils and wrinkles on the surface, a deposited silver nanolayer could be arranged into a flexible and wrinkled plasmonic

nanostructure, which therefore, forms a large-area SERS ‘hot spot’. As a representative illustration, Rhodamine 6G is used as a probing molecule and the limit of detection (LOD) of our SERS test strip is at the level of 10-10 M.

9506-55, Session PS

PDMS based micro-optics and microchannels for lab-on-a-chip application

Mária Pardelová, Dusan Pudic, Daniel Jandura, Peter Gaso, Univ. of Zilina (Slovakia)

Polydimethylsiloxane (PDMS) is a silicone elastomer with properties which make it attractive for different optical applications. PDMS is a highly light-transparent material in the wide wavelength range, chemically inert, thermally stable, permeable to gases, isotropic and homogeneous, simple to handle and manipulate, and with interesting rheological properties. In waveguide optics, PDMS is widely used in soft lithography as a mold and also as a appropriate material for creating of optofluidic channels because of its favorable chemical and optical properties, and its simple manufacture by rapid prototyping. PDMS waveguides have recently received considerable attention because of their potential for interfacing with other photonic or electronic devices, such as monolithic integration of waveguides and fluidic channels in PDMS.

We describe a new technology for the fabrication of PDMS optical waveguides with implemented photonic crystal (PhC) structure in the surface. PhC structure in the PDMS waveguides leads to modification of their transmission properties. Different one and two-dimensional PhC structures in the PDMS surface were prepared. In the fabrication process, we use combination of few lithographic techniques. PhC structure is firstly patterned in thin photoresist layer by interference lithography and after that, the photoresist pattern is transferred to the PDMS surface by imprinting process. Waveguide channels in thin photoresist layer are prepared by direct laser writing lithography. This technology allows the fabrication of PDMS waveguides in a wide range of parameters and variable periods of photonic crystals. Final structures are investigated by confocal microscope and atomic force microscope. We demonstrate wide potential of the prepared PDMS optical waveguides with surface PhC structure for different applications and sensing devices.

9506-56, Session PS

Development of fast FBG interrogator with wavelength-swept laser

Tatsuya Yamaguchi, Yukitaka Shinoda, Nihon Univ. (Japan)

The objective of this research is the construction of a structural health monitoring system that uses fiber Bragg grating (FBG) to determine the health of structures such as bridges and buildings and mobile structures such as aircraft. An FBG is a diffraction grating that is formed in the core of an optical fiber and has the characteristic that the reflected wavelength is proportional to strain. In the research reported here, we develop fast FBG interrogator for real-time measurement of the reflected wavelength of a multipoint FBG to monitor the broadband vibration of a structure. For high-speed measurement of the reflected wavelength of a multipoint FBG, we fabricated a wavelength-swept laser constructed of a semiconductor optical amplifier and tunable fiber Fabry-Perot filter incorporated into a fiber ring resonator. The wavelength-swept laser is swept across a 1.55 μm wavelength band by varying the transmitted wavelengths of the tunable optical filter that is inserted into the resonator. With the objective of increasing the speed of the wavelength-swept laser, we measured the laser output intensity and the bandwidth of the sweeping wavelength to determine the dependence on the wavelength sweeping frequency and the resonator length of the ring resonator. On the basis of those results, we set the sweeping frequency of the wavelength-swept laser to 10 kHz for the experiments. The real-time measurement system measures the reflected wavelengths of the multipoint FBG that have different Bragg wavelengths in real time at intervals of 0.1 ms and a data acquisition system sampling frequency of 20 MHz. The system also displays the results on the screen. This FBG interrogator, which combines a wavelength-swept laser and a real-time measurement system, is capable of measuring wavelength within a standard deviation of 2?10-3 nm or less. We have demonstrated that the FBG interrogator is able to measure vibration that has a resonance frequency of 440 Hz at intervals of 0.1 ms with a multipoint FBG.

9506-57, Session PS

Modeling and simulation with systematic technical error based on image replication spectral imaging technology

Yangyang Liu, Qunbo Lv, Linlin Pei, Jianwei Wang, Academy of Opto-Electronics (China)

The image replication imaging spectrometer (IRIS) is a novel snapshot spectral imaging technology. The IRIS enables spectral demultiplexing of an image in a snapshot and offers such characteristics as simple structure and high stability, so it has advantage in recording spectral information of varied scenes. Based on the theory of imaging model of 8-band IRIS system, in this paper we simulated the principle of the 16-band IRIS system , analysed the error mechanism of the various imaging devices in imaging process, and the carried on the modeling and simulation to get the various error influence scope in the 16-band IRIS system, prove the feasibility and superiority of this system research and support theoretical research and practical operation for image replication imaging spectrometer.

9506-58, Session PS

Evaluation of an affinity-amplified immunoassay of graphene oxide using surface plasmon resonance biosensors

Nan-Fu Chiu, Teng-Yi Huang, Chun-Chuan Kuo, National Taiwan Normal Univ. (Taiwan)

This work develops a highly sensitive immunoassay sensor for use in graphene oxide sheet (GOS)-based surface plasmon resonance (SPR) chips. This sensing film, which is formed by chemically modifying a GOS surface, has covalently bonds that strongly interacts with the bovine albumin serum (BSA), explaining why it has a higher sensitivity. This GOS film-based SPR chip has a BSA concentration detection limit that is 100 times higher than that of the conventional Au-film-based sensor. The affinity constants (KA) on the GOS film-based SPR chip and the conventional SPR chip for 100 ?g/ml BSA are 80.81932?106 M-1 and 15.67081?106 M-1, respectively. Therefore, the affinity constant of the GOS film-based SPR chip is 5.2 times higher than that of the conventional chip. With respect to the protein-protein interaction, the SPR sensor capability to detect angle changes at a low concentration anti-BSA of 75.75 nM on the GOS film-based SPR chip and the conventional SPR chip is 36.1867 mdeg and 26.1759 mdeg, respectively. At a high concentration, anti-BSA of 378.78 nM on the GOS film-based SPR chip and the conventional SPR chip reveals 2 times increases in the SPR angle shift. Above results demonstrate that the GOS film is promising for highly sensitive clinical diagnostic applications.

This paper is the fundamental studies of functionalized graphene for nanoplasmonic properties with advanced biosensing mechanisms. We disclose a specificity design of numerous carboxyl-modified can provide modulation of surface plasmons (SPs) coupling, high-performance affinity for sensing layer an immunological reaction advantage. The functionalized graphene sheets based SPR biosensors have three advantages; including high performance, high sensitivity and excellent molecular kinetic response. In the future, the functionalized graphene sheets will have real value and the specific contribution in nanophotonic devices and SPR diagnosis devices. We wish to highlight the essential characteristics of functionalized graphene based SPR biosensor to assist researchers in developing and advancing suitable biosensors for unique applications.

9506-59, Session PS

Highly birefringent fiber-based temperature sensor utilizing the wavelength interrogation

Jan Militky, Miroslava Kadulová, Dalibor Ciprian, Petr Hlubina, VŠB-Technical Univ. of Ostrava (Czech Republic)

New spectral interferomeric methods utilizing the interference of polarization modes in a highly birefringent elliptical-core fiber to measure the temperature are analysed theoretically and experimentally. First we consider an experimental setup [1] comprising a white-light source, a polarizer, a delay line, a sensing birefringent fiber, an analyzer and a spectrometer. As the delay line, a birefringent quartz crystal of a suitable thickness is used to resolve a channeled spectrum in a range as wide as possible. Temperature sensing by this method is based on the wavelength interrogation, i.e., the position of a chosen spectral interference fringe is measured as a function of temperature. Employing the setup, we carried out temperature sensing in the range from 300 to 370 K. A part of the sensing fiber, which is placed in a chamber, is exposed to temperature changes, and the shift of the wavelength position of the chosen spectral interference fringe is measured. The temperature sensitivity measured at different wavelengths is decreasing. We revealed that the fiber is suitable for temperature sensing at a wavelength of 600 nm. Second we consider a setup with another interferometer (represented by a polarizer, a birefringent quartz crystal and an analyzer) to increase the sensitivity of the temperature sensing. In this setup, the resultant channeled spectrum is with envelope which shifts with the temperature. We analyze the new sensor theoretically and show that temperature sensing is once again possible by using the wavelength interrogation and that the sensitivity is substantially increased.

[1] P. Hlubina, M. Kadulova, D. Ciprian, P. Mergo: Temperature sensing using the spectral interference of polarization modes in a highly birefringent fiber. Opt. Lasers Eng., submitted.

9506-60, Session PS

Fiber Bragg grating sensors as a tool to evaluate the influence of filler on shrinkage of geopolymer matrices

Stefania Campopiano, Agostino Iadicicco, Francesco Messina, Claudio Ferone, Raffaele Cioffi, Univ. degli Studi di Napoli Parthenope (Italy)

Geopolymer matrices represent one of the main sustainable alternatives to ordinary Portland cement (OPC) and other clinker-based blended cements. Real scale applications are limited and, so, a relevant amount of data is still needed to assess the actual early age and long-term behavior of these systems.

Particularly, the early-age monitoring of geopolymers represent a key parameter for mix design optimization. Most of the available methods for the measurement of temperature evolution due to polycondensation kinetics and early age deformations are related to laboratory activities. The upscaling to in situ techniques represents a crucial step toward technological assessment.

The early-age monitoring of geopolymers could be carried out by indirect methods based on calorimetry, hydrostatic weighing, ultrasonic waves, electrical resistivity, mechanical parameters, etc. However, these methods require delicate experimental setups which can be implemented only in laboratory. Furthermore, they cannot measure the temperature and shrinkage simultaneously, unless properly coupled. On the other hand, conventional direct methods based on electrical and mechanical strain gauges of measuring the shrinkage cannot be applied because no gauge-points could be established before the sample is hardened.

In order to overcome these limitations, in this paper we have successfully simultaneously measured the early-age shrinkage and temperature changes of metakaolin-based geopolymers by using properly embedded FBG-based sensors.

Our attention has been focused on Fiber Bragg Grating (FBG) sensors also due to their unique advantages such as small dimension, multiplexability, immunity to the electromagnetic interference, high sensitivity etc..

It is worth noting that alkali activated metakaolin represents a reference system in geopolymer science. The fast polycondensation kinetics that involves this precursor determines relevant shrinkage phenomena which increase early age cracking risk, depending on the degree of restraint of structures that, in the case of civil engineering works, is usually high.

Starting from a case study by authors related to the design of externally bonded fiber reinforced geopolymers for strengthening of existing structures, the matrix was optimized in terms of quartz filler content. Quartz is a quite expensive admixture which can be added in order to mitigate shrinkage phenomena as far as it acts as a rigid skeleton opposing to volumetric contraction. The measurements carried out by means of FBG sensors allowed to reduce filler content respect to the abovementioned work. Particularly, quartz content can be reduced by 50%. Together with this, an accurate measurement of inner temperatures was also carried out. The relevant temperature associated to polycondensation (about 65°C) limit the designed metakaolin geopolymer to non-massive structures, since thermal cracking could occur, unless research will be able to assess the viability of retardants already available for traditional cements or develop specific ones for geopolymers.

The experimental results confirm that FBG can represent an accurate method for shrinkage and temperature measurements for geopolymers. The optimization of the experimental setup here presented and the consequential application in real scale structures for remote sensing, could help to create database on inner temperatures and early age deformations, which will increase the knowledge of this new class of binders.

9506-61, Session PS

FBG based novel sensor design for low vacuum measurement with high sensitivity

Vengal Rao Pachava, Srimannarayana Kamineni, Sai Shankar Madhuvarasu, Venkata Reddy Mamidi, National Institute of Technology, Warangal (India)

This article demonstrates design and implementation of an fiber Bragg grating (FBG) based novel sensor for in-vitro measurement of low vacuum with high sensitivity. Measurement of low vacuum has been found potential applications in chemical and metallurgical process industries. The conventional sensors used for vacuum measurement have been being suffered by the low resolution and sensitivity, and are limited in harsh environments due to electromagnetic interference (EMI) and corrosion. In contrast, the fiber Bragg grating (FBG) sensors have distinguished advantages and have been widely implemented to monitor strain, temperature, pressure, vibration, current, structural health of civil and aerospace structures.

The designed sensor head consists of a commercial syringe barrel with plunger, metal spring, pressure chamber, FBG of Bragg wavelength 1551.53 nm as sensing element and a safeguarding outer tube. The sensor is configured by firmly fixing the FBG between the plunger and a rigid support provided to the safeguarding tube. Under vacuum pressure, the metal spring gets compressed and causes an axial strain on the fiber which results in a shift in Bragg wavelength of FBG. A broadband light source (1525-1565 nm) is used to illuminate the FBG. The pressure chamber is evacuated in steps of 2 cm Hg and the corresponding shift of Bragg wavelength is measured using an optical spectrum analyzer (OSA).

Theoretical evaluation of the sensor has been made and compared with experimental results. Experimental results show that the resonance wavelength of FBG is shifted from 1551.53 nm to 1553.29 nm within the range of applied vacuum from 0 cm Hg (Zero referenced against atmospheric pressure) to -66 cm Hg. The vacuum pressure sensitivity of the sensor is found to be 27.03 pm/cm Hg which is well agreed with the theoretically calculated sensitivity of 36.1 pm/cm Hg, and is approximately 6400 times to that of a bare FBG. Also, the shift of Bragg wavelength found to linear with the change in vacuum with a linear coefficient of 0.9988. The prominent feature of the sensor is an in vitro measurement

of vacuum, which avoids the efforts of inserting a sensor into the pressure chamber where the vacuum pressure to be measured. The designed FBG based vacuum gauge enables the system to be compact, cost effective, simple in design, easy to implement in real time applications and has the advantage of fiber optics.

9506-62, Session PS

Strain measurements of a multilayer panel via fiber Bragg gratings as novel approach for deflection monitoring of tracking particle detectors

Agostino Iadicicco, Univ. degli Studi di Napoli Parthenope (Italy); Massimo Della Pietra, Univ. degli Studi di Napoli Parthenope (Italy) and Istituto Nazionale di Fisica Nucleare (Italy); Gabriella Gaudioc, Istituto Nazionale di Fisica Nucleare (Italy); Stefania Campopiano, Univ. degli Studi di Napoli Parthenope (Italy)

In this work authors propose to calculate the deflection of planar panels from the longitudinal surface strain measurements by means of FBG (fiber Bragg grating) sensors arrays properly bonded to or embedded in panels. To this aim a simple post processing analysis of FBG strain measurements is proposed and discussed. A relationship between the longitudinal strain and the vertical deflection is derived by classical beam theory. Indeed, a second derivative relationship exists between the displacement orthogonal to the surface and the strain component parallel to it. However, this approach needs to know the neutral axis of the panel and thus the strain measurements by means of FBG sensors has to be applied on both surface of the panel.

The usefulness of the proposed technique can find important application in deflection monitoring of a novel detector, micromegas (MM), based on a micro mesh gaseous structure will be installed as a tracking detector in the ATLAS experiment at LHC (Large Hadron Collider) at CERN (European Organization for Nuclear Research) by the end of 2018, during a major upgrade of the experiment. The design of this upgrade has been done but not yet finalized.

The aforementioned detector consists of a planar electrode (drift electrode), a gas gap of a few millimeters thickness and a thin metallic mesh at typically 100–150 ?m distance from the readout electrode. To maximize the performance of the detector the geometry of drift and read-out electrodes has to be known with a precision of few tens of ?m. Consequently any sensing solution capable to detect the geometry changes such as deflection of the drift and read-out panels compatible with hard environmental condition at CERN is welcome.

In order to meet all these requirements, authors propose the use of FBGs to measure the detector panel deflection with resolution of a few microns. Indeed FBGs are complying with hard requirements such as radiation hardness resistance, insensitivity to magnetic field, small dimensions and low mass, minimal need of services, extreme precision and high strain resolution (about 1μ?) and with large multiplexing capability.

Thus, in order to validate the proposed methodology, measurements of the surface strain and then of the deflection of a relatively miniaturized MM panel prototype have been carried out . Successively we present experimental results of the in-direct deflection measurements on a full size MM panel (with trapezoidal shape). Here a five sensors array is bounded on the panel surface whereas two more gratings are used for the estimation of the neutral axis. Deflection measurements with resolution of few tens of microns are successfully achieved.

9506-63, Session PS

Magnetic field measurement using a fiber laser sensor in ring arrangement

Ivo M. Nascimento, INESC Porto (Portugal); José M. Baptista, INESC Porto (Portugal) and Univ. da Madeira (Portugal); Pedro A. S. Jorge, INESC Porto (Portugal); José L. Cruz Muñoz, Univ. of Valencia (Spain); Miguel V. Andrés, Univ. de València (Spain)

In this work an optical fiber laser with loop configuration was developed for magnetic field measurement. The transducer element is an FBG written in a HiBi fiber which is wavelength modulated using a magneto restrictive material that applies deformation in the presence of the magnetic field. The laser has a bandwidth of 450 MHz and operates in single polarization. A shift of 260 pm was observed in the laser operating wavelength for a magnetic field of 15.75 mT. Moreover, a maximum sensitivity of 18.62 pm/mT in the linear regime operation was achieved. The system provides a narrow emission line that is dependent on the magnetic field magnitude enabling high resolution interferometric measurement schemes.

9506-64, Session PS

Quantum noise limit of phase microoptical gyro sensitivity

Vladimir Y. Venediktov, Yuri V. Filatov, Egor V. Shalymov, Saint Petersburg Electrotechnical Univ. “LETI” (Russian Federation)

Microoptical gyros, based upon the passive optical resonators, represent the fast developing field of gyro and interferometery technique. Earlier we have shown the possibility of measuring the rotation speed with the use of phase characteristics of such a gyro. In this paper we consider the sensitivity limitations of such a device in comparison with other types of microoptical and optical gyros.

9506-65, Session PS

Automatic recognition system of aquatic organisms by classical and fluorescence microscopy

Mathieu Lauffer, Frédéric Genty, Samuel Margueron, Lab. Matériauy Optiques, Photonique et Systèmes (LMOPS) (France); Jean-Paul Collette, IMS Supélec (France); J. C. Pihan, BioCapTech (France)

Phytoplankton plays a fundamental role in the living world. It is a dioxygen generator and the most important carbon dioxide fixer on Earth. However, under certain conditions, its development may become so excessive that it could be harmful to other vegetal and animal aquatic life in the water ponds in which it grows: it is the “hyper eutrophication” phenomenon. Such a situation leads to dramatic consequences on environment due to the difficulties that arise for photosynthesis and gas exchanges of other plant species. At the extreme limit, this can cause the death of the whole aquatic ecosystem. Moreover, many of these invasive species can present also a risk for human health. Especially, many kinds of cyanobacteria are potentially toxic due to their ability, in many conditions, to produce one or more toxins. On many occasions, both animal (fish, cattle) and human poisonings have been unfortunately observed in the world. It appears therefore essential to strengthen the vigilance on controlling the proliferation of plankton and toxins with the necessity of risk evaluation. In a first approach, the recognition and the identification of aquatic organisms, necessary for such a control, are usually performed only by specialists algologists from microscopic observations. Nevertheless, in certain circumstances, it may be useful to dispose of an automatic recognition system to improve the monitoring of high-risk water ponds and optimize human intervention of specialists algologists. The development of such an automatic system of recognition of aquatics organism is more and more considered.

In order to identify aquatic organisms, an original optical microscopy set up was developed in which the incident and emitted light beams are filtered in wavelengths. Such a set up enables the acquisition of classical microscopic images and microscopic images of fluorescence emission of the vegetal material under different illumination. These different images are then analyzed and processed by two algorithms of segmentation to collect characteristics data of the vegetals morphology and pigments compositions useful thereafter for their automatic recognition. The first algorithm consists in sliding the picture into several regions by "watershed" segmentation originating from the gradient magnitude. This processing enables in a first approach to extract morphological characteristics of the vegetal material. Then, a "k-means" segmentation is applied to fluorescence images. Using again the results of the "watershed" segmentation, this new processing provides a classification of the fluorescence intensities of the different regions previously defined. Finally, all these different characteristic parameters linked to morphology and fluorescence emission of the vegetal species are collected to build a database useful for automatic optical recognition.

This research is funded by BIOCAPTECH, Region Lorraine and Europe.

9506-66, Session PS

Gold and aluminum based surface plasmon resonance biosensors: sensitivity enhancement

Mykola Biednov, National Taras Shevchenko Univ. of Kyiv (Ukraine) and Univ. of Hamburg (Germany); Tatyana Lebedeva, Pavel Shpilovuy, Glushkov Institute of Cybernetics (Ukraine)

In this work we considered Gold and Aluminum thin films coated with additional dielectric layers as sensing platforms. Operation of these sensors is based on measuring shift in the position of the reflectivity dip in angular reflectivity spectrum of the sensor. Shift can be caused by changes in the refraction index of either liquid that interacts with sensors surface (refractometric measurements) or thin adjacent biolayer on top of the sensor due to immobilization of the target molecules (biosensing). Calculations based on Fresnel equations and transfer matrix formalism allowed us to make comprehensive analysis of the angular sensitivity, shape of the reflectivity dip and dynamic range of the sensors with different dielectric coatings. Calculations were performed for both cases of bio and refractometric sensing. Results showed different dependence of the sensitivity of Au an Al based sensors upon refraction index of the dielectric coating. For Au-based surface Plasmon resonance sensor up to two times increased sensitivity can be achieved using dielectric coating with high refraction index 2.3 and proper thickness. For sensors based on aluminum we were able to achieve 50% increased angular sensitivity. At the same time width of the reflectivity dip increased proportionally to the optical thickness of the dielectric coating.

For estimating sensors quality we analyzed ratio of the angular sensitivity to the width of the reflectivity dip. This ratio decreased with increase in optical thickness of the dielectric, however angular sensitivity of the sensor increased significantly. Deposition of the additional dielectric layer with high refraction index such as Niobium Oxide can improve not only angular sensitivity but also the chemical and mechanical stability of the proposed sensor.

9506-67, Session PS

Optical sensing of rainbow for non-contact gauging of diameter and refractive index of an axisymmetric transparent fiber

Grzegorz Swirniak, Wroclaw Univ. of Technology (Poland)

Optical measurement systems exploit a unique and inherent feature of light – its ability to act at a distance. With the use of light, any particles, materials and components may be characterized noninvasively, completely without mechanical contact. Optical systems may function in real time, which is often critical for industry applications. The most natural and widely-used technique at micron to millimeter scales is perhaps microscopy which fundamentally relies on shadow-cast mechanism and image analysis. The technique operates on intuitive cause-effect relationships between the object and its image so that individual objects may be characterized as well as dispersed samples. Variety of non-imaging techniques are also available including interferometry, where mutual exchange of energy between an object and light is analyzed in terms of wave interactions. Working in terahertz band (at optical frequencies) enables to measure with a sub-wavelength precision at the expense of increased instrument complexity and data analysis.

The task considered in this work is to measure simultaneously the diameter and index of refraction of an axisymmetric transparent fiber by examining one of the most spectacular phenomenon in nature – rainbow formed by light scattered from fiber. For this purpose, a beam of light of low-temporal coherency is used which enables to achieve unambiguous mathematical relationships between features of the rainbow and the fiber. The method is intended for a high-precision non-contact characterization.

In this paper we shall focus on: (i) high-angle scattering aspects of low-coherent radiation, (ii) discussion on how the diameter and index of refraction of the fiber influence the scattered field, (iii) formulation and assessment of the mathematical relationships for fiber characterization.

9506-68, Session PS

Hybrid organic-inorganic semiconductor transducer for optical and electrical sensing

Alessandro Calio', Consiglio Nazionale delle Ricerche (Italy); Antonio Cassinese, Univ. degli Studi di Napoli Federico II (Italy); Maurizio Casalino, Consiglio Nazionale delle Ricerche (Italy); Jane Politi, Mario Barra, Luca De Stefano, Univ. degli Studi di Napoli Federico II (Italy)

Porous silicon (PSi) optical transducers have been used by more than twenty years in chemical and biological sensing by academic and industrial researchers [1]. PSi is widely employed as photonic material due to the possibility of fabricating high quality optical structures, such as Bragg or rugate filters, microcavities etc. The sensing mechanism is based on the change of the PSi refractive index on exposure to the substances to be detected, due to their infiltration or capillary condensation in the pores; the consequence of the refractive index variation is a change in the reflectivity spectrum of the devices. Due to its sponge-like morphology, PSi is an excellent optical transducer, but exhibit very poor electrical performances, due to its low conductivity. In the field of organic semiconductors, N,N'-1H,1H-perfluorobutyldicyanoperylene-carboxydi-imide (PDIF-CN2) is a very promising compound thanks to its interesting charge transport properties, making it particularly attractive for the development of high-mobility n-type organic filed-effect transistors [2]. In this work, non-symmetric optical microcavities modified by deposition of PDIF-CN2 were fabricated; their optical and electrical properties have been investigated in terms of reflectivity and current respectively, in order to realize a dual signal sensor for biochemical sensing. Non-symmetric microcavities are constituted by a ?/2 layer sandwiched between two Bragg reflectors (BRs) which have different numbers of layers, and the sequence is: HLHLHLHLHLHLLLLHLHLHLHLHLHLHLHLHLHLH, where H and L are high and low refractive indexes. PSi photonic structures were fabricated by electrochemical etching of p++ crystalline silicon (0.001-0.005 Ωcm resistivity) in hydrofluoric acid (HF, 50% in volume), water, and ethanol solution (1:1:1) in dark and at room temperature. PDIF-CN2 has been deposited on PSi microcavities by organic molecular beam deposition (OMBD), by generating a red shift of about 5÷6 nm of reflectivity spectrum and an increase of electrical current of about 5 order of magnitude. We have then performed time-resolved optical and electrical measurements in order to characterize the dynamic of devices in presence of iso-propanol as target analyte mixed to nitrogen carrier. Devices exposed to iso-propanol mixed to nitrogen showed an increase of electrical current and intensity of optical spectrum higher than devices exposed to nitrogen. Both the optical and electrical sensing techniques are completely reversible, which makes the sensor re-usable. So as, we have finally obtained a dual parameters sensor for bio-chemical species.

9506-69, Session PS

TDLAS at 2.05 um for the CO2 concentration measurement

Alina Pranovich, Martin Divoky, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Ivan Prochazka, Czech Technical Univ. in Prague (Czech Republic); Tomás Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Our goal is to construct a differential absorption lidar (DIAL) based on a tuneable parametric generator for precise concentration measurement of a range of pollutants and greenhouse gases in the atmosphere.

The first step of the development is to design an experimental setup based on a continuous light source for measurement at a defined track without spatial resolution. The second stage is to replace the continuous diode driver by a pulse driver, which will add spatial resolution. During these two steps the requirements for the parametric generator will be determined. The last step would be to replace the diode with the parametric generator that increases precision and range of generated wavelengths up to 12 um.

Due to the high absorption coefficient, the absorption peak of CO2 near 2.05 um was selected for the test setup. The light source of the system is a tuneable laser diode operating in continuous mode. The initial radiation from the diode laser is divided into three parts: the first part of the beam is directed to CO2 cell for wavelength calibration, the second part is directed to the retro reflector, and the third part is used for diode output power monitoring.

The receiving system consists of a focusing optics and a photodiode. The absorption is determined by comparing the intensities of the detected light on wavelengths absorbed and not absorbed by CO2 molecules.

The experimental setup for the CO2 concentration measurement in continuous mode and the results of the absorption are presented.

9506-70, Session PS

Chemo-optical sensors consisting of porous periodic structures built of Va2O5 and nanosized zeolites

Katerina Lazarova, Institute of Optical Materials and Technologies (Bulgaria); Hussein Awala, J. Grand, V. Georgieva, Ecole Nationale Supérieure d'Ingenieurs de Caen et Ctr. de Recherche (France); M. Vasileva, Erintche M. Spassova, R. Georgiev, Institute of Optical Materials and Technologies (Bulgaria); Svetlana Mintova, Ecole Nationale Supérieure d'Ingenieurs de Caen et Ctr. de Recherche (France); Tsvetanka Babeva, Institute of Optical Materials and Technologies (Bulgaria)

The possibility of preparing porous structures with one-dimensional periodicity via layer-by-layer deposition of sol-gel derived Va2O5 films and nanosized zeolite particles with BEA and LTL types framework structure is studied. Optical properties of layers including refractive index (n), extinction coefficient (k) and thickness, (d) are determined through measuring transmittance and reflectance spectra followed by modeling. The influence of post deposition treatment on the optical constants and thickness of the layers is studied by in-situ ellipsometry in the temperature range of 60 - 450 oC. Besides multilayer structures with quarter-wave design comprising different number of layers are prepared. The surface and cross-sectional morphologies and the structures are characterized by scanning electron microscopy and X-ray diffraction, respectively. The surface roughness of the layers is obtained from high-resolution optical profiler images.

The sensing properties of these structures are studied by measuring transmittance and reflectance spectra in visible range and FTIR spectroscopy prior to and after exposure to vapors of acetone, alcohols and water. Furthermore, the potential of the porous periodic structures based on Va2O5 and nanosized zeolites for chemo-optical sensing will be demonstrated.

9506-71, Session PS

A silicon-based peptide biosensor for label-free detection of cancer cells

Nicola M. Martucci, Univ. degli Studi di Napoli Federico II (Italy); Ilaria Rea, Istituto per la Microelettronica e Microsistemi (Italy); Immacolata Ruggiero, Univ. degli Studi di Napoli Federico II (Italy); Monica Terracciano, Luca De Stefano, Istituto per la Microelettronica e Microsistemi (Italy); Nunzia Migliaccio, Univ. degli Studi di Napoli Federico II (Italy); Principia Dardano, IMM - CNR (Italy); Paolo Arcari, Univ. degli Studi di Napoli Federico II (Italy); Ivo Rendina, Istituto per la Microelettronica e Microsistemi (Italy); Annalisa Lamberti, Univ. degli Studi di Napoli Federico II (Italy)

Cancer is a leading cause of death worldwide. New therapies, including minimal residual disease treatments, crucial for patient survival, seem to strongly depend on the capabilities of detecting cancer cells. Biosensing technology, taking advantage of the properties of biological systems combined to advanced materials, is providing rapid, reproducible, and highly sensitive cell detection. Here, a new strategy for highly selective and sensitive direct detection of lymphoma cells by exploiting the interaction between a peptide and its B-cell receptor has been reported. In particular, an idiotype peptide (pA20-36), able to specifically bind the B-cell receptor of A20 cells in mice engrafted with A20 lymphoma, has been used as molecular probe. pA20-36 peptide was immobilized on the silicon surface following a proper functionalization strategy developed and optimized on PSi sample, used as a model system for the silicon surface: the nanostructured peculiar morphology allows the immobilization of a greater number of molecules with respect to a flat support and a number of functionalization investigation methods could be more easily exploited. Silanol groups on the oxidized PSi surface, formed by hydroxylation with aqueous sulfuric acid, react with APTES producing siloxane linkages. The aminosilanized surface was then activated by the homobifunctional crosslinkers BS3 providing a carboxyl group for the anchorage of an amine-ended peptide. The functionalization of PSi surface was also confirmed by spectroscopic reflectometry. Once optimized in terms of reagents and reaction conditions, the functionalization procedure was applied on a flat crystalline silicon support. In this case, each passivation step was monitored by spectroscopic ellipsometry that quantified film thickness changes after thermal oxidation (SiO2), silanization (APTES), and cross-linker functionalization (BS3). To investigate the efficiency of the silicon chip to uniformly bind a peptide on its surface, increasing concentrations of labeled peptide was used; the fluorescence intensities of the biochip surface, evaluated by means of a fluorescent macroscope, showed a dose dependent behavior. Successively, peptide modified silicon chip as biosensor for label-free detection of cancer cells was exploited. The device was able to capture A20 cells: coverage of 85% of silicon surface and detection efficiency of 8.5?10-3 cells/?m2 was obtained. As negative control, the device was not able to capture A20 cells if functionalized with a random peptide, whereas no 5T33 myeloma cells, a surface IgG-positive B-cell line unable to bind to pA20-36 peptide, were observed when incubated on the chip functionalized with pA20-36. These results, besides to be useful for the study of other specific bindings between antibodies and their ligand peptides, allowing to find and characterize new specific receptor-ligand interactions, for instance through the screening of a recombinant phage library, provide a new basis for the development of unique tools for the targeting of patient-specific neoplastic B cells during the minimal residual disease.

9506-72, Session PS

3D imaging of translucent media with a plenoptic sensor based on phase space optics

Xuanzhe Zhang, Bohong Shu, National Univ. of Defense Technology (China); Shaojun Du, National Univ of Defense Technology (China)

Different from traditional imaging technology, the phase space optics task is to obtain a 4D matrix of the object light field, called "space and spatial frequency" joint distribution, from which 3D distribution of the translucent media can be calculated. If with higher transparency, the media should be treated as multi-layered phase screens illuminated by extended beacon, and calculated from the beacon joint distribution: firstly, to calculate all phase distributions on different angles of view, each of them respectively corresponding to a certain part of the beacon 4D matrix and being equal to its first moment; secondly, to calculate 3D phase distribution through tomography algorithm. If with lower transparency, the media could be directly calculated from its own joint distribution with the similar algorithm, what we need to do is retain only defocus item on each angle of view on the second step to get a depth map. In this paper, Plenoptic sensor, consisted of micro lens array (MLA) and CCD which located at the focal plane of MLA, has been proved to be a very practical tool for phase space imaging, whose data corresponds to the intensity of windowed Fourier transform of light field, so-called Spectrogram, belonged to the famous Cohen Class. After that, taking a waterfall device for instance, two methods for 3D imaging have been presented, and the results have been discussed in the end.

9506-73, Session PS

Experimental results for characterization of a tapered plastic optical fiber sensor based on SPR

Nunzio Cennamo, Luigi Zeni, Seconda Univ. degli Studi di Napoli (Italy)

The experimental results obtained with two different Plastic Optical Fiber (POF) geometries, tapered and not-tapered, for a sensor based on Surface Plasmon Resonance (SPR) are presented. SPR is used for determining the refractive index variations at the interface between a gold layer and a dielectric medium (aqueous medium). In this work SPR sensors in POF configurations, useful for bio-sensing applications, have been realized for the optimization of the sensitivity and experimentally tested.

The advantages of using POFs rely on the fact that the properties of POFs, that have increased their popularity and competitiveness for telecommunications, are exactly those that are important for optical sensors based on optical fibers. Moreover, a further advantage of POF sensors is that they are simpler to manufacture than those made using silica optical fibers. In general, the optical fiber employed is either a glass one or a plastic one. For low-cost sensing systems, POFs are especially advantageous due to their excellent flexibility, easy manipulation, great numerical aperture, large diameter, and the fact that plastic is able to withstand smaller bend radii than glass.

Measurements were carried out with an experimental setup arranged to measure the transmitted light spectrum and were characterized by a halogen lamp, illuminating the optical sensor system, and a spectrum analyzer.

The plastic optical fiber has a PMMA core of 980 ?m and a fluorinated polymer cladding of 20 ?m. The fabricated not-tapered POF sensor was realized removing the cladding of a plastic optical fiber along half the circumference, spin coating on the exposed core a buffer of Microposit S1813 photoresist (the thickness of photoresist buffer was about 1.5 ?m), and finally sputtering a thin gold film using a sputtering machine (the gold film so obtained was 60 nm thick). The realized sensing region was about 10 mm in length.

The tapered POF sensor has been realized as follows. The plastic optical fiber, without protective jacket, was heated at 150 degrees Celsius and stretched with a motorized linear positioning stage until the taper ratio reached 1.8. After this step the POF was embedded in a resin block and the same method was used to prepare the not-tapered optical fiber sensor.

These two different SPR-POF sensors (tapered and not-tapered) with a planar gold layer in contact with six different water-glycerin solutions, with refractive index ranging from 1.333 to 1.385, are tested.

The results show that the sensitivity of the SPR sensor in a tapered POF is higher with respect to the case without the tapered POF, when the refractive index of aqueous medium increases.

This is a good factor for forthcoming bio/chemical sensors implementation where on the gold surface there is a bio or chemical layer for the selective detection and analysis of analyte in aqueous solution.

9506-74, Session PS

Magneto-plasmonic response as a perspective tool to magnetic field sensing

Petr Otipka, Jaroslav Vlcek, Michal Lesnák, VŠB-Technical Univ. of Ostrava (Czech Republic); Jaroslav Sobota, Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic)

The non-reciprocity of magneto-optical reflection response by surface plasmon excitation in the planar Au/Fe/Au/glass nano-systems with prism coupling is studied. These structures are intended as magnetic field sensor units combining magneto-optical (MO) and surface-plasmon-resonance (SPR) effects. Unlike our previous work [1], where directly the reflection has been discussed, the ability of MO-SPR systems to magnetic field sensing is analysed using incidence-angle-depending response function (Rpp(+) – Rpp(-))/(Rpp(+) + Rpp(-)), where Rpp denotes the reflectance of p-polarized beam; and, the sign in upper index relates to the orientation of external magnetic field. The newly proposed sensitivity criteria F and K (the magnitude and inflexed tangent of the response function oscillation) are applied in transverse MO configuration. Mathematical model based on the own matrix algorithm is applied to simulate the diffraction response to varying external magnetic field at the wavelength 632.8 nm. The sample design is based on a detailed analysis response of the thicknesses combination of metallic layers. Obtained theoretical results are compared with experiments realized using the measuring device Multiskop (Optrel GbR, Germany). To this purpose, the equipment has been completed by digitally controlled electro-magnet, which enables production of predefined magnetic field.

References

[1] Vlcek, J., Lesnák, M., Pi?tora, J., ?ivotsk?, O.: Magneto-optical sensing of magnetic field, Optics Communications 286, 2013, pp. 372-377

9506-75, Session PS

Graphene-like coatings for biosensors devices

Paola Zuppella, Francesca Gerlin, Sara Zuccon, Alain J. Corso, IFN-CNR LUXOR Lab. (Italy); Enrico Tessarolo, Marco Nardello, Davide Bacco, Univ. degli Studi di Padova (Italy); Maria G. Pelizzo, IFN-CNR LUXOR Lab. (Italy)

The interest in graphene–like materials involves many research areas, including the development of biosensors devices. We have recently studied the use of graphene/metal bilayer for surface plasmon resonance (SPR) equipment devoted to detection of chemical processes and biomolecules recognition. The dual role of graphene is to protect the metal layer underneath and to enhance the bioaffinity by adsorbing biomolecules with carbon–based ring structures. Depending on the application, it may be necessary the laser and chemical treatments of graphene to improve the performances of the whole device. The processing effects will be investigated by near edge X-ray absorption

fine structure (NEXAFS) spectroscopy. The use of synchrotron light is mandatory for NEXAFS analysis since a continuous EUV source of selected polarization is required. The ideas, the analysis and the results are the subjects of this work.

9506-76, Session PS

Single particle UV sensor and effect of subsequent heat treatment on the morphology and optical properties of unique ZnO nanorod

Umair Manzoor, King Saud Univ. (Saudi Arabia); Do K. Kim, KAIST (Korea, Republic of); Abdulrahman A. Alazba, Muhammad T. Amin, King Saud Univ. (Saudi Arabia); Arshad S. Bhatti, COMSATS Institute of Information Technology (Pakistan)

In this study, a unique Zinc Oxide (ZnO) nanorod was isolated and subsequently heat treated at different temperatures. ZnO nanorods were synthesized by vapor transport method. Scanning electron microscope (SEM) micrographs of a unique nanorod after periodic heat treatments, gave direct evidence of a systematic degradation. X-Ray diffraction (XRD) results suggest that crystal quality improved by annealing. Optical properties can be tuned by carefully adjusting the annealing conditions. Single nanostructure based UV sensor was fabricated and the results clearly suggested a potential for using ZnO as sensitive single particle sensor for UV light.

9506-78, Session PS

Photoluminescence characterization of ZnO nanowires functionalization

Jane Politi, Univ. degli Studi di Napoli Federico II (Italy); Mariano Gioffre', Ilaria Rea, Luca De Stefano, Istituto per la Microelettronica e Microsistemi (Italy)

Nanostructured photoluminescent materials are optimal transducers for optical biosensors due to their capacity to convert molecular interactions in light signals without contamination or deterioration of the samples. In recent years, nanostructured biosensors with low cost and readily available properties have been developed for such applications as therapeutics, diagnostic and environmental.

ZnO is a wide bandgap (3,37 eV) material with a large exciton-binding energy (60 meV) that allows an efficient excitonic emission even at room temperature, this makes the ZnO a promising material for photonics application. Moreover ZnO is biocompatible, chemical stable and environmentally friendly, which makes it a useful material for biomedical applications. In recent years ZnO nanostructures have gained a great interest in scientific community and a large variety of morphologies was investigated. The hydrothermal synthesis is the easier method to obtain ZnO nanowires (ZnO NWs) vertically aligned to the surface with a high crystallinity quality. Changing the process parameters it is also possible to modulate the nanowires density and height. The large surface-to-volume ratio, the low process temperature and the ZnO bio-compatibility makes it a good candidate for bio-sensing application. The hydrothermal process consist in an aqueous solution of a precursor and a reagent where is placed a ZnO-seeded substrate. The solution was prepared by dissolving in D.I. water an alkaline reagent, hexamethylenetetramine ($C_6H_{12}N_4$) and a Zn^{2+} salt ($Zn(NO_3)_2$), that act as a precursor, with different concentrations. The solution was then heated at 90ºC with a Si substrate, with the sputtered ZnO thin film, immersed upside down. ZnO NWs surface is highly hydrolysed, so it is covered by hydroxyl (-OH) reactive groups. Starting from -OH groups it was developed a functionalization strategy using an an amino-therminal silane such as 3-amino?propyl?triethoxysilane (APTES). The aminosilane is able to reticulate on the surface and it provides a reactive residues for biomolecules binding or cross-linkers binding. After silanization procedure, aminotherminal surface is available and functionalization strategy could continue using cross-linkers for proteins conjugation. To reduce intramolecolar cross-linking, it is advisable to use a longer spacer arm. One very useful cross-linker is bis-sulfo-succinimidylsuberate (BS3). BS3 have a good leaving group like sulfo-N-hydroxysulfosuccinimide (sulfo-NHS). Sulfo-NHS react with primary amines at pH 7-9 to form stable amide bonds, so as it can be used to bind residues of lysines aminoacid present in most of proteins. In this study we used a model protein able to orient antibodies, such as Protein A with the perspective to realize a ZnO NWs based lab-on-chip for diagnostic applications.

The nanostructures and the biomodification of ZnO NWs were experimentally characterized by several techniques such as scanning electron microscopy (SEM), Fourier Trasform-Infrared (FTIR) spectroscopy, water contact angle (WCA) and Photoluminescence (PL) in order to evaluate modulation, wettability, optical and structural characteristic of functionalized ZnO NWs.

9506-79, Session PS

Optical sensors based on the molecular condensation nuclei detector

Vladimir D. Kuptsov, Saint-Petersburg State Polytechnical Univ. (Russian Federation); Vadim Katelevskii, Neorganika (Russian Federation); Vladimir P. Valyukhov, Saint-Petersburg State Polytechnical Univ. (Russian Federation)

Molecular condensation nuclei (MCN) detector is a specialized optical sensor which provides for monitoring of various chemicals impurity in the environment and diagnosis of diseases in human exhaled air (“electronic nose” biosensor). Structurally MCN detector is included in the highly sensitive gas analyzers based on MCN method. The article describes the fundamental principles, specific features and application fields of the advanced highly sensitive MCN method. The MCN method is based on the application of various physico-chemical processes to the flow of a gas containing impurities. As a result of these processes aerosol particle that are about 10^6 times larger than the original molecule of the impurity are produced. The ability of the aerosol particle to scatter incident light also increases ~10^14÷10^16 times compared with the original molecule and the aerosol particle with the molecule of the impurity in the center is easily detected by light scattering inside a photometer. By measuring of the light scattering intensity is determined concentration of chemical impurities in the air. Aerosol particles in the MCN detector are formed in the condensing devices through overgrowth of the molecule detectable impurity by molecules so-called «developer» substance. At the final stage of the analysis in the MCN detector is measured light scattering by aerosol particles which is proportional to the concentration of determined impurities in the environment. For calculations of the scattered radiation is applicable Mie’s theory considering the scattering of light by spherical particles whose size is comparable to the wavelength of light. We have determined that the light scattering by aerosol particles is interferometric and is comparable within an order of magnitude with light scattering by the air inside a 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 photodetector.

9506-80, Session PS

Engineered metallic nanogap structures for plasmonic biosensing and surface-enhanced spectroscopy

Xiaoshu Chen, Univ. of Minnesota, Twin Cities (United States); Daehan Yoo, Hyeong-Ryeol Park, Shailabh Kumar, Avijit Barik, Jonah Shaver, Daniel Mohr, The Univ. of Minnesota, Twin Cities (United States); Sang-Hyun Oh, Univ. of Minnesota, Twin Cities (United States)

The first part of this presentation will focus on template-stripping techniques [Nagpal et al., Science (2009) 325, 594] for making ultra-smooth patterned metals. By combining template stripping with optical

interference lithography, we can routinely produce large-area plasmonic nanohole arrays for SPR and SERS biosensing. Recently, we have also successfully developed nano-imprint lithography technique to make large-area (millimeter-scale) free-standing gold and silver nanohole arrays. After asymmetric surface modifications to alternate hydrophobic and hydrophillic surfaces across the membrane, we can readily pass sample droplets through these nanopore arrays, and demonstrated improved detection time for analyte molecules. Next, we will focus on atomic layer lithography for making sub-nanometer-wide gaps in metal films [Chen et al., Nature Communications (2013) 4, 2361]. By creating vertically oriented nanogaps that can couple incident light into tightly confined gap plasmon modes, we can perform highly sensitive detection of surface-adsorbed molecules using SERS, SEIRA, and even terahertz time-domain spectroscopy using gaps that are as small as 1 nm. Possible future applications of these novel optical nanostructures will also be discussed.

9506-81, Session PS

Research on optical fiber microphone array based on Sagnac interferometer

Hongyan Wu, Jian Wang, Fudan Univ. (China)

Extensive attention has been paid to optical fiber microphone because of its especial merits, such as anti-electromagnetic interference, corrosion resistance, high sensitivity, safety and reliability. In the present study, a kind of optical fiber microphone array based on Sagnac interferometer is proposed. On the basis of the high sound quality of optical fiber microphones, the acoustic source localization theory is tested and verified in practice. The results prove the accuracy of localization exactly. Besides its feasibility, the scientific value and application prospect, such as in passive radar and ultrasonic detection field, are great.

9506-82, Session PS

Skin melanoma detection with a multispectral imaging equipment

Ilze Lihacova, Uldis Rubins, Univ. of Latvia (Latvia); Alksandrs D. Derjabo, Latvian Oncology Ctr. (Latvia); Janis Spigulis, Univ. of Latvia (Latvia)

A multispectral imaging method was developed using multispectral imaging equipment that allows to obtain skin spectra in 450- 950 nm range. Sensitive parameter for skin melanoma was obtained using three narrow- band wavelengths- 540nm, 650nm and 950nm. The novel method for melanoma detection was developed and adjusted for optical device. Broad- band LEDs (450nm, 545nm, 660nm and 940nm) and polarizers were added to digital video- microscope. Equipment leading software was established for device control. Results shows that melanoma sensitive parameter is higher inside malignant pathology area than normal skin, but lower than normal surrounding skin for benign pigmented pathologies.

9506-83, Session PS

Determination of plume temperature distribution based on the ratios of the radiation intensities of multiple CO2 lines

S?awomir Czieszczyk, Politechnika Lubelska (Poland)

Optical method are commonly used for hot gas diagnostic. The spectral remote sensing method considered here is widely applied for industrial and environmental monitoring [1-4]. It is a passive single-ended sensor technique in which the radiation intensity emerging from a studied object is analyzed. In this article, a new inversion scheme for retrieving the gas temperature distribution that utilizes a high resolution CO2 spectrum between 2350 cm-1 and 2400 cm-1 is proposed. The quantitative investigation of heated-gas radiation emission to determine the temperature and the gas mixture by infrared spectroscopy requires two components in addition to an optical radiation sensor, an appropriate spectral database and efficient inversion techniques. In this study, calculations of the one-dimensional radiative transfer equation were used to simulate the spectral radiation intensity. The gas spectrum is modeled using widely known HITRAN line-by-line methods. Next, the temperature distribution was parameterized and expressed in terms of approximation parameters. The inversion model is build based on neural networks. Each neural network estimates one parameter (i.e., the NN response) based on a given spectrum (i.e., the NN input). To increase the quality of the retrieval, spectrum preprocessing and feature-extraction methods are applied. The proposed new approach utilizes the ratios of the radiation intensity of multiple CO2 lines instead of spectral intensities only. This technique eliminates the errors caused by inaccuracies in the absolute radiation intensity measurement. For example, this situation can occur when studied object (plume) radiation not fulfils whole spectrometer field-of-view (FOV). Different optical paths for various axisymmetric temperature distributions and CO2 contents were studied by simulation. The proposed retrieval methodology shows good characteristics in hot gas temperature profile (one dimensional distribution) retrieval problem.

1. S. Czieszczyk, Passive Open-Path FTIR Measurements and Spectral Interpretations for in situ Gas Monitoring and Process Diagnostics, Acta Physica Polonica A 126, 2014, 673-678.

2. E. García-Cuesta, at all, Temperature Profile Retrieval in Axisymmetric Combustion Plumes Using Multilayer Perceptron Modeling and Spectral Feature Selection in the Infrared CO2 Emission Band, Applied Spectroscopy 68(8), 2014, 900-908.

3. K. Gross, at all, Remote Identification and Quantification of Industrial Effluents via Imaging Fourier-Transform Spectroscopy 44(24), 2010, 9390-9397.

4. P. Al Khoury, at all, Inversion of spectroscopic data, application on CO2 radiation of flame combustion, Inverse Problems in Science and Engineering, 2005, 219-240.

9506-84, Session PS

Application research in nonuniformity correction algorithm of IRFPA for infrared measuring system

Yi Yang, Baihong Shu, Shaojun Du, National Univ. of Defense Technology (China)

The nonuniform response of the sensors are increasingly prominent with infrared focal plane arrays (IRFPAs) being more and more used in infrared measuring systems, which gives uncorrected images and measurement error. Nonuniformity correction (NUC) techniques have been developed and accomplished to perform the necessary calibration for most IR sensing applications. These correction techniques fall into two primary categories: 1) reference-based correction using calibrated images on startup and 2) scene-based techniques that continually recalibrate the sensor for parameter drifts. The mainstream IRFPAs in the current market, cooled or uncooled, mostly used the so-called "two-point" correction method, which assume the detector response is linear and uniform in the temperature range of concern, actually not the case. As a result, sometimes the correct effect is not ideal. This paper begins with the theory-based analysis on merits and faults of several nonuniformity correction algorithms attracting broad attention in recent years, like two-point correction, multipoint correction, temporal high pass filter correction (THFC), artificial neural network correction (ANNC), constant statics correction (CSC), etc. And using existing infrared images sequences, algorithm validation is respectively carried out on these methods. A improved adaptive Nonuniformity correction algorithm is proposed, combining knowledge and experience about the measuring objects. The simulation results and analysis show that the method can effectively improve image quality and eliminate ghost.

9506-85, Session PS

Aeronautical fibre optic fuel gauging sensor

Giovanni Onorato, Gianluca Persichetti, Immacolata A. Grimaldi, Genni Testa, Romeo Bernini, Istituto per il Rilevamento Elettromagnetico dell'Ambiente (Italy); Carlo A. M. Rens, Floris H. Overwater, National Aerospace Lab. NLR (Netherlands)

With the increased occurrence of flights in hazardous weather (lightning strikes) and considering the Composite Aircraft (where strikes or induced arcs can penetrate low electrical conductive composite materials more easily) and the More-Electric Aircraft (where the related high voltage level may induce electric arcs), it is necessary to avoid the presence of any ignition source in the fuel tank where fatal accidents could occur due to the ignition of fuel or vapours.

Today aeronautical gauging is based on capacitive sensor using metal wiring inside the tank. Spark generation in presence of high electromagnetic radiations is obviously representing a risk of ignition source. As a solution a fuel gauging sensor based on an array of total internal reflection (TIR) point sensors is developed. Respect to conventional TIR sensors the new design permits to be sensitive to common jet fuels (Jet-A, JP4 and JP7) but also to operate with new alternative fuels. Besides fuel gauging the sensor has the feature to determine the presence of free water in the fuel tank. Above all the sensor doesn't require aircraft calibration, temperature compensation.

A prototype with 16 point sensors multiplexed on a single fibre has been fabricated which are interrogated simultaneously by Optical Time Domain Reflectometry (OTDR) at a wavelength of 1550nm. The optic gauging sensor has been characterized in a dedicated test bench simulating the dynamics of the fuel tank in an aircraft.

9506-86, Session PS

Remote optoelectronic sensors for monitoring of nonlinear surfaces

Andrey Petrochenko, Igor Konyakhin, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

With the advent of high-tech methods of construction of large-scale structures is impossible to disregard the problems associated with the safe operation of these facilities. In the problems of monitoring the state of the major construction projects survey is only possible with the use of different sensors, including optoelectronic. In turn, the data received from the tens and even hundreds of sensors to be processed in real time, to ensure an adequate level of safety in the operation of the facilities.

This article describes the design and implementation of software and hardware optoelectronic sensors system control of nonlinear deformations of surfaces such as roofs and facades of large-scale structures. Deformation of these objects is, as a rule, the nature of the deflection, the value of which must be checked regularly, especially during peak periods. The developed electro-optical sensor includes electro-optical converter and target point, consisting of three LEDs emit infrared.

Direction of the review and clearance of the measuring unit are opposite so that the reporting unit was the sighting target for opto-electronic converter subsequent block.

Determination of the spatial position of the measuring unit is divided into two main stages: determination of the spatial position of the point shooting (just the coordinates of the surface) and the angular position of the block in the space (the coordinates of the sighting purpose of the block).

During the investigation, mathematical model was developed opto-electronic system of sensors to monitor the deformation of nonlinear surfaces and confirmed the possibility of the technical implementation of this system, as well as program implementation of algorithms for identifying non-linear distortion surface, using the simplex method of calculating the spatial position of the intermediate points of the surface. The basis of this method uses an bundle adjustment algorithm for constructing a continuous surface. During the experiment the measurement error equal to 1 micron.

The data obtained in the course of the experiment showed that the developed algorithm can be applied to high-speed high-precision measurement of optical-electronic systems.

9506-87, Session PS

Method of simultaneous measurement of bending forces and temperature using Bragg gratings

Piotr A. Kisala, Politechnika Lubelska (Poland)

This paper presents the method of measuring two components of bending force and temperature. For this purpose, a station with a thermal chamber has been designed and a bracket used in further measurements on which Bragg gratings have been mounted. The performance of simultaneous measurements of force and temperature was possible through the use of an appropriate layout of the sensor. The method of indirect measurement was used, using information deriving from the spectrum of the Bragg grating, placed on the bracket. A universal measuring system scheme was proposed for measuring sizes measured in the form of force components, acting in two directions, perpendicular to the grating axis.

Spectral characteristics of the sensor's gratings do not retain full symmetry, which is due to the geometry of the sensor's bracket and the related difference in the distribution of axial stress of the gratings. For the purposes of the work, information on the width change of the standardised sum of transmission spectra was used to determine the value of applied force. In this situation, an increase in the sensitivity of this change on the force is obtained in relation to the system, in which only information on the width of the spectrum of one of the gratings would be used.

A change in the spectral width value was observed along with the increase in bending force from 0 to 50 N. The value of the sensitivity coefficient of spectral width on force, defined as the ratio of half-width changes to changes in force amounted to, respectively: for FBG1 2.6e-3 nm/N, while for the second grating 1.2e-3 nm/N. The sensitivity value of the whole sensor system amounted to 5.8e-3 nm/N, which is a greater value than the sum of the sensitivity of individual gratings.

The sensor used in the experiment can be treated as a module for development, through its multiplication on a single optical fibre. This way, the head of the sensor reaches larger physical sizes, in exchange enabling a measurement of force and temperature in n places, thus determine the distribution of force and temperature.

9506-88, Session PS

Investigating temperature effects on the spectral lines of blue laser diodes for monitoring NO2 gas pollution

Khaled Gasmi, Watheq Al-Basheer, Abdulaziz Aljalal, King Fahd Univ. of Petroleum and Minerals (Saudi Arabia)

Temperature effects on the spectral lines of two Fabry-Perot GaN-based blue laser diodes obtained from Toptica and Roithner Laser Tech are experimentally investigated over the temperature range 5 0C to 60 0C in steps of 0.5 0C. A high resolution monochromator SPEX 1403 with a nominal resolution of 0.003 nm is used in this study. A detailed comparison on the number of modes, mode spacing, emission range and change of emission wavelength per degree Celsius will be presented in this paper. The results of this comparison are used to investigate the suitability of the employment of these laser diodes in open-path detection of NO2 gas pollution.

9506-89, Session PS

Evolution of blue laser diode spectral lines with applied current in the range 446-448 nm

Watheq Al-Basheer, Abdulaziz Aljalal, Khaled Gasmi, King Fahd Univ. of Petroleum and Minerals (Saudi Arabia)

High resolution spectral lines study is performed on the emissions of a blue laser diode as a function of applied current. The range of applied current used is between the threshold current of 20 mA and 100 mA with a 0.2 mA increment. With this range of current, the observed emission spectra are between 446 and 448 nm. Typically, 21 longitudinal modes are observed with a mode spacing of 0.05 nm. This mode spacing is found to be in good agreement with the predicted values calculated using the GaN index of refraction and the length of laser cavity. The peak location of each longitudinal mode is measured to shift uniformly with a rate of 0.0045 nm/mA. The intensity and wavelength of each longitudinal mode are observed to be stable over extended period of time. Selected longitudinal modes will be employed to detect traces of pollution gases.

9506-90, Session PS

Active differential optical absorption spectroscopy for NO2 gas pollution using blue light emitting diodes

Abdulaziz Aljalal, Khaled Gasmi, Watheq Al-Basheer, King Fahd Univ. of Petroleum and Minerals (Saudi Arabia)

Availability of high intensity light emitting diodes in the blue region offer excellent opportunity for using them in active Differential Optical Absorption Spectroscopy (DOAS) to detect air pollution. Their smooth and relatively broad spectral emissions as well as their long life make them almost ideal light sources for active DOAS. In this study, we report the usage of a high-intensity blue light emitting diode in an active DOAS setup with an open path of 300 m to measure traces of NO2 gas and achieving few parts per billion detection limit. Details of the setup and its optimization will be presented along with a comparison of its performance with other DOAS setups using conventional light sources.

9506-91, Session PS

Volume holographic gratings as optical sensor for heavy metal in bathing waters

Gaetano Bianco, CGS S.p.A. (Italy); Maria Antonietta Ferrara, Istituto per la Microelettronica e Microsistemi (Italy); Fabio Borbone, Federica Zuppardi, Antonio Roviello, Univ. degli Studi di Napoli Federico II (Italy); Valerio Striano, Consorzio Antares S. c. a. r. l. (Italy); Giuseppe Coppola, Istituto per la Microelettronica e Microsistemi (Italy)

Robust, inexpensive, label-free, flexible sensors can be realized by holograms which can be engineered to be sensitive to a wide range of analytes [1].

Sensor holograms utilize the diffraction principle of transmitting volume holographic grating (VHG) recorded within a photopolymer appositely functionalized to detect a specific stimulus or analyte. Holographic sensors sensitive to a wide range of analytes, such as pH [2], alcohol [3], water [4], glucose [5], a variety of enzymes [6], bacterial cells [7] and physical stimuli have been designed.

In this work, a new photopolymer was used as sensitive material to record VHG. It was based on a sol-gel matrix opportunely functionalized and it was formed by condensation of alkoxysilanes functionalized with organic pendant groups and they are characterized by interpenetrating organic and inorganic networks. A photopolymer average thickness of about 30μm was deposited by using Doctor Blade method. The experimental set up used to record VHG was a typical Mach Zehnder interferometer. A laser source at 532 nm was used to modify photopolymers refractive index. A grating of 494 lines/mm was obtained.

A change in the swelling state or cross-linking density of the polymer can be caused by the interaction of an analyte with the hologram. This leads to a change in the recorded hologram.

It is well known that a VHG diffracts the incident beam only when the Bragg phase-matching condition is met. According to Kogelnik's two-wave coupled wave theory [8], the efficiency with which volume holograms can diffract incident light depends on the deviation from the Bragg condition, highlighting angular and wavelength dependencies.

Considering an incident white light, if the holographic sensor is subject to any physical or (bio)chemical mechanism that changes spacing of the fringes (?) or the average refractive index (n), changes in the wavelength (colour) of the transmitted hologram can be observed [1]. While, considering an incident monochromatic light, due to VHG angular selectivity, the changes in the holographic sensor caused by its interaction with a specific analyte can be observed by an angle shift of the diffracted maximum intensity.

In conclusion, we propose a photopolymer which allows the fabrication of high efficiency transmitting VHG sensitive to an opportune analyte. Therefore, a versatile sensor hologram can be recorded.

References:

[1] A. Kabilan, A.J. Marshall, A. Horgan, C.D. Creasey, S.J. Kew, K.E.S. Dean, S.F. Terrell, L.J. Affleck, NSTI-Nanotech 2006, www.nsti.org, ISBN 0-9767985-8-1 3, 467-470 (2006).

[2] A.J. Marshall, et al., Analytical Chemistry 75(17), 4423-4431 (2003).

[3] A.G. Mayes, et al., Analytical Chemistry 71(16), 3390-3396 (1999).

[4] J. Blyth, et al., Analytical Chemistry 68(7), 1089-1094 (1996).

[5] A. Domschke, S. Kabilan, R. Anand, M. Caines, D. Fetter, P. Griffith, K. James, N. Karangu, D. Smith, M. Vargas, J. Zeng, A. Hussain, X. Yang, J. Blyth, A. Mueller, P. Herbrechtsmeier, C.R. Lowe, 0-7803-8692-2/04/$20.00 IEEE, 1320-1323(2004).

[6] S. Kabilan, et al., Biosensors & Bioelectronics 20, 1602-1610 (2005).

[7] M.C. Lee, et al., Analytical Chemistry 76(19), 5748-5755 (2004).

[8] H. Kogelnik, Bell Sys. Tech. J. 48, 2909–2947 (1969).

9506-92, Session PS

Cable television monitoring system based on fiber laser and FBG sensor

Peng-Chun Peng, Jun-Han Huang, National Taipei Univ. of Technology (Taiwan); Shin-Shian Wu, National Chi Nan Univ. (Taiwan); Wei-Yuan Yang, Po-Tso Shen, National Taipei Univ. of Technology (Taiwan)

Optical fiber cable television (CATV) systems with low attenuation, light weight, and high flexibility characteristics are extensively deployed to provide broad bandwidths to subscribers. They can provide more channels than analog wireless television systems, and satisfy the demand for high video quality. When such an optical fiber cable television system has been installed, a real-time optical link monitoring system is crucial. Monitoring should be performed without affecting the delivery of the services to the subscribers. Furthermore, the monitoring system should preferably be implemented at the network node. In this work, we propose and experimentally demonstrate a cable television monitoring system based on a multiwavelength fiber laser and fiber Bragg grating (FBG) sensors. The multiwavelength fiber laser comprises a hybrid amplifier with an erbium-doped fiber amplifier and a semiconductor optical amplifier, a fiber loop mirror with a polarization controller and an optical coupler as a cavity mirror, a section of single mode fiber (SMF), and the fiber Bragg grating sensors acting as another cavity mirrors. In contrast to conventional schemes, the proposed system performs much better performances in the signal-to-noise ratio and power level. Experimental results showed the feasibility of the cable television monitoring system with a stable signal-to-noise ratio of over 30 dB and sufficiently high output power, and the link quality of the downstream signals can be

monitored in real time. The carrier-to-noise ratio (CNR), composite second-order (CSO), and composite triple beat (CTB) values in various cable television channels after 10 km of transmission are higher than the threshold value. Good performances of CNR, CSO, and CTB are obtained for cable television applications.

9506-93, Session PS

Fast correction algorithm for lens array distortion

Chao Li, Qian Chen, Mao Chen, Tian Man, Ajun Shao, Nanjing Univ. of Science and Technology (China)

The integral imaging (II) system, which was first proposed by Lippmann , has been widely developed and has attracted attention mostly because it uses incoherent light and provides a continuous viewpoint without any special glasses . In general, a single imaging lens is used to control the size, depth, and viewing angle of the reconstructed image in the II system . However, the II system with a single imaging lens also produces a distorted 3D image because the single imaging lens produces a distorted 3D image. There are many kinds of distortion due to some reasons such as manufacture installation and technics. Meanwhile, most algorithms in the field of computer vision (CV) are based on the ideal pinhole imaging model, so how to solve the distortion coefficient and correct the lens distortion is an important issue in the CV. Theoretically, there are three main types of distortion generally considered such as radial distortion, tangential distortion and thin lens distortion. Usually, thin lens distortion is relatively small, so we only consider radial and tangential distortion in our work.

There has been plenty of papers about lens distortion correction which can be divided into two types . The first one is based on lens calibration method in CV field, and the distinctive feature is that it combines the calibration of distortion coefficient and the calibration of lens interior and exterior parameters together. In this algorithm, the author usually established corresponding relation between feature points in world coordinate and 2D feature points in image coordinate, and calculate distortion coefficient and other lens parameters by nonlinear optimization. The accuracy is high but it needs a large number of feature points. The second one is based on uncalibrated lens which can be used to solve distortion coefficient according to the principle of perspective projection invariance.

In this paper, we put forward a new straight lines fast correction algorithm which is for distortion correction of uncalibrated lens array with unknown collinear feature points in world coordinate. Without known lens parameters and any world coordinates point in 3D space, the distortion parameters of lens array can be estimated based on the perspective projection invariant of straight lines. Also, we adopt automatically detecting chessboard corners and linear interconnected algorithm to improve the extracting accuracy.

9506-94, Session PS

Magneto-plasmonic nanomaterials for biosensing applications

Maria Grazia Manera, Istituto per la Microelettronica e Microsistemi (Italy); Pierpaolo Lupo, Franca Albertini, Consiglio Nazionale delle Ricerche (Italy); Cesar de Julián Fernández, Istituto dei Materiali per l'Elettronica ed il Magnetismo (Italy); Adriano Colombelli, Roberto Rella, Istituto per la Microelettronica e Microsistemi (Italy)

Surface Plasmon Resonance (SPR) is known as a leading technology for label-free biosensing [1]. It is based on the optical detection of refractive index changes occurring at a metal/dielectric interface upon a proper choice of the metal layer, its thickness as well as on the excitation light beam. Biological and chemical analysis are achieved by functionalizing the gold surface with surface bioreceptors and measuring the shift of corresponding optical signals when a biomolecular reaction occurs.

In this work a proper combination of metal and ferromagnetic materials tailored on the nanoscale is used as novel magneto-plasmonic transducer for biosensing applications. Such a combination of materials can produce a great enhancement of the magneto-optic (MO) effects when the Plasmon resonant condition is satisfied. The MO enhancement is strongly localized at the plasmon resonance and strongly depends on the refractive index of the dielectric medium [2,3].

This phenomenon is exploited in this work to demonstrate the possibility to use the enhanced MO signal as proper transducer signal for investigating biomolecular interactions in liquid phase. Small variations of the refractive index will induce large changes in the MO response, allowing using the proposed platform as novel transducer for optical biosensing .

A comparison between sensing performance of traditional SPR (Surface Plasmon Resonance) and magneto-optic SPR (MOSPR) transducing techniques is presented.

Proper combination of Au and Co metals materials tailored on the nanoscale are prepared on suitable glass substrates by physical techniques.

Functional characterization of the prepared transducers is carried out by recording refractive index changes of ethanol solutions in order to get relative calibration curves. Therefore, the realized transducers are properly functionalized by thiol chemistry and investigated for antigen-antibody interactions recording. The sensing performances in terms of sensitivity, limit of detection, specificity are taken into account. Finally, a comparison between of "standard" plasmonic detection techniques and the proposed magneto-plasmonic detection demonstrates a significant increase in the sensing performance of the investigated materials with respect to standard plasmonic transducers.

Higher sensing performance in terms of sensitivity and lower limit of detection of the MOSPR biosensor with respect to traditional SPR sensors is demonstrated.

[1] P. Schuck, Annu. Rev. Biophys. Biomol. Struct. 26, 541-566 (1997)

[2] González-Díaz, J. B., García-Martín, A., Armelles, G., García-Martín, J. M., Clavero, C., Cebollada, A., Lukaszew, R. A., Skuza, J. R., Kumah, D. P., Clarke, R., , Phys. Rev. B 76, 153402 (2007).

[3] Manera, M. G., Montagna, G., Ferreiro-Vila, E., Gonza?lez-García, L., Sa?nchez-Valencia, J. R., Gonza?lez-Elipe, A. R., Cebollada, A., Garcia-Martin, J. M., Garcia-Martin, A., Armelles, G., et al., J. Mater. Chem., 21, 16049?16056, (2011).

9506-95, Session PS

Forest of silica nanowires decorated with plasmonic nanoparticles for biosensing applications

Maria Grazia Manera, Adriano Colombelli, Annalisa Convertino, Antonietta Taurino, Roberto Rella, Istituto per la Microelettronica e Microsistemi (Italy)

Recently metal nanoparticles (NPs) have attracted a great interest because of their remarkable optical properties. Significant attention has been paid to the Localized Surface Plasmon Resonance modes that Au NPs are able to support when stimulated by incident light under specific conditions. Many efforts have been devoted to increase the sensitivity of traditional LSPR biosensors by forming highly ordered array of NPs, but these strategies often require a fine control of the fabricated structures and the use of very expensive fabrication techniques. In this work we follow a different approach, testing the sensing capabilities of a new and cheaper plasmonic material. We perform a numerical and experimental analysis of a highly disordered system of silica nanowires (NWs) decorated with Au NPs. These systems present unique light trapping properties due to the combination of the highly diffusivity of transparent silica NWs, with the selective absorption resonances given by Au NPs. A similar system represents an efficient and cheap approach to obtain a very dense metal NPs ensemble, easily accessible to biomolecules due to the micro-porous structure of the system.

9506-96, Session PS

Standard turn-around point and sol-gel coated long period fiber gratings as optical platforms for label-free biosensing: a comparative study

Francesco Chiavaioli, Istituto di Fisica Applicata Nello Carrara (Italy); Palas Biswas, Central Glass and Ceramic Research Institute (India); Cosimo Trono, Ambra Giannetti, Sara Tombelli, Istituto di Fisica Applicata Nello Carrara (Italy); Somnath Bandyopadhyay, Surnimal Jana, Susanta Bera, Aparajita Mallick, Central Glass and Ceramic Research Institute (India); Riccardo Falciai, Francesco Baldini, Istituto di Fisica Applicata Nello Carrara (Italy)

Long period fiber gratings (LPGs) have been proposed as label-free biosensors since a few years. LPGs are a growing, effective and alternative choice with respect to other label-free optical platforms, such as surface plasmon resonance, interferometric configurations, structures using different optical fibers and optical resonators. A chemical/biochemical interaction taking place along the grating portion induces a change in surrounding refractive index (RI), which yields a change in the transmission spectrum of the fiber. Different types of LPGs - standard, turn-around point (TAP) and sol-gel coated - were manufactured in order to assess the optical characteristics and thus to enhance the RI sensitivity of these devices. First, the proposed sensors were characterized as optical refractometer in order to provide an overview of the sensor performance in terms of volume RI sensitivity. Second, thanks to the use of a thermo-stabilized low-volume flow cell, which allowed to carry out long-term measurements not affected by temperature and/or strain fluctuations or drifts, it was possible to implement some immunoassays and to achieve a full calibration curve of the assays. The functionalization of the fiber surface was implemented using Eudragit L100 copolymer. After that, the IgG/anti-IgG immunoassays were completed in order to analyze the antigen/antibody interaction. Following the same model assay but using different LPG types, a comparative study of the biosensor performance was carried out. We experimentally demonstrated that the use of a high-order cladding mode implied not only an enhancement of the sensor as a refractometer measuring volume RI changes, but also an enhancement of the sensor performance as biosensor measuring surface RI changes. This was true in the case of both TAP and coated LPGs, with values of limit of detection (LOD) lower than 0.5 10-9M. Finally, in order to evaluate the real performance and feasibility of LPG-based biosensors, they were characterized using human serum as complex matrix for the first time with respect to what proposed in the literature concerning LPG-based biosensors. Besides accomplishing the feasibility of the used model assay, the achieved results demonstrated the goodness of the assay specificity.

9506-97, Session PS

Monte Carlo simulation for underwater propagation of a Gaussian beam

Jae-Ihn Kim, Hanwha Corp. (Korea, Republic of); Min-Sik Jo, Hyung-Rok Kim, Agency for Defense Development (Korea, Republic of)

We describe the radiative transfer of a Gaussian beam in water using the Monte Carlo technique offering basic propagation behaviors. The simulation shows in which manner the energy of the initial Gaussian beam is redistributed as it propagates in a turbid medium, and also depicts the dependence of the propagation behavior on the beam quality factor. In addition, the averaged diffuse attenuation coefficient is deduced. Our results may widen the applicability of LiDARs in Korea.

9506-98, Session PS

A novel 'Gold on Gold' biosensing scheme for an on-fiber immunoassay

Nirmal S. Punjabi, Indian Institute of Technology Bombay (India); Jitendra Satija, Vellore Institute of Technology (India); Soumyo Mukherji, Indian Institute of Technology Bombay (India)

Localized surface plasmon resonance (LSPR) based fiber-optic biosensors (FOB) are finding widespread applications now-a-days because of their inherent advantages like, ease of use, high sensitivity, ergonomic design,multiplexed sensing, etc. The performance of these plasmonic biosensors primarily depends upon the biosensor matrix, optoelectronic properties of plasmonic nanostructures, and the interactions between the analyte and bioreceptor molecules. Therefore, the selection of an appropriate bioassay is very crucial for designing of a LSPR based ultra-sensitive FOB. Significant amount of research is under-way to improve the performance of these FOB by coupling with various sensing technologies or by modifying the surface chemistry, etc. Among various detection schemes, absorbance based fiber-optic sensors have shown the potential for improving the sensitivity, along with its capability to provide a simple, field deployable, low cost diagnostic tool. In this paper, we propose a novel 'gold on gold' biosensing scheme for absorbance based FOB. In this assay, first a gold nanoparticle layer is formed at the sensing region of the fiber-optic probe by incubating an amino-silanized probe in a colloidal gold solution. Thereafter, the receptor antibodies, i.e. Human immunoglobulin G (HIgG) were immobilized by using standard alkanethiol based bioconjugation chemistry. Finally, biosensing was done for different concentrations of gold nanoparticle tagged analyte, i.e. Goat anti-Human immunoglobulin G (Au-GaHIgG). The sensor response was observed to be more than five-fold compared to the control bioassay, in which the sensor matrix was devoid of gold nanoparticle film. This increased sensor response in the newly developed plasmonic bioassay was due to a greater change in the effective refractive index (RI) of this antigen-antibody complex compared to the control assay, which in turn reduced the RI contrast between the fiber core and the cladding (formed by the antigen-antibody complex) in the sensing region. Consequently, this increased the penetration depth of the evanescent wave and thereby more absorption of the light was observed in the sensing region. This novel scheme also demonstrated the potential in improving the limit of detection for the fiber-optic immunoassays.

9506-36, Session 8

Raman fiber probes for biophotonics *(Invited Paper)*

Juergen Popp, Leibniz-Institut für Photonische Technologien e.V. (Germany)

Raman spectroscopy has matured to become one of the most powerful analytical methods in biophotonics i.e. for addressing biological / biomedical and life science problems. The advancement of Raman spectroscopy as an emerging biophotonic tool in recent years is based on steady improvements in instrumentation for excitation and collection, and in particular on the availability of fiber optic probes. The potential to couple the Raman system via optical fibers to the point of measurements has enabled many new applications to emerge. Here we briefly review and summarize some of our latest results concerning the development and application of compact on-site Raman sensing concepts for biophotonics, especially for medical applications and environmental sensing. We will start with introducing novel Raman fiber probes for in-vivo tissue screening to reliably diagnose and screen cancer and other diseases in internal organs like e.g. colon, stomach or aorta. Furthermore, we present novel miniaturized and highly sensitive Raman gas sensing approaches that allow for multi-gas analysis in high temporal resolution. Urgent issues for Raman gas sensing include in-situ characterization of variations in microbial gas transformation in the soil. Raman multi-gas sensing helps to monitor the composition and temporal and spatial variation of biogenic gases that result from the complex interdependencies of aboveground and belowground physical, chemical, and biological processes and for the built-up of a database for ecosystem analysis. Finally, we will present

concepts for fiber enhanced Raman spectroscopy for drug monitoring by utilizing innovative optical hollow core fibers allowing for a fast, sensitive and selective quantification of drugs in very small volumes. These fibers act as a miniaturized sample cell for analyte flow and Raman excitation light guiding improving the sensitivity required for the detection of low concentrated drugs.

Acknowledgments

Funding of our research from the BMBF (German Research Ministry), DFG, EU, EFRE, FCI and state of Thuringia (TMBWK and TMWAT) is highly acknowledged.

9506-37, Session 8

Optofluidic jet waveguide approach for Raman spectroscopy

Gianluca Persichetti, Genni Testa, Romeo Bernini, Istituto per il Rilevamento Elettromagnetico dell'Ambiente (Italy)

Among available methods for laser spectroscopy of liquids, Raman spectroscopy represents a very effective technique, due to its extreme selectivity. However, Raman scattering suffers from low detection sensitivity due to the weak cross section related to the phenomenon itself. In order to overcome this issue, in recent years, a great effort has been addressed towards the development of new solutions. In particular, optofluidic approaches offer promising results, providing innovative optical waveguides. However all the proposed optofluidic waveguides are surrounded by solid structure generating light scattering and autofluorescence affecting the device performances.

In the present work, a simple but effective solution is presented. The waveguide of this optofluidic sensor consists of a high speed liquid jet. A stable stream is produced by injecting the liquid solution under analysis into a capillary providing, at the same time, the waveguide used to deliver the Raman signal to be detected.

In this approach, the refractive indices of air and water determine a high potential in the collection efficiency of the waveguide, as the numerical aperture of a water jet is NA=0.88. Moreover, unlike different optofluidic waveguides, the smoothness of the stream avoids background noise coming from the scattering arising from the surface roughness or the possible autofluorescence due to the surrounding materials.

The waveguiding properties of a liquid jet has been already successfully exploited in fluorescence spectroscopy, providing high sensitivity detection also in this field of application.

By adopting a self-aligned configuration, the liquid waveguide is directly coupled to a multimodal optical waveguide connected to a spectrometer.

Two possible excitation approaches have been explored, each of them providing specific advantages. In order to exploit the maximum excitation volume, a probe consisting of two side by side optical fibers has been fabricated. One fiber is used to deliver laser excitation in the liquid and the other collects the Raman signal.

In order to minimize the mismatching between the jet diameter and the collection optical fiber size, a different excitation configuration has been adopted. A single optical fiber, with diameter close to the jet diameter size, has been used for Raman signal collection whereas an excitation laser sources has been directed impinging orthogonally to the liquid stream direction.

Experimental measurements has been performed on both of these setups considering ethanol-water solutions. The results attest very high sensitivity enhancement of our optofluidic sensor with respect bulk measurements providing limit of detections very competitive with respect literature results.

In order to test the potentiality of our sensor in water quality analysis and monitoring, additional measurements have performed on potassium nitrate solution showing the effectiveness of the proposed approach in Raman spectroscopy and opening new perspective in this field.

9506-38, Session 8

Discrimination and classification of acute lymphoblastic leukemia cells by Raman spectroscopy

Stefano Managò, National Research Council (Italy); Carmen Valente, Institute of Protein Biochemistry (Italy); Peppino Mirabelli, SDN, Istituto di Ricerca Diagnostica e Nucleare (Italy); Anna Chiara De Luca, Consiglio Nazionale delle Ricerche (Italy)

B-cell acute lymphoblastic leukemia (ALL) is a fast-growing cancer of lymphocytes (B cells) and the most common cancer in childhood. It accounts for 80% of leukemia and approximately 25% of all cancers diagnosed under age 14.

A firm diagnosis of hematological malignancies requires the identification and classification of leukemic cells. This is routinely achieved by morphological and immunophenotypic characterization of the cells sample from bone marrow or peripheral blood [1,2]. Anyway morphological approaches are, in some situations, of low sensitivity [3] and, it is currently impractical to perform a comprehensive, undirected molecular analysis of hematolymphoid malignancies owing to the myriad different genes involved [4].

Optical spectroscopy techniques are now widely used in the study of biomolecules and their functioning within live cells. Raman spectroscopy as one such technique is emerging as powerful tools to study the response of biosystems at single cell level because it is non-invasive, provides the intrinsic information of a cell and does not require any external labeling.

In Raman technology, a laser light of a certain wavelength shines on a sample, which causes molecules in the sample to vibrate and emit a Raman spectrum. From that spectrum, scientists can identify protein, lipid, and other chemical concentrations, as well as distinguish normal cells from cancerous ones [5,6].

In this work we demonstrate the use of Raman spectroscopy to identify normal B cells, collected from different healthy patients, and three ALL cell lines (RS4;11, REH and MN60). The cell lines RS4;11 and REH are two cellular model system derived from human immature B cell acute lymphoid leukemia and both models are classified as L2 in the FAB classification system. Conversely, the MN-60 cell line is more differentiated and, due to the surface expression of immunoglobulin and other B cell activation antigens, it is classified as FAB-L3. As all four cell types belong to the human B lymphoid lineage, they look very much alike. However, since they show different membrane protein expression and differentiation level they vary in their composition and therefore also in their Raman spectra. More precisely, we observed an increase in RNA and protein concentration and a decrease in cellular DNA concentration in leukemic compared to normal cells, due to an increase of transcription and replication and, consequently, de-condensation of the chromatin structure in cancer cells.

In order to quantify the capability of our system to sort leukemia/normal cells, we performed Principal Component Analysis (PCA) and a sorting accuracy of 97% for differentiating between three leukemia cell lines has been obtained.

References:

[1] J. M. Peters Arch Pathol Lab Med 135, 44-54 (2011)

[2] R. Di Noto, P. Mirabelli, L. Del Vecchio Leukemia 21, 4 (2007)

[3] J.W. Vardiman et al. Blood. 114, 937 (2009)

[4] K. Mrózek et al. Curr Opin Hematol. 16, 64 (2009)

[5]E. Canetta et all. J. Biomed. Opt. 16, 037002 (2011).

[6]P.R. Jess et al. Int J Cancer 121, 2723 (2007)

9506-39, Session 9

Hydrophilic upconversion nanoparticles for use in biosensing and bioimaging
(Invited Paper)

Otto S. Wolfbeis, Univ. Regensburg (Germany)

No Abstract Available

9506-40, Session 9

Fibre tip pH sensor for tumor detection during surgery

Matthew R. Henderson, Erik P. Schartner, David F. Callen, P. Grantley Gill, Tanya M. Monro, The Univ. of Adelaide (Australia)

Surgery on breast cancer now commonly involves a conservative surgery method, where a section of tissue containing the tumour is removed, to improve cosmetic outcomes and quality of life. Following surgery, the margins of the removed section are assessed pathologically to ensure that the entire tumour has been removed. Unfortunately, approximately 15-20% of margins show incomplete removal and require a subsequent operation to remove the remaining tumour. Tumour detection during surgery could allow the removed section to be enlarged appropriately, reducing the likelihood of requiring subsequent surgery.

It has been shown in the literature [1,2] that the extracellular pH in the vicinity of a tumour is lowered compared to that of normal tissue. While various methods exist to record tissue pH, to date it has been found to be difficult to measure the pH of small areas of tissue as would be required for the detection of tumour margins.

In this work we report on the fabrication of an optical fibre tip pH sensor, by photopolymerising acrylamide polymer [3], with an embedded pH-sensitive fluorophore, on the tip of a 200 micron silica fibre.

The fibre tip probe has a much smaller measurement area than standard commercial electrode pH meters (which are commonly larger than 10 mm). Only the fibre tip is modified and so it has the same size and flexibility of the base 200 micron silica fibre, which allows access into confined or otherwise difficult to access areas. The fluorescence signal from the pH-sensitive fluorophore is read out remotely from the unmodified end of the fibre section. Using a fibre-based system also allows multiplexing with other sensing techniques, such as biomarker detection or other spectroscopic methods. This method could also be modified for use with smaller diameter fibres to further reduce the sample size required for pH measurements to be performed.

In this work we demonstrate the use of these optical fibre probes on tissue samples, as the initial step towards a tumour-sensitive probe for use during surgery.

[1] Gerweck, L. E. Tumor pH: Implications for treatment and novel drug design, Seminars in Radiation Oncology, 1998, 8, 176 – 182.

[2] Gerweck, L. E. & Seetharaman, K. Cellular pH Gradient in Tumor versus Normal Tissue: Potential Exploitation for the Treatment of Cancer, Cancer Research, 1996, 56, 1194 – 1198.

[3] Song, A.; Parus, S. & Kopelman, R. High-Performance Fiber-Optic pH Microsensors for Practical Physiological Measurements Using a Dual-Emission Sensitive Dye, Analytical Chemistry, 1997, 69, 863 – 867.

9506-41, Session 9

Fiber-optic pH sensing system with microscopic spatial resolution

Ondrej Podrazky, Jan Mrázek, So?a Vytykácová, Jana Probostová, Ivan Kasík, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

The concentration of H+ ions expressed as pH plays an important role in many biological processes and its measurement at microscopic scale can be valuable for research in the fields of experimental botany, medicine, biotechnology, etc. The resolution at the level of individual cells and the possibility of real-time pH measurement can help to understand physiological processes in tissues of living organisms ranging from plants to human body.

Although the ph micro-electrodes are used for more than 40 years they suffer from fragility, need of reference electrode (and thus limited spatial resolution) and interference with EM field. The pH-optodes, on the other hand, have limited pH-range (typically 2-3 pH units), but they are firm, the referencing can be realized within the sensitive layer and they are insensitive to EM field.

A sensing system is presented for measurement of pH in the range from 5.5 to 7.5 with microscopic resolution (50 micrometers or less). Ion-paired 8-hydroxypyrene-1,3,6-trisulfonic acid trisodium salt (HPTS, pyranine) was used as an opto-chemical transducer and it was immobilized onto tips of tapered fiber-optic probes by sol-gel method. The principle of detection consists of excitation of the transducer alternatively by 405 nm and 450 nm laser light coupled to the fiber-optic probe while the fluorescence response is collected by the same probe in backward direction. Since the absorption band of the transducer shifts from approx. 400 to 450 nm with the increasing pH value, fluorescence intensities at approx. 515 nm for each excitation wavelength are measured and their ratio, which is proportional to pH, is calculated. The ratiometric approach allows compensation of temperature-induced effects, photobleaching, matrix swelling, etc.

The influence of optical fiber type, probe tip geometry and immobilization matrix composition to the sensor performance will be presented as well as some examples of in-vivo pH measurements.

9506-42, Session 9

Study of the grafting of dyes for the design of a pH optode

Mathias Fages, Denis M. G. Doizi, Guy Deniau, Commissariat à l'Énergie Atomique (France)

Nowadays, industrial processes need to be improved to match the challenges of the 21st century: optimization of resources, minimization of pollution, sustainable development ... One way to achieve these goals is to develop new analytical techniques performing in-line measurements in the heart of the process. The improvements brought by such techniques have multiple benefits, such as real-time control of the process. To meet these expectations, a patented process developed in the laboratory, GraftFastTM, is currently used to design a pH sensor.

A pH indicator is grafted on an optical fiber; this system is called an optode. Because the optical properties of the dye vary with the pH, the shifts of the absorbance spectrum of the dye can be linked to the actual pH of the medium, provided that this pH is within the field of measurement of the optode. Of course, different dyes will lead to different fields of measurement, and so the whole range of pH can be theoretically covered.

Such a device already exists, but, until today, the dye has been dropped off on the fiber using physical entrapment or electrostatic attraction. As a result, there have been long term stability issues concerning the desorption of the dye, provoking the drift of the strength of the optical signal over time and the contamination of the measuring medium.

Our approach to solve this problem is to covalently graft the dye on the fiber, which should increase the lifetime of the optode and prevent any contamination issues. The GraftFastTM process uses diazonium salts intermediates to provide this strong bond between the substrate and the dye. Moreover, it is a one-pot, simple and fast process, so it can be used to produce an effective low-cost optode.

Such an optode could have several fields of application, such as the control of processes, the control of the corrosion state of the concrete or environmental monitoring.

The main goal of our research work is to deposit a thin gold layer on a PMMA or a silica optical fiber of ten or so nanometers, so as to allow transmission properties of this layer, and then to covalently graft a dye on this layer. An interesting dye, the neutral red, has been studied during the first two years of this PhD work. Using GraftFastTM, it has been successfully grafted on our reference substrate, silica lamellas

covered with a thick gold layer, and the experimental conditions of the grafting have been optimized to maximize the thickness of the dye layer. An innovative experimental method to increase furthermore this thickness has also been developed. Another interesting pH indicator, rhodamin 560, is also currently being tested, as it would provide another field of measurement. A few prototypes of a thin gold layer of about 15 nanometers on a silica lamella have also been made, proving the feasibility of such an assembly while keeping transmissive properties of the whole system. The differences of the grafting of the dye on a thin or a thick gold layer are currently under study.

9506-43, Session 10

Localised hydrogen peroxide sensing for reproductive health

Malcolm S. Purdey, Erik P. Schartner, The Univ. of Adelaide (Australia) and ARC Ctr. of Excellence for Nanoscale BioPhotonics (Australia); Melanie L Sutton-McDowall, Lesley J Ritter, Robinson Research Institute, School of Paediatrics and Reproductive Health, The Univ. of Adelaide (Australia) and Institute for Photonics & Advanced Sensing, The University of Adelaide (Australia) and ARC Centre for Nanoscale BioPhotonics (Australia); Jeremy Thompson, The Univ. of Adelaide (Australia) and ARC Ctr. of Excellence for Nanoscale BioPhotonics (Australia); Tanya M. Monro, The Univ. of Adelaide (Australia) and ARC Ctr. of Excellence for Nanoscale BioPhotonics (Australia) and Univ. of South Australia (Australia); Andrew D. Abell, The Univ. of Adelaide (Australia) and ARC Ctr. of Excellence for Nanoscale BioPhotonics (Australia)

The production of reactive oxygen species (ROS) is known to affect the developmental competence of embryos. Hydrogen peroxide (H2O2) an important reactive oxygen species, is also known to causes DNA damage and defective sperm function. Current techniques require incubating a developing embryo with an organic fluorophore which is potentially hazardous for the embryo. What we need is a localised ROS sensor which does not require fluorophores in solution and hence will allow continuous monitoring of H2O2 production without adversely affect the development of the embryo. Here we report studies on such a fibre-based sensor for the detection of H2O2 that uses a surface-bound aryl boronate fluorophore carboxyperoxyfluor-1(CPF1). Optical fibres present a unique platform due to their desirable characteristics as dip sensors in biological solutions. Attempts to functionalise the fibre tips using polyelectrolyte layers and (3-aminopropyl)triethoxysilane (APTES) coatings resulted in a limited signal and poor fluorescent response to H2O2 due to a low tip surface density of the fluorophore. To increase the surface density, CPF1 was integrated into a polymer matrix formed on the fibre tip by a UV-catalysed polymerisation process of acrylamide onto a methacrylate silane layer. The polyacrylamide containing CPF1 gave a much higher surface density than previous surface attachment methods and the sensor was found to effectively detect H2O2. Using this method, biologically relevant concentrations of H2O2 were detected, enabling remote sensing studies into ROS releases from embryos throughout early development.

9506-44, Session 10

Cancer-cells on a chip for label-free optic detection of secreted molecules

Ophélie I. Berthuy, Loïc J. Blum, Christophe A. Marquette, Univ. Claude Bernard Lyon 1 (France)

To unravel cell complexity, living-cell chips have been developed that allow delivery of experimental stimuli but also measurement of the resulting cellular responses. We have been developing a new concept for multiplexed detection of biomolecules secreted by different cancer cells. In the present report, we are making the proof of concept of cells small populations spotting, culture and secretion detection on a gold surface (from 1 to 100 cells). For that purpose, antibodies and different cell lines were spotted using a piezoelectric spotter (sciFLEXARRAYER S1, SCIENION, Germany).

In order to keep the cells in a hydrated media during the robotized micropipetting and to address different cell lines on a single chip, a biocompatible alginate polymer was used. This approach enables the encapsulation of the cell in a very small volume (50 nL), directly on the substrate and permits a precise control of the number of cells in each alginate beads. After 24h culture, the adherent cells are ready for SPRi experimentation. To enable the detection of secreted proteins, various antibodies are immobilized in an organized manner on a SPRi sensor and permitted the multiplex detection of different proteins secreted by the different cultured cell lines.

Evidence of the real-time detection will be presented for Prostate Specific Antigen (PSA) and ?-2-microglobulin (B2M) secreted by prostate cancer cells following induction by dihydrotestosterone (DHT). Different kinetics for the two secreted proteins were then demonstrated and precisely determined using the chip.

There is no doubt that our chip will, in a near future, be applied to more multiplexed and complex biological secretion systems for which kinetic data are at the moment not reachable using standard cellular biology tools.

9506-45, Session 10

Studies of excitation of whispering gallery modes in a polymer coated silica cylindrical microresonator

Vishnu Kavungal, Qiang Wu, Gerald Farrell, Yuliya Semenova, Dublin Institute of Technology (Ireland)

Whispering gallery mode (WGM) microresonators (MRs) are attractive photonic devices due to their small mode field volume, narrow spectral linewidths and high Q-factors. Such MRs have been shown to have potential use in many areas, including studies of nonlinear optics, quantum electrodynamics and for low threshold micro lasers. One of the most promising applications of WGM MRs is in the area of optical sensing, where such resonators demonstrate a higher sensitivity than bulk fibre counterparts.

WGMs can be supported by a variety of resonator geometries, such as spheres, cylinders or disks and the choice of the particular resonator for a given application is usually influenced by three major factors: the achievable value of the Q-factor, the ease of fabrication and the ease of interconnection.

For cylindrical resonators based on a section of optical fibre there are a number of potential advantages that make such resonators worth exploring: (1) very simple fabrication process as optical fibers are highly uniform in diameter, allowing large numbers of identical resonators to be fabricated and providing a high degree of repeatability; (2) optical fibers can be easily manipulated and mounted, and (3) the alignment for optimal coupling of the excitation light into the fiber MR depends on only one angular degree of freedom, as opposed to two for experiments involving microspheres. As a result the optical setup for cylindrical fiber-based microresonator experiments is more straightforward.

Here we present the results of our studies of whispering gallery modes excited in a cylindrical MR formed by a short length of a standard single mode silica fiber with its existing PMMA coating intact with an overall diameter of 240 ?m.

The light coupling to the micro cylinder was achieved by a full fiber taper placed in close contact with the fiber microcylinder. Narrow WGM resonances are observed in the transmission spectrum of the fiber taper with a maximum Q factor of ~105. As a demonstration the structure has been used as a sensor for variations of surrounding temperature. Early experimental results indicate that the shape of the WGM spectrum remains largely unchanged with the increase of temperature. Blue shift of the WGM resonances in the order of 5 pm/0C is observed along with an increase in the extinction ratio of the resonances by ~2 dB when the temperature was increased from 20 to 550C.

Compared to a pure polymer fiber MR, the polymer coated silica fiber structure has better mechanical stability and hence more easy to handle

in the experiments. Since the overall silica cladding diameter of the fiber is only 125 ?m and the overall fiber diameter with the PMMA coating is 240 ?m, most of the WGMs are confined in PMMA coating. This indicates that the results of this study could be extended to a wider class of cylindrical MRs based on various materials, including plastic fibers, standard silica fibers coated with other functional polymer layers, for example for sensing of humidity, volatile organic components, etc.

9506-46, Session 10

Optical micro-bubble resonators as promising biosensors

Ambra Giannetti, Andrea Barucci, Simone Berneschi, Alessandro Cosci, Franco Cosi, Daniele Farnesi, Gualtiero Nunzi Conti, Istituto di Fisica Applicata Nello Carrara (Italy); Stefano Pelli, Istituto di Fisica Applicata Nello Carrara (Italy) and Ctr. Studi e Ricerche "E. Fermi" (Italy); Silvia Soria Huguet, Sara Tombelli, Cosimo Trono, Istituto di Fisica Applicata Nello Carrara (Italy); Giancarlo C. Righini, Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi (Italy) and Istituto di Fisica Applicata Nello Carrara (Italy); Francesco Baldini, Istituto di Fisica Applicata Nello Carrara (Italy)

Optical micro–bubble resonators (OMBRs) based on Whispering Gallery Modes (WGMs), with their small mode volumes (few hundreds of ?^3/n^3), high quality factor Q (comprised between 10^7 and 10^8) and long storage lifetime for the trapped photon inside the cavity, have gained an increasing interest in many fields of photonics. Generally, these micro-resonators are obtained starting from a micro-capillary by means of a particular fabrication process, which increases the radial dimension of the initial micro-tube along the axial direction. In our laboratories, we fabricated OMBRs by heating a slightly pressurized capillary with a rotating arc discharge. High quality factors Q (> 10^7) were obtained for these micro-cavities and their capability of working as refractometers was demonstrated. If compared with their bulk counterpart, such as optical microspheres, these hollow resonant microstructures present the advantage to combine the aforementioned WGM resonator properties with the intrinsic capability of integrated microfluidics. This feature makes them a suitable candidate for the development of highly sensitive label–free biosensors. Their operation is based on the fact that, given a small enough wall thickness of the bubble, the WGM optical field extends on both sides of the wall, so that it is possible to couple light into the resonator from an outer waveguide, and at the same time to have interaction of the WGM field with the inner fluid and analyte. Because WGMs are morphology-dependent modes, any change on the OMBR inner surface (due to chemical and/or biochemical binding) causes a shift of the resonances position and reduces the Q factor value of the cavity. By measuring this shift, it is possible to obtain information about the concentration of the analyte to be detected. A crucial step for the development of an OMBR-based biosensor is represented by the functionalization of its inner surface. In this work we report on the development of a physical and chemical process able to guarantee a good homogeneity of the so deposed bio-layer and, contemporary, to preserve a high quality factor Q for the cavity (> 10^5). The OMBR capability of working as bioassay was proved by different optical techniques, such as the real time measurement of the resonance broadening after each functionalization step and fluorescence microscopy.

9506-47, Session 10

Cell internalization of theranostic agents using polymethyl-methacrylate nanoparticles

Ambra Giannetti, Barbara Adinolfi, Istituto di Fisica Applicata Nello Carrara (Italy); Mario Pellegrino, Univ. di Pisa (Italy); Giovanna Sotgiu, Consiglio Nazionale delle Ricerche (Italy); Sara Tombelli, Cosimo Trono, Istituto di Fisica Applicata Nello Carrara (Italy); Greta Varchi, Istituto per la Sintesi Organica e la Fotoreattività (Italy); Francesco Baldini, Istituto di Fisica Applicata Nello Carrara (Italy)

Nanoparticle and nanomaterial technologies in the biomedical field are significantly impacting the development of both therapeutic and diagnostic (theranostic) agents. The use of an antisense oligonucleotide which acts as molecular beacon (MB) being able to generate a fluorescent signal when it hybridizes with the target mRNA, may represent an innovative strategy that conjugates the ability of sensing specific mRNA with the pharmacological silencing activity preventing the overexpression of proteins associated to pathologic conditions. This oligonucleotide optical switch constitutes then a theranostic agent, which is a highly promising and fascinating tool for simultaneous intracellular detection and silencing of specific mRNA molecules. In this paper, the mRNA specific for survivin was chosen as target: survivin is an intracellular protein belonging to the family of Inhibitors of Apoptosis Proteins (IAP), through which tumor cells can acquire resistance to apoptosis and its over-expression was demonstrated in different tumors of various localizations, such as breast, esophagus, pancreas, colon, stomach, and others.

Polymethyl-methacrylate (PMMA) nanoparticles (NPs) were used as nanocarriers to enter the cells and a complete optical characterization of the nanostructures used to internalize MBs was performed. PMMA NPs are intrinsically fluorescent, thanks to the presence of fluorescein entrapped within their core during their synthesis, in order to determine optically their localization.

Two different MBs for survivin mRNA were used, having at their extremities Atto647N (?abs 644 nm, ?em 669 nm) and Blackberry Quencher 650 (?max ~ 650 nm, useful absorbance between 550 and 750 nm) as fluorophore/quencher pair. They were characterized in vitro and their functionality was verified both in solution and after their immobilization onto the PMMA NPs. In particular, the sensitivity of the MBs was investigated by recording the fluorescence of the MB in different buffers and after incubation for different times with increasing concentrations of the target. PMMA NPs, and MB-adsorbed onto them were then tested on human lung carcinoma A549 cells and on human dermal fibroblasts (HDFa) as negative controls, in terms of cell vitality and internalization. These experiments provided clear evidence of the subcellular distribution of nanoparticles in living cells and of their ability to promote the MB internalization.

We have shown that oligonucleotide optical switches, together with NPs, can play a fundamental role in achieving quantitative information on intracellular events. The conducted analytical characterization demonstrated that they can be used not only as simple on-off elements but also as real sensors.

9506-48, Session 10

Adapting long gauge vibrofibre to measure fracking activities down well for successful oil and gas exploration and production

Peter Kung, QPS Photronics Inc. (Canada); Maria I. Comanici, McGill Univ. (Canada)

The long Gauge Vibrofibre, a newly developed distributed vibration sensor which involves terminating a long length of ordinary Telecom fiber of up to one kilometer with an in-fiber cavity structure, shows the entire structure can detect vibrations over a wide frequency range of 5 Hz to 2,000 Hz. The sensing fiber muse be packaged loosely in a 900 micron Teflon tube to protect the sensor. QPS has performed further experiment and adapt the sensing fiber to be a germanium free, pure core fiber and the terminating cavity on the same fiber type. The cavity is written with Femto second laser creating damaged gratings which works well up to 500 degrees C. If both sensing fiber and cavity involves polyimide fiber, the solution would be ready for down well application, where there is high temperature and pressure. Additional refinement was performed on the laser transmitter: first we optically locked the laser to reduce its line width and achieve longer coherent length. The sensing fiber can therefore

be extended to several kilometers. The performance of this new solution will not be affected by photo darkening due to hydrogen ingress; there is no germanium doping usually found in standard Telecom fiber for hydrogen to react, causing optical loss. The power of the laser can also be optimized to reduce detector saturation resulting in improved signal to noise. This new technology relies on analysis of the vibration spectrum to indicate production activities. The terminating cavity can be used to monitor the worst case temperature down the well. A simpler and lower cost version of the solution can be introduce to monitor the vibration of the wind turbine Generator, the gear box and the blade, the fiber simply becomes routed through all the critical components and record vibration signature giving diagnostic information. A firmware program residing inside the intelligent controller tracks the operating point on the selected interference fringe and provides a counter measure in the form of TEC current and laser drive to keep the laser locked . The added laser current is an indirect measurement of the environmental temperature change. For example in a large industrial Motor the termination cavity can measure the working temperature of the working Motor while the specially designed routing of the sensing fiber can be used to capture the vibration signature of the critical component in the motor driven process.

The process of vibration and temperature becomes a time shared process. The long Gauge technology performs best by disabling dithering of the transmitting laser; a procedure to broaden the line width of the laser and reduce the interference effect . Dithering must be restored during temperature measurement, Temperature change is a slow process and produces disturbance very similar to cable noise, dithering suppresses the cable noise and make the temperature measurement more accurate. Long Gauge sensor spectrum has been benchmarked with a large Motor equipped with multiple piezoelectric vibration sensors proving the ability to capture many channel measurement with a single fiber.

9506-49, Session 10

Solid-surface fluorescence of polycyclic aromatic hydrocarbons on polysaccharide fiber matrices

Svetlana M. Rogacheva, Anna V. Strashko, Tamara I. Gubina, Yuri Gagarin State Technical Univ. of Saratov (Russian Federation); Anna Shipovskaya, Yuri Gagarin State Technical Univ. of Saratov (Russian Federation) and N.G. Chernyshevsky Saratov State Univ. (Russian Federation); Elena V. Volkova, Andrey G. Melnikov, Yuri Gagarin State Technical Univ. of Saratov (Russian Federation)

Solid-surface fluorescence (SSF) is a modern method which combines solid phase extraction with high sensitive luminescence determination in solid-sorbent phase. The method is successfully applied for trace quantification of various organic and inorganic compounds such as polycyclic aromatic hydrocarbons (PAHs), medicines and metals in different media. There are different solid materials which are suitable for SSF applications. silica gel, zeolite, foamed polyurethane, cellulose, are among them. Polysaccharide materials cellulose diacetate (CDA) and chitosan (CTS) are also promising matrices.

The purpose of present research was to determine the possibility of pyrene (a model compound in studies on PAHs) sorption on the surface of CDA and CTS fibrous matrices and their further application for SSF measurements.

In experiments we used ethanol and aqueous micellar solutions with pyrene concentration 2•10-5 M. The latter were prepared by using sodium dodecyl sulfate (SDS), cetyltrimethylammonium bromide (CTAB) and polyoxyethylene(10)mono-4-isooctylphenyl ether (TX-100). The concentration of surfactant solutions was 10-2 M.

The sorption of fluorescent probes was performed in dynamic mode. The fluorescence spectra of pyrene in solution and in an adsorbed state on solid matrices were recorded using LS 55 fluorescent spectrometer from Perkin-Elmer (USA). The fluorescence of pyrene was measured within the spectral range 350–450 nm. The excitation radiation wavelength was 320 nm.

It was determined that the sorption of pyrene from its ethanolic solution on the fibers proceeds weakly. But after sorption on the CDA fibers the pyrene signal intensity increased. Its signal on both types of CTS fibers is almost zero.

When using aqueous micellar solutions of pyrene the maximum intensity of fluorescence was observed in the presence of CTAB, the lowest one in the case of SDS at the same concentration of pyrene in the medium. This gives evidence of the highest concentration of pyrene in the micelles of the cationic surfactant.

From the changes in the signal intensity after sorption and the values of the extraction degree of pyrene we concluded that the CDA fibers had a greater sorption capacity than the CTS ones. Pyrene sorption on the CDA fibers proceeded better from the aqueous micellar media with TX-100 (the extraction degree was 82.9%). When the CTS fiber was used, the maximum extraction degrees of pyrene (74.2%, 72.1%) were observed for the TX-100 solution as well.

It was established that pyrene signal was greatly enhanced in the adsorbed state on CDA. It was much higher than the signal in solution, probably, due to concentration of pyrene molecules at the surface of the CDA fibers in a micellar layer. There was no pyrene signal on the CTS fibers of the both forms, in spite of the high extraction degree of the probe in the medium with TX-100. It may be explained by probe penetration into the pores of CTS fibrous material and fluorescence quenching.

These results can be used in the design of chemical sensors for PAHs detection.

The results of this work were obtained in the framework of the state task No 4.1299.2014/K of the Russian Ministry of Education and Science.

Conference 9507: Micro-structured and Specialty Optical Fibres

Wednesday - Thursday 15–16 April 2015

Part of Proceedings of SPIE Vol. 9507 Micro-structured and Specialty Optical Fibres IV

9507-1, Session 1

Chalcogenide glass fiber for mid-infrared sensing: state of the art and recent achievements *(Invited Paper)*

Bruno Bureau, Johann Troles, Catherine Boussard-Plédel, Virginie Nazabal, Univ. de Rennes 1 (France); Laurent Brilland, PERFOS (France); Jacques Lucas, Jean Luc Adam, Univ. de Rennes 1 (France)

The glass-forming ability of chalcogens elements has been known for several decades but, compared to oxide glasses, especially silicates, this class of vitreous materials is just emerging in particular in order to shape optical fibers. The main attention paid to these materials relies on their large optical window extending in the mid-infrared giving access to molecular fundamental vibrational modes shifted far in the IR. This exceptional transparency, associated with suitable viscosity/temperature dependence is a favorable context to seize the opportunity to develop innovative optical fibers for mid-infrared sensing. Different kind of optical fibers were designed during the past decades including tapered fibers, doped optical fibers, single mode fibers and microstructured fibers, depending on the targeted applications. Indeed, the optical sensors operating in the mid IR region, where are located the main signatures of molecules and biomolecules, are playing an important role in the development of analytical techniques giving in-situ information on metabolic patterns. Such chalcogenide glass fibers are efficient and easy way to record such infrared spectral data that enable in situ and real time studies with no sampling. Numerous pioneer works have been carried out in different domains of application, such as: pollutant in waste water, fermentation process, bacterial contamination in food, bacterial biofilm spreading, identification of tumoral tissues and of biological liquid in biology and medicine (collaboration with the public Hospital), CO2 detection to strike against the global warming or detection of exo-planet with the European Space agency, for examples.

The talk will be devoted to the description of the last achievements in the field following three main strategies. First the extension of the transmission of the fibers by working on new telluride glasses, second the development of rare earth doped optical fibers serving both as remote sources and sensing devices, and third the shaping of sophisticated microstructured fibers to detect gaseous species or generated supercontinuum in the mid-infrared.

9507-2, Session 1

Special optical fibers doped with nanocrystalline holmium-yttrium titanates (HoxY1-x)2Ti2O7 for fiber-lasers

Jan Mrázek, Ivan Kasík, Jan Bohacek, Jana Probostova, Jan Aubrecht, Pavel Honzátko, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Ondrej Podrazky, Jakub Cajzl, Institute of Photonics and Electronics ASCR (Czech Republic)

Nanocrystalline rare-earth doped yttrium titanates, which crystallize in a pyrochlore structure with general formula (RExY1-x)2Ti2O7 (RE=rare-earth element), have been widely investigated in recent years for their interesting luminescence properties. Comparing to the yttrium-free rare-earth titanates with the general formula RE2Ti2O7, which are mainly optically inactive, the presence of yttrium ions in the pyrochlore structure enormously improves the luminescence properties of contained rare earth elements. Holmium belongs to the elements widely used in the construction of novel high-power lasers and amplifiers operating around 2 ?m. This spectral region is a part of so called “eye safe” wavelength region. An absorption of eye tissue is minimal in this spectral region thus a risk of eye damages inflicted by a laser beam is significantly reduced. Such advantage makes (HoxY1-x)2Ti2O7 the progressive material for novel optical amplifiers and high power fiber-lasers.

In this contribution we present a route to active optical fibers doped by (HoxY1-x)2Ti2O7. Nanocrystalline (HoxY1-x)2Ti2O7 pyrochlores were prepared by sol-gel method providing colloidal solutions, bulk powders and thin films. Structural and optical properties of prepared materials were determined. Nanocrystals with optimal optical properties were incorporated into porous silica frit deposed by MCVD technique into a substrate silica tube which was processed into a preform. Prepared preform was drawn into an optical fiber. Optical and waveguiding properties of the fiber were determined and the fiber was tested as an active medium in a fiber laser.

The presented approach led to the formation of homogenous nanocrystalline (HoxY1-x)2Ti2O7 powders and thin films with tailored grain sizes ranging from 10 nm to 200 nm. Optimal concentration of Ho3+ ions in the pyrochlore lattice was reached for x=0.03. Prepared nanocrystals were successfully incorporated into a core of active optical fiber. Numerical aperture of prepared fiber was around 0.15. All prepared samples provided an intensive emission at 2,2 ?m under an excitation at 450 nm.

The results present fundamental information about processing of nanocrystalline (HoxY1-x)2Ti2O7 bulk powders and thin film during the preparation of active optical fibers. The promising application of prepared nanocrystals in the field of lasers and planar optical amplifiers is widely discussed in the contribution. Optical properties of prepared active optical fibers were compared to the properties of pure nanocrystalline (HoxY1-x)2Ti2O7.

Acknowledgement

This work was financially supported by the project M100671202 of the Grant Agency of Academy of Sciences.

9507-3, Session 1

Spectral broadening in low OH content and dispersion-managed tellurite fiber for compact mid-IR sources

Clement Strutynski, Jeremy Picot-Clemente, Foued Amrani, Oussama Mouawad, Frederic Désévédavy, Jean-Charles Jules, Gregory Gadret, Bertrand Kibler, Lab. Interdisciplinaire Carnot de Bourgogne (France); Dinghuan Deng, Tonglei Cheng, Yasutake Ohishi, Toyota Technological Institute (Japan); Frédéric Smektala, Lab. Interdisciplinaire Carnot de Bourgogne (France)

Interests in Mid Infrared optical technology increasingly grew during the last decade. This scientific topic has a strong applicative potential in different domains, such as health, telecommunications, spectroscopy, defense and many others. Providing reliable, stable and compact light sources that cover a broad spectral bandwidth is part of the main research axes. This spectral enlargement can be achieved through the phenomenon of Super Continuum Generation (SCG) that occurs, amongst others, in microstructured optical fibers (MOF). For this purpose, a large variety of glass families were investigated these past years. Among them, we focussed on tellurite based glasses for the fabrication of our waveguides. This vitreous material, well known for its nonlinear optical properties as well as its wide transparency window from visible up to 6µm, is a good candidate for the manufacturing of Mid-IR optical systems. Nevertheless, the hydroxyl absorptions prevent its use beyond 2.8µm for optical fibers, and therefore retrains spectral broadening further in the IR.

In this work, we report the efforts made to reduce water absorption in our TeO2 based glass systems. Different purification processes were explored

such as the dehydration of the raw materials and the melted glass, as well as the use of controled atmosphere during the fabrication. In the end, our protocol allowed to reduce the OH compounds concentration under 1ppm (mass) in our tellurite material, thus leading to an attenuation level as low as 10 dB/m at 3.4μm in our optical fibers.

With this extension of our waveguide's efficiency range, a successful SC spreading up to 4000nm in a TeO2-ZnO-ZnF2-Na2O microstructured fiber (MOF) was achieved. An optical parametric oscillator seeds with Ti-sapphire laser was used as light source generating 200fs pulses with 10kW peak power at a repetition rate of 76MHz at pump wavelength around 2μm. This wavelength, where commercial compact sources exist, matches with the managed zero dispersion wavelength (ZDW) of the MOF designed for these experiments. Moreover, taperization of the fiber allowed the supercontinuum to reach the visible wavelengths.

9507-4, Session 1

Silica optical fibers with high oxygen excess in the core: a new type of radiation-resistant fiber

Pavel F. Kashaykin, Fiber Optics Research Ctr. (Russian Federation) and Ogarev Mordovia State Univ. (Russian Federation); Aleksander L. Tomashuk, Fiber Optics Research Ctr. (Russian Federation) and Ulyanovsk State Univ. (Russian Federation); Mikhail Y. Salgansky, Institute of Chemistry of High-Purity Substances of the Russian Academy of Sciences (Russian Federation); Alexey N. Abramov, Institute of Chemistry of High-Purity Substances of the Russian Academy of Sciences (Russian Federation) and N.I. Lobachevsky State Univ. of Nizhni Novgorod (Russian Federation); Lyudmila D. Iskhakova, Fiber Optic Research Center (Russian Federation); Nikolay S. Lobanov, National Research Centre "Kurchatov Institute" (Russian Federation); Konstantin N. Nishchev, Ogarev Mordovia State Univ. (Russian Federation); Alexey N. Gurynov, Institute of Chemistry of High-Purity Substances of the Russian Academy of Sciences (Russian Federation); Eugeny M. Dianov, Fiber Optics Research Ctr. (Russian Federation)

Nuclear industry, space, military applications, etc. require special radiation-resistant optical fibers in which radiation-induced attenuation (RIA) of the propagating light would be minimized. Until recently, F-doped-silica-core fibers ("F-doped fibers") were believed to be undeniably the most radiation-resistant fiber type for applications in the optical communication spectral windows in the near-IR range (?~1.3-1.55 μm). However, newly developed undoped-silica-core fibers, of which the perform core is synthesized in high O2 excess (HOE) conditions in the vapor-gas mixture ("HOE-fibers"), also proved to be promising and to have a potential advantage over the F-doped fibers. This Report is devoted to the HOE-fibers and their comparison with the F-doped fibers.

The radiation-induced color centers (RICC) that can cause RIA in the optical communication spectral windows have been found to be the same for both HOE- and F-doped fibers: a Cl-associated RICC – Cl(0)-center – and two types of self-trapped holes (STH1 and STH2). The RIA due to the Cl(0)-center peaks in the UV-range, the RIA due to STH1 at long wavelengths in the near-IR range (? > 1.8 μm), and the RIA due to STH2 in the visible range. As this takes place, the optical communication spectral windows are affected by the intense band tails of these RIA.

The Cl(0)-center has been found to be virtually fully suppressed in both the fiber types. This is so because chlorine incorporation into silica during preform fabrication is eliminated (in F-doped fiber preforms by the presence of F-containing reagents in the vapor-gas mixture, in HOE-fiber preforms by the presence of excess O2 molecules).

The STH2 precursors are known to be deformed SiO4 tetrahedrons; therefore, the more strained is the silica network, the higher will the STH2 concentration be under radiation. In F-doped fibers, fluorine atoms prevent the formation of strained few-member rings in the silica network thereby reducing the STH2 concentration. In HOE-fibers, strain and its consequent STH2 are suppressed by a large concentration of peroxy linkages, because the latter increase the ring member numbers of the silica network.

The last RICC – STH1 – is not suppressed in the F-doped fibers, but, for so far unknown physical reason, is suppressed in the HOE-fibers. It is this fact that makes the HOE-fibers more promising than the F-doped fibers.

In the Report, we will show that strain and its consequent RIA in the HOE-fibers strongly depend on the fiber drawing tension and on how close are the core and cladding glass transition temperatures Tg to each other. To minimize RIA, the drawing tension should be reduced to as low as possible, whereas Tg should be equalized by accurate matching of the O2 excess extent in the core to the F-content in the cladding. RIA at ?=1.55 μm in HOE-fibers optimized in this way will be argued to become lower than that in the commercial F-doped fibers. We will also present a direct experimental comparison in which HOE-fibers are tested under ?-radiation in identical conditions with a commercial radiation-resistant fiber to exhibit many times lower RIA than the latter.

9507-5, Session 1

Hollow core negative curvature fiber with layers of photoaligned optically anisotropic material

Denis Bogdanovich, Irkutsk State Technical Univ. (Russian Federation); Abhishek K. Srivastava, Hong Kong Univ. of Science and Technology (Hong Kong, China); Andrey D. Pryamikov, Fiber Optics Research Ctr. (Russian Federation); Alexander S. Biryukov, A. M. Prokhorov General Physics Institute (Russian Federation); Vladimir G. Chigrinov, Hong Kong Univ. of Science and Technology (Hong Kong, China)

Over the last decade microstructured optical fibers containing different anisotropic materials have been intensively developed. These fibers due to their design and high sensitivity of anisotropic materials to external influences, such as electric and magnetic fields, pressure, and temperature allow to control their optical properties.

In this paper we present microstructured hollow core negative curvature fiber layered with optically anisotropic material that is sensitive to external linearly polarized UV radiation.

Microstructured hollow core negative curvature fibers have a relatively simple structure and being made of pure silica glass are able to localize the light within the range of 1 to 10 microns with the loss of approximately 50 dB / km.

To effectively adjust optical properties of the fibre, it is necessary that either the inner surface of the cladding capillaries or the core boundaries be layered with material that can change its properties under external influence.

We calculated the spectrum for HC05-70 fiber made of pure silica glass with core diameter 15.6 mkm, number of capillaries 8, capillary wall thickness 0.7 mkm and gap between the capillaries 2 mkm, and with added layers of SD1 azo dye on its inner surface of cladding capillaries in the isotropic state. The presence of additional layers in the fiber structure leads to a shift of the photonic bandgaps position, without altering their shape or increasing the level of optical losses. The shift in the position of photonic band gaps for fibers with layers of SD1 azo dye of 25 nm and 50 nm thicknesses, compared with hollow fibre, was 30 nm and 45 nm respectively. In order to achieve optical anisotropy, SD1 azo dye molecules can be aligned by being exposed to linearly polarized UV radiation.

We used HC05-70 fiber to fabricate two samples of 4.5 cm each; one of them had SD1 azo dye layers on the inner surface of cladding capillaries, while the other had SD1 azo dye layers on the core-cladding boundary. There was a shift in the position of photonic bandgaps. From the comparison with the calculated spectrum for the fiber structure containing SD1 azo dye layers in the isotropic state on the inner surface of the capillaries, it followed that the thickness of the created layers was several nanometers.

The sample with SD1 azo dye layer on the core boundary was studied

for linearly polarized light propagation: a) with SD 1 azo dye layer in the isotropic state; b) with azo-dye layer molecules aligned by linearly polarized UV radiation along and across the fiber axis. It was detected that depending on the rotation angle of polarized light plane, a change of amplitude and shift of band gap center occurred. A greater spectrum shift was exhibited by the structure with SD1azo dye molecules that were perpendicular to the fiber axis.

The proposed optical fiber can be used as an active component of all-fiber devices such as high-power fiber lasers, polarization controllers and polarization filters, dispersion compensators, and fiber sensors.

9507-6, Session 1

Low-bending loss square-core optical fiber for optical communication

P. F. Liu, Jiun-Yu Sung, Chi-Wai Chow, National Chiao Tung Univ. (Taiwan); Chien-Hung Yeh, Feng Chia Univ. (Taiwan); Gary Chou, Prime Optical Fiber Corp. (Taiwan); Ci-Ling Pan, National Tsing Hua Univ. (Taiwan)

In order to provide higher bandwidth to end-users, network operators are placing the optical fiber closer and closer to the user sides. Different fiber-to-the-x (FTTx) technologies have been proposed, such as fiber-to-the-building (FTTB), fiber-to-the-home (FTTH) and even fiber-to-the-desk (FTTD). Due to the low cost, low transmission loss and wide bandwidth, optical fibers are replacing the copper cables in home networks and data center networks. When optical fibers are deployed in home networks and data center networks, bending loss becomes an important issue. It is highly desirable that these optical fibers can be handled like typical electrical cables. Recently, researchers have proposed and demonstrated several schemes to decrease the bending loss of optical single-mode fiber (SMF), such as using depressed cladding, trench assisted, ring assisted and hole assisted schemes. However, these schemes require to carefully tailor-made the refractive index profile of the fiber.

In this work, we propose and demonstrate a novel square-core SMF for transmission. Although square-core fiber has been proposed recently, they are used for high optical power delivery in industrial processing tools with core size larger than 400um x 400um. In here, we reduce the square-core size to 10um x 10um, and we propose a high bandwidth-distance product square-core SMF for optical communication. With the geometrical similarity to the square waveguides in photonic integrated circuits (PICs), the square-core SMF could provide lower coupling loss. The square-core SMF is fabricated using the same fiber drawing tower as conventional standard SMF. In square-core SMF fabrication, it first starts with a square preform (silica rod) before fiber drawing. It is produced by milling the cladding portion of a circular perform forming a square perform. Although the cross-section of the cladding is square shape, the core shape is still circular. Then in the fiber drawing process, by proper controlling the drawing speed and temperature, the surface tension will make the cladding turn into circular shape; and the fiber core will change from circular shape to almost square shape. Owing to a higher optical confinement factor of the square-core SMF, the bending-loss experiment results show that the square-core SMF has ~ 3 dB power improvement when compared with the standard SMF. A 10-Gb/s on-off keying (OOK) transmission experiments using the 200m, 500m and 1km square-core SMF are performed. Negligible power penalty between square-core SMF and standard SMF is observed. We believe that our proposed square-core SMF can be a potential candidate for future home network with lower bending loss and simpler manufacturing process.

9507-7, Session 2

Highly nonlinear chalcogenide suspended-core fibers for applications in the mid-infrared *(Invited Paper)*

Enrico Coscelli, Federica Poli, Univ. degli Studi di Parma (Italy); Jianfeng Li, Aston Univ. (United Kingdom); Annamaria Cucinotta, Stefano Selleri, Univ. degli Studi di Parma (Italy)

Recently, non-silica glass fibers have attracted great attention because of their potential applications in telecom such as signal regeneration, wavelength conversion in the infrared and mid-infrared (IR) supercontinuum (SC) generation. In particular, chalcogenide glasses, based on a mixture of chalcogen elements such as sulphur, selenium and tellurium with other elements such as arsenic, germanium, antimony and gallium, have been investigated, thanks to their superior nonlinear characteristics with respect to silica and to their transparency window extending to the mid-IR. Nonlinear coefficient two to three orders of magnitude larger than silica one has been measured in chalcogenide glass. The higher refractive index of these glasses leads to longer material Zero-Dispersion Wavelength (ZDW), which is detrimental for applications in the mid-infrared, since the large normal group-velocity dispersion at telecom wavelengths significantly distorts short pulses and does not allow anomalous dispersion pumping for SC generation. As a consequence, waveguides and fibers with a properly tailored dispersion profile need to be developed to fully exploit the potential of chalcogenide glasses. To this aim, Suspended-Core Fibers (SCFs), whose cross-section is characterized by a few micrometer-sized core suspended between large air-holes by a few small glass struts, are an excellent candidate, due to their large NA, tight mode confinement and strong waveguide dispersion.

In this contribution, the effects on the chromatic dispersion and nonlinear properties of the structural parameters of chalcogenide SCFs are taken into account to provide guidelines for the design of nonlinear fibers with ZDWs matching with specific sources in the 1.5 ?m – 2.5 ?m range. Numerical simulations have been carried out in the range between 1 ?m and 3.5 ?m with a full-vector modal solver based on the finite-element method, to assess the effects of glass composition, core diameter and, for the first time, of number and width of the glass struts which sustain the core. The simulation results have shown that, for a given glass composition, the effects of the number and size of the glass struts on the dispersion properties are relevant if core diameter is smaller than 2 ?m, which is the range most suitable to enhance nonlinear effects, and can be successfully exploited to provide tailored dispersion characteristics. For instace, if As_2S_3 glass is used as the bulk material, it is possible to obtain two ZDWs: one at a shorter wavelength, depending mainly on the core size, located between 1.5 ?m and 2.0 ?m, and a second one at a longer wavelength, which can be tuned over about 700 nm by acting on the strut thickness. Furthermore, nonlinear coefficient as high as 9000 1/(W km) and dispersion close to zero have been obtained at 2 ?m with As_2S_3 SCF, which are excellent characteristics for SC generation exploiting Tm-doped fibers as pump source. At presentation time, comprehensive results taking into account all the structural parameters will be shown, demonstrating the versatility of chalcogenide SCFs and the possibility to adapt their design to nonlinear applications over a wide spectrum of wavelengths in near- and mid-IR.

9507-8, Session 2

Microfluidic flows and heat transfer and their influence upon optical modes in microstructure fibres

Edward M. Davies, Imperial College London (United Kingdom); Paul Christodoulides, George Florides, Kyriacos Kalli, Cyprus Univ. of Technology (Cyprus)

No Abstract Available

9507-9, Session 2

Large mode area aperiodic fiber designs for robust singlemode emission under high thermal load

Romain Dauliat, Leibniz-Institut für Photonische Technologien e.V. (Germany) and XLIM Institut de Recherche (France); Enrico Coscelli, Federica Poli, Univ. degli Studi di Parma (Italy); Aurélien Benoît, XLIM Institut de Recherche (France) and EOLITE Systems (France); Dia Darwich, Raphaël Jamier, XLIM Institut de Recherche (France); Kay Schuster, Stephan Grimm, Leibniz-Institut für Photonische Technologien e.V. (Germany); Annamaria Cucinotta, Stefano Selleri, Univ. degli Studi di Parma (Italy); François Salin, EOLITE Systems (France); Philippe Roy, XLIM Institut de Recherche (France)

For two decades now, fiber lasers have been subject to a perpetually revived effervescence for power scaling driven by their versatility, rendering them appropriate for a wide range of applications. As a consequence, a tremendous ascent in emitted power has been performed by resorting to Yb-doped fibers. This led to attain up to 10 kW in CW [Stiles2009] or GW peak power in femtosecond pulses regime [Hadrich2013]. Unfortunately, fiber designers must deal with two major limitations emerging in fiber architectures used commonly in the high power regime: i/~the photodarkening [Koponen2008], implying a significant increase of the background losses, and reducing the laser efficiency and ii/~the thermal induced modal instabilities [Jauregui2012c], strongly degrading the spatial mode quality when the output average power exceeds a certain threshold. While the first phenomenon can be efficiently mitigated by adjusting the material composition of the active core [Jetschke2008], modal instabilities, which result from the heat load of the gain medium, depend on both the laser architecture and the ability of the fiber structure to discriminate High-Order-Modes (HOMs).

In order to overcome the limitation imposed by modal instabilities on a robust singlemode emission in high power/energy regime, several works have been achieved on rod-type double-cladding Photonic Crystal Fibers (PCFs) [Limpert2005], joining together the advantages of optical fibers and rod crystals, and providing effective mechanisms for HOM suppression. Among the most relevant approaches, one can easily identify many very large mode area fiber geometries belonging to the class of leaky structures [Dong2009b,Limpert2012,Coscelli2014,Dauliat2014]. These fibers take benefit of the inherent larger shrinking of the unwanted HOMs to perform an efficient mode filtering while ensuring a strong interaction of the fundamental Gaussian mode with the gain region. They also offer some flexibility in devising tailored fiber structures since it has been theoretically emphasized that the widespread hexagonal photonic crystal cladding structuration is not strictly required. Indeed, pentagonally structured cladding [Stutzki2011a] as well as aperiodic cladding array provide higher levels of HOMs delocalization [Benoit2014b]. The absence of cladding symmetry shuns the resonance of HOMs on the cladding and dodges partially the mode coupling by minimizing the spatial overlap between the core fundamental mode and the cladding modes.

Based on a careful consideration of the degrees of freedom offered all along the fiber fabrication, we investigate the potential of three different VLMA fibers under heat load: symmetry-reduced air-silica PCFs [Coscelli2014], aperiodic all-solid LPFs [Dauliat2014], and air-silica LPFs, considered as present state-of-the-art structures [Limpert2012]. This work aims to demonstrate the ability of these designs for a selective HOMs delocalization and thus preserve a robust singlemode emission with the increase of the heat load. At presentation time, structural principles influencing their resistance to the temperature load will be discussed such as the impact of air holes / solid inclusions size. We also intend to evoke that the range of average absorbed/output power for which a robust singlemode operation is available can be shifted to fulfil user requests in term of power range even if at low power, the fiber is only confining slightly the fundamental mode.

9507-10, Session 2

Investigation of optical thin films printed on the surface of facets of photonic crystal fibers

Michal Lucki, Stanislav Kraus, Richard Zeleny, Czech Technical Univ. in Prague (Czech Republic); Johann Zehetner, Dana Seyringer, FH Vorarlberg (Austria); Jan Látal, VŠB-Technical Univ. of Ostrava (Czech Republic); Franti?ek Perecár, VŠB - Technical University of Ostrava (Czech Republic)

Optical fibers are widely used in various applications as a medium for transport of optical signals or energy of light. This transport can be realized on long distance, compared to free space optics, which significantly extends reach of applications. Free space optics and fiber optics are combined in practice to yield the maximum performance of individual components forming a particular system. In such cases, light coupling from free space into fibers is required and it is frequently implemented with the use of lenses. An optical signal coupled into a fiber may also need certain modifications of spectral and spatial properties to allow its propagation down the fiber or reduce the amount of power carried in.

The above requirement has been fulfilled by modifying surface of facets of photonic crystal fibers. By extrusion of a certain amount of host material from the surface, one can obtain a structure resembling a thin film or an opaque layer for certain wavelengths. Several different structures of photonic crystal fibers and materials are considered to show influence of such thin-film on signal properties.

This investigation is carried out in context of abilities of ablation of material from surfaces of photonic crystal fibers. Only certain shapes and geometrical arrangements can be considered. One of the goals is to specify, which of them are key for potential modification of spectral characteristics of photonic crystal fibers. The printed structures could potentially work like a thin-film ablation.

Rigorous and versatile finite difference method has been employed to model propagation of light, its incidence onto a surface of the photonic crystal fiber, and subsequent propagation down the fiber. The simulations are carried on small pieces of photonic crystal fibers, with the length of tens of micrometers, due to well-known demands of the simulation technique on computational resources. Nevertheless, such a simplification is valid, since the structure is longitudinally uniform beyond the thin-film layer. However, this is aspect is not covered in the presented paper and it is our ongoing effort. Finally, the goal is to verify if the investigated structures can work as a slot waveguide.

9507-11, Session 2

Propagation of laser pulse with a few cycles in layered medium with time-dependent dielectric permittivity

Vyacheslav A. Trofimov, Eugeniy V. Pedan, Lomonosov Moscow State Univ. (Russian Federation)

On the base of computer simulation we investigate a propagation of laser pulse with a few cycles in a linear layered medium with dielectric permittivity modulated in time. This means that we consider, so called, temporal photonic crystal. Such kind of crystal can be created, for example, by additional laser beams propagating perpendicular to a direction of propagation of a laser beam under consideration. Therefore, such photonic crystal may be induced for various ranges of frequencies: from optical range of frequencies to infrared range of frequencies. The process under consideration is described by 1D Maxwell's equations.

We investigated light energy localization in such time-dependent structure in dependence of both absolute phase of pulse, and duration of dielectric permittivity increasing. We believe that considering scheme of laser pulse interaction with medium can be used in processing of data by optical methods.

9507-29, Session PS

Highly birefringent dispersion compensating quasi-photonic crystal fiber

Soeun Kim, Yong Soo Lee, Chul-Sik Kee, Gwangju Institute of Science and Technology (Korea, Republic of); Chung Ghiu Lee, Chosun Univ. (Korea, Republic of)

Simultaneous achievement of high birefringence, broadband large negative dispersion and true single mode operation for optical fiber would provide a new solution for optical communication and sensing systems. A high level of birefringence in fiber optics has found various

applications in fiber-optic sensing and coherent optical communications by controlling the polarization cross-talk. Broadband negative dispersion in optical fiber is necessary to compensate for chromatic dispersion in conventional single-mode fiber (SMF) over a wide range of wavelengths in wavelength division multiplexing systems. In addition, single-mode operation is the fundamental enhance the communication capacity. Several solutions for these issues based on conventional step index optical fibers have been individually proposed. However, there has been no integrated solution that addresses all of these issues simultaneously. An integrated solution to combining various optical functions could not only enhance the system performance but also initiate the development of novel functional components. However, it has been a technical challenge to simultaneously control the polarization, dispersion, and single-mode operation because there are trade-offs among those properties in conventional step index optical fibers. In recent years, photonic crystal fiber (PCF) design has been developed widely owing to PCF's unique properties, such as birefringence, anomalous dispersion properties, and single mode operation, by flexing design of air-hole structures, which cannot be realized in conventional step index optical fibers. In this study, we proposed a new PCF design that can simultaneously provide a high birefringence, a large negative dispersion, and true single mode operation. The PCF is based on a quasi-photonic crystal cladding structure. The optical properties of the guided modes were analyzed numerically by the finite element method with the perfectly matched layer as a boundary condition.

9507-30, Session PS

Microfluidic overpass enabled by laser nanofabrication

Yan He, Jilin Univ. (China)

Experimental fabrication of the microfluidic high-way was enabled by direct laser writing based on two photon photopolymerization technique, which has been proved a powerful tool for 3D micronanofabrication. Flow tests confirm that, with the help of post integrated overpass structures, the 2D microchannels show 3D flow property. The unique overpass structure at the junction of the 2D microchannels would be considered as an enabler to 3D microfluidic chips

9507-31, Session PS

Nanoimprint lithography using TiO2-SiO2 ultraviolet curable materials

Satoshi Takei, Toyama Prefectural Univ. (Japan)

Ultraviolet nanoimprint lithography has great potential for commercial device applications that are closest to production such as optical gratings, planar waveguides, photonic crystals, semiconductor, displays, solar cell panel, sensors, high-brightness LEDs, OLEDs, and optical data storage. I report and demonstrate the newly TiO_2-SiO_2 ultraviolet curable materials with 20-25 wt% ratio of high titanium for CF_4/O_2 etch selectivity using nanoimprint lithography process. The multiple structured three-dimensional micro- and nanolines patterns were observed to be successfully patterned over the large areas. The effect of titanium concentration on CF_4/O_2 etch selectivity with pattern transferring carbon layer imprinting time was investigated. CF_4/O_2 etching rate of the TiO_2-SiO_2 ultraviolet curable material was approximately 3.7 times lower than that of the referenced SiO_2 sol-gel ultraviolet curable material. The TiO_2-SiO_2 ultraviolet curable material with high titanium concentration has been proved to be versatile in advanced nanofabrication.

9507-12, Session 3

Speciality optical fibres for astronomy *(Invited Paper)*

Simon C. Ellis, Australian Astronomical Observatory (Australia); Joss Bland-Hawthorn, The Univ. of Sydney (Australia)

Astrophotonics is a rapidly developing area of research which applies photonic technology to astronomical instrumentation. Such technology has the capability of significantly improving the sensitivity, calibration and stability of astronomical instruments, or indeed providing novel capabilities which are not possible using classical optics.

I will review the development and application of speciality fibres for astronomy, including multi-mode to single mode converters, notch filters and frequency combs.

In particular I will focus on our development of instruments designed to filter atmospheric emission lines to enable much deeper spectroscopic observations in the near-infrared. These instruments employ two novel photonic technologies. First, we have developed complex aperiodic fibre Bragg gratings which filter over 100 irregularly spaced wavelengths in a single device, covering a bandwidth of over 200 nm.

However, astronomical instruments require highly multimode fibres to enable sufficient coupling of into the fibre, since atmospheric turbulence heavily distorts the wavefront. But photonic technologies such as FBGs, require single mode fibres. Therefore we have developed the photonic lantern, which enables efficient coupling from a MMF to an array SMFs and vice versa.

I will present the results of laboratory tests of these technologies and of on-sky experiments made using the first instruments to deploy these technologies on a telescope. These tests show that the FBGs suppress the night sky background by a factor of 9. Current instruments are limited by thermal and detector emission. Planned instruments should improved the background suppression even further, by optimising the design of the spectrograph for the properties of the photonic components.

Finally I will present ongoing research to develop multi-moded multi-core fibre Bragg gratings, which enable multiple gratings to be written into the same device simultaneously, and the development of complex notch filters using microring resonators, and plans for future astrophotonic instrumentation.

9507-13, Session 3

Birefringent optical fiber with dispersive polarization axes for sensing applications

Karol Tarnowski, Alicja Anuszkiewicz, Wroclaw Univ. of Technology (Poland); Krzysztof Poturaj, Pawel Mergo, Univ. of Maria Curie-Sklodowska (Poland); Waclaw Urbanczyk, Wroclaw Univ. of Technology (Poland)

Recently the effect of dispersion of the axes was investigated for the first time in optical fiber [1], both theoretically and experimentally. This phenomenon relies upon spectral dependence of the polarization planes of the guided modes. It can be achieved in a side-hole fiber by combining linear birefringence induced by a pair of holes located in the cladding and the elliptical core tilted with respect to the symmetry plane of the holes. In the fabricated fiber rotation of the principal polarization axes by 14.5° over the spectral range from 500 to 1100 nm was reported .

In this presentation we analyzed possible application of this type of fiber in sensing. By finite element modeling, we investigated a sensitivity of birefringence to pressure. In this fiber, the applied pressure influences both the value of modal birefringence as well as the orientation of polarization axes. Moreover, using a Jones matrix formalism, we analyzed a spectral interface pattern, which can be obtained by placing a fiber of this type in a polariscopic system. We proposed an experimental procedure allowing to measure the dependence of polarization axes orientation upon wavelength. Additionally, we show that for a polarizer not orthogonal to an analyzer, two zero contrast wavelengths in the spectral interference pattern can be expected.

[1] K. Tarnowski, A. Anuszkiewicz, K. Poturaj, P. Mergo, and W. Urbanczyk, Birefringent optical fiber with dispersive orientation of polarization axes, Optics Express, 22(21), pp. 25347-25353, 2014.

9507-14, Session 3

Nanostructured tapered optical fibers for paticle trapping

Mark Daly, Viet Giang Truong, Síle G. Nic Chormaic, OIST Graduate Univ. (Japan)

Optical micro- and nanofibres have recently gained popularity as tools in quantum engineering using laser-cooled, neutral atoms. In particular, atoms can be trapped around such optical fibres and photons coupled into the fibres from the atoms could be used to transfer quantum state information within the system in a uni-directional manner. It has also been demonstrated that such fibres can be used to manipulate and trap silica and polystyrene particles in the 1-3 micron range and particle sorting based on size is feasible when higher order optical modes are transmitted through the tapered fibres.

Recently, we proposed using a focussed ion beam (FIB) in order to mill a nanoslot into the waist of a tapered optical fibre and simulated the attainable atom trap parameters that would be achievable. Here, we present details on the design and fabrication of these nanostructured optical fibres for integration into trapping platforms across two very different regimes (i) submicron particle trapping in fluid and (ii) trapping of laser-cooled Rb atoms. The optical fibres are tapered using a custom-built, heat-and-pull rig to approximately 1-2 micron waist diameter prior to processing using a focussed ion beam. A slot of about 360 nm width and 8 micron length is milled right though the waist region of the optical fibre. This size can be altered by varying the processing time in the FIB. Details on the fabrication steps necessary to ensure high optical transmission though the fibre post processing are included.

To date we have achieved transmissions over 80% across a broad range of wavelengths, in particular in the 700-1100 nm range that is of particular interest to us, since these wavelengths are valid for tapping biological samples and are also suitable for far off resonance trapping of rubidium atoms. We also present simulations results on the impact of varying the slot parameters on the trap depths achievable and we have considered milling multiple traps within a single tapered fibre in order to generate a network of trapped particles within the slots. This work demonstrates even further the functionality of micro- and nano-optical fibres as trapping devices across a range of regimes.

9507-15, Session 3

Specialty fibers for high power lasers and amplifiers *(Invited Paper)*

Jayanta K. Sahu, Univ. of Southampton (United Kingdom)

No Abstract Available

9507-16, Session 4

Soft glass photonic crystal fibres and their applications *(Invited Paper)*

Ryszard Buczynski, Mariusz Klimczak, Dariusz Pysz, Grzegorz Stepniewski, Institute of Electronic Materials Technology (Poland); Bartlomiej Siwicki, Warsaw Univ. of Technology (Poland); Jaroslaw Cimek, Ireneusz Kujawa, Institute of Electronic Materials Technology (Poland); Bernard Piechal, Univ. of Warsaw (Poland); Ryszard Stepien, Institute of Electronic Materials Technology (Poland)

No Abstract Available

9507-17, Session 4

Progress in the fabrication of optical fibers by the sol-gel granulated silica method

Jonas Scheuner, Dereje Etissa, Univ. Bern (Switzerland); Sönke Pilz, Berner Fachhochschule Technik und Informatik (Switzerland); Manuel Ryser, Univ. Bern (Switzerland); Hossein Najafi, Berner Fachhochschule Technik und Informatik (Switzerland); Woojin Shin, Gwangju Institute of Science and Technology (Korea, Republic of); Valerio Romano, Univ. Bern (Switzerland) and Berner Fachhochschule Technik und Informatik (Switzerland)

The granulated silica method based on sol-gel materials production gives a high degree of flexibility with respect to dopant type, its concentration and the desired microstructure in the production of optical fibres. The method is rapid and yields a homogeneous distribution of the dopants even at high concentration levels. It further gives the possibility to precisely control the refractive index of the rare earth activated and of the optically passive materials. This allows to very precisely match the refractive index of differently doped materials or adapt it in such a way as to obtain very low index contrasts required for large mode area fibers or all solid leakage channel fibers.

By refining the production process of the method the background losses have been lowered to such a point that it is possible to build large mode area active fibres as well as all solid leakage channel fibres.

In this paper we will present our latest progress in the synthesis of the manufactured optical materials by transmission electron microscopy analysis as well as the optical properties (background losses, absorption, gain) of recently drawn Ytterbium-doped step index fibres and on an all solid leakage channel fibre. Their waveguide properties are characterised by near field imaging while the refractive index profile is measured by a confocal technique in two dimensions.

9507-18, Session 4

Fabrication of three dimensional microstructure fiber

Ying Luo, Jie Ma, Zhe Chen, Jinan Univ. (China); Huihui Lu, Jinan Univ (China); Yongchun Zhong, Jinan Univ. (China)

A method of fabricating colloidal crystal micro-structured fiber is presented. Silica microspheres were coated around the surface of a micro-fiber through isothermal heating evaporation induced self-assembly method. Scanning electron microscopy (SEM) image shows that the colloidal crystal has continuous, uniform, and well-ordered face-centered cubic (FCC) structure, with [111] crystallographic direction normal to the surface of micro-fiber. The transmission peak of this micro-structured fiber is about 715 nm, which is due to the partial band-gap of FCC structure. This micro-fiber with three-dimensional photonic crystals structure is very useful in the applications of micro-fiber sensors or filters.

9507-19, Session 4

Investigation of passive and active silica-tin oxide nanostructured optical fibers fabricated by “inverse dip-coating” and “powder in tube” method based on the chemical sol-gel process and laser emission

Geoffroy Granger, Univ. Stuttgart (Germany); Christine Restoin, Philippe Roy, Raphaël Jamier, Sébastien

Rougier, XLIM Institut de Recherche (France); Jean-René Duclere, Univ. de Limoges (France); Andre Lecomte, SPCTS (France); Romain Dauliat, Leibniz-Institut für Photonische Technologien e.V. (Germany); Jean-Marc Blondy, XLIM Institut de Recherche (France)

Recently, researches have shown that it is possible to achieve nanostructured core fiber by incorporating dielectric (ZrO2), ceramic (YAG, Y2O3), semi-conductor (SnO2), metallic nanoparticles (Au), or quantum dots in an amorphous matrix. These nanoparticles dispersed in a silica matrix exhibits original nonlinear optical properties or offer a great potential for optical amplification as the rare earth ions doping concentration can be higher than into conventional amorphous medium.

In this paper, we present the fabrication and the characterization of SiO2-SnO2-(Yb3+) nanostructured optical fibers. The experimental procedure follows two approaches: "sol-gel inverse dip-coating" (IDC) and "sol-gel powder in tube" (PIT). In each case several tin oxide concentrations (20 to 90 mol% in case of IDC, 30 and 40 mol% for PIT) are realized at a unique acid rate [A] define by [H+]/([Si]+[Sn]) fixed at 0.5. Microstructural (XRD: X-ray diffraction, TEM: Transmission Electron Microscopy), chemical (EDX: X-ray analysis) as well as linear optical investigations on powder (photoluminescence (PL)) and on fiber (transmission, attenuation, Refractive Index Profile (RIP)) has been carried out. XRD patterns achieved on powder after the accurate heat treatment indicate that SnO2 crystalizes in a cassiterite phase in form of nanoparticles (NP) according to TEM pictures. The size of the crystal varies from 4 to 50 nm for tin oxide concentration ranging from 20 to 90 mol% (evaluated by Scherrer's formula). EDX measurements demonstrated that these NP are made from pure SnO2.

The PIT approach leads to larger transmission band with losses reaching down to 3 dB/m and 0.2 dB/m respectively in the visible (VIS) and infrared (IR) range and a conservation of more crystallite (RIP and EDX conclusion) source of Rayleigh diffraction at short wavelength. Concerning the IDC fibers, the tin oxide concentration, evaluated by Lorentz-Lorenz formula, is lower than the PIT fibers and the VIS attenuation is equal to 0.5 dB/m. These low average losses demonstrate the pertinence and the quality of these two processes.

The introduction of ytterbium ions in the core of PIT fibers directly in the first chemical step leads to laser emission from 1050 to 1100 nm depending on to the fiber length under pumping with a Ti:Saph laser (? = 850 nm). The PL studies achieved on powders with and without SnO2 realized under the same conditions (time and temperature of the heat treatment) show clearly the influence of the tin oxide nanoparticles on the Yb3+ luminescence properties; the discretization of the absorption and emission bands between 850-1100 nm and the lifetime has been measured and is equal to 10 μs in the IR PL.

9507-20, Session 5

Fibre Bragg gratings inscribed in low loss CYTOP polymer optical fiber using a femtosecond laser

A. Lacraz, M. Polis, A. Theodosiou, Charalambos Koutsides, Kyriacos Kalli, Cyprus Univ. of Technology (Cyprus)

No Abstract Available

9507-21, Session 5

Experimental investigation of Bragg gratings growth dynamics in polymer fibers of different types

Gabriela Statkiewicz-Barabach, Dominik Kowal, Wroclaw Univ. of Technology (Poland); Pawel Mergo, Univ. of Maria Curie-Sklodowska (Poland); Waclaw Urbanczyk, Wroclaw Univ. of Technology (Poland)

We demonstrate a possibility of fabrication of Bragg gratings in polymer fibers with multiple reflection peaks by using He-Cd laser (?=325 nm) and a standard phase mask.The existence of 0th, ±1st, ±2nd, ±3rd diffraction orders behind the phase mask of period ?=1.052 μm translates into complex interference pattern and consequently into longitudinal modulation of refractive index containing different spatial frequencies. As a result, good quality higher order Bragg peaks placed at ?B/2=782 nm and 2?B/3=1040 nm for the grating with the primary peak at ?B=1555 nm were observed in the microstructured fiber. For the grating in the PMMA/PS fiber, additional peaks at ?B/3=525 nm 2?B/5=628 nm were present in the reflection spectrum. Growth dynamics and temperature response of higher order reflection peaks were studied experimentally in these two types of polymer fibers. Moreover, we demonstrate fabrication of type I, type II and mixed Bragg gratings using a phase mask of period ?=885 nm in standard polymer fiber with a core made of PMMA/PS copolymer and in mPOF with the photosensitive inclusion in the core. Additionally, we studied an influence of fibers annealing on the growth dynamics and long term stability of Bragg gratings of different types fabricated in standard polymer fiber with a core made of PMMA/PS copolymer.

9507-22, Session 5

Optimisation of polymer optical fibre based interferometric sensors

Andreas Pospori, David J. Webb, Aston Univ. (United Kingdom)

Polymer optical fibres (POFs) have received increased interest in recent years due to their different material properties compared to silica based optical fibres (SOFs). Biocompatibility, a higher failure strain and the greater elasticity of POFs are potential advantages over SOFs and these characteristics are useful in the sensor application field. The much lower Young's modulus of POF as compared to SOF means that POF sensors have much less effect on any compliant structures that are being monitored and also renders POF based sensors much more sensitive to fibre stress than those fabricated from SOF. The lower Young's modulus also offers sensitivity enhancement when POF is used to sense acoustic waves. However, some considerable drawbacks still exist in POF technology, perhaps the main one being the high fibre loss and this needs to be taken into account when designing interferometric sensors constructed from POF. In the absence of loss the strain sensitivity of a fibre interferometer is proportional to its cavity length, however when interferometers are constructed from POF, increasing the cavity length can result in sensitivity reduction at some point due to the attenuation along the optical path. Therefore, evaluating the cavity length that maximises the sensitivity is important in order to optimise the performance of a POF based interferometric fibre sensor.

In this work, we have investigated the consequences of the much higher loss of POF on the achievable sensitivity of fibre interferometers used to sense stress. The loss leads to a reduction in the signal level obtained from two-beam interferometers, while in the case of Fabry-Perot interferometers the finesse can also be significantly reduced. A simulation model of the sensor response has been constructed in the MATLAB environment where the optimum optical length can be determined. The model describes the relationship between sensitivity and the key sensor parameters, which are the reflectivity of the mirrors used to form the interferometer, the cavity length and the attenuation. We have studied operation at a set of frequently used wavelengths in poly(methyl methacrylate) based fibre, low-loss perfluorinated polymer fibre and silica fibre. Using this simulation, we can identify those regimes in which POF based sensors offer enhanced performance over their silica counterparts.

9507-23, Session 5

High performance liquid level monitoring system based on polymer fiber Bragg gratings embedded in silicone rubber diaphragms

Carlos A. F. Marques, Aston Institute for Photonics Technologies (United Kingdom); Gang-Ding Peng, The

Univ. of New South Wales (Australia); David J. Webb, Aston Univ. (United Kingdom)

Liquid-level sensing technologies have attracted great prominence, because such measurements are essential to industrial applications, such as fuel storage, flood warning and in the biochemical industry. Traditional liquid level sensors are based on electromechanical techniques; however they suffer from intrinsic safety concerns in explosive environments. In recent years, given that optical fiber sensors have lots of well-established advantages such as high accuracy, cost-effectiveness, compact size, and ease of multiplexing, several optical fiber liquid level sensors have been investigated which are based on different operating principles such as side-polishing the cladding and a portion of core, using a spiral side-emitting optical fiber or using silica fiber gratings.

The present work proposes a novel and highly sensitive liquid level sensor making use of polymer optical fiber Bragg gratings (POFBGs). The key elements of the system are a set of POFBGs embedded in silicone rubber diaphragms. This is a new development building on the idea of determining liquid level by measuring the pressure at the bottom of a liquid container (with 80 cm of height), however it has several critical advantages. The system features several, FBG based pressure sensors as described above placed at different depths. Any sensor above the surface of the liquid will read the same ambient pressure. Sensors below the surface of the liquid will read pressures that increase linearly with depth. The position of the liquid surface can therefore be approximately identified as lying between the first sensor to read an above-ambient pressure and the next higher sensor. This level of precision would not in general be sufficient for most liquid level monitoring applications; however a much more precise determination of liquid level can be made by linear regression to the pressure readings from the sub-surface sensors. There are numerous advantages to this multi-sensor approach. First, the use of linear regression using multiple sensors is inherently more accurate than using a single pressure reading to estimate depth. Second, common mode temperature induced wavelength shifts in the individual sensors is automatically compensated. Thirdly, temperature induced changes in the sensor pressure sensitivity are also compensated. Fourthly, the approach provides the possibility to detect and compensate for malfunctioning sensors. Finally, the system is immune to changes in the density of the monitored fluid and even to changes in the effective force of gravity, as might be obtained in an aerospace application.

The performance of an individual sensor was characterized and displays a sensitivity (54 pm/cm), enhanced by more than a factor of 2 resulting from the much lower elastic modulus of POF, when compared to a sensor head configuration based on a silica FBG published in literature, which displayed a sensitivity of 23 pm/cm. Furthermore, the temperature/humidity behavior and measurement resolution were also studied in detail. The proposed configuration also displays a highly linear response, high resolution and good repeatability. The results suggest the new configuration can be a useful tool in many different applications, such as aircraft fuel monitoring, and biochemical and environmental sensing, where accuracy and stability are fundamental.

9507-24, Session 6

High-precision confocal reflection measurement for two dimensional refractive index mapping of optical fibers *(Invited Paper)*

Philippe R. Raisin, Jonas Scheuner, Univ. Bern (Switzerland); Valerio Romano, Univ. Bern (Switzerland) and Berner Fachhochschule Technik und Informatik (Switzerland); Manuel Ryser, Univ. Bern (Switzerland)

A novel all-in fiber setup for the measurement and acquisition of two-dimensional refractive index maps of optical fibers is introduced. It is completely based on fiber-optical components, thus the system is compact, robust and delivers reproducible measurements. The refractive index is derived from the point wise confocal measurement of the Fresnel reflection with a beam tightly focused on a sample surface. With our setup we currently reach a precision of <10-4 refractive index units. This tool provides the needed feedback for the development and fabrication of fibers with very low index contrast such as large mode area (LMA) fibers.

9507-25, Session 6

Characterization of double-clad thulium-doped fiber with increased quantum conversion efficiency

Jan Aubrecht, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Jakub Cajzl, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic) and Institute of Chemical Technology (Czech Republic); Pavel Peterka, Pavel Honzátko, Ondrej Podrazk?, Filip Todorov, Ivan Ka?ík, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

Thulium-doped fiber lasers are becoming important high-power laser sources operating in the near-infrared region around 2 micrometers mainly because of their use in material processing (e.g., plastics), biological imaging, atmospheric transmission and LIDAR for pollution monitoring; pumping of solid state lasers (crystals, Ho-doped fiber), spectroscopy and generation of supercontinuum in mid-infrared range. These sources are attractive despite the low quantum conversion efficiency of the upper laser level of the 2 micrometer transition in thulium-doped silica fibers, which is about 10 % compared to ~100% quantum conversion efficiency of the ytterbium- and erbium-doped fibers, at around 1 micrometer and 1.5 micrometer, respectively. The lower quantum conversion efficiency increases the laser threshold but has almost no effect on the laser slope efficiency. Therefore, high-power, continuous-wave fiber lasers can be built even with active medium of somewhat impaired quantum conversion efficiency. High quantum conversion efficiency is required especially in devices such as optical amplifiers, ASE (Amplified Spontaneous Emission) sources, or Q-switched pulsed sources. Recently, it was demonstrated that the quantum conversion efficiency of laser transitions of thulium in silica-based fiber hosts can be improved by modification of the local environment of the rare-earth ions in silica glass [1]. The modifiers tested so far were, e.g., the alumina, germanium oxide and bismuth oxide. We have shown that modification of the local environment of the thulium ions by high concentration of alumina lead to improvement of the fluorescence lifetime and quantum conversion efficiency by about two times compared to the low-alumina content environment [2]. Particularly, the method of doping with alumina nanoparticles is promising as it allows high concentration of alumina yet without the unwanted phase separation effects [3].

In this paper we present experimental results of characterization of the developed optical fibers in double-clad fiber geometry for cladding optical pumping at wavelength of 0.79 micrometers. The fibers were fabricated by the modified chemical vapor deposition and solution doping methods and coated with polymer with lower refractive index than silica. The fibers were characterized in terms of their spectral attenuation, fluorescence lifetime, refractive index profile, and performance in fiber laser and wideband ASE source setups.

References:

[1] Dussardier, B., Blanc, W., and Peterka, P., [Tailoring of the local environment of active ions in rare-earth- and transition-metal-doped optical fibres, and potential applications], book chapter in Selected topics on optical fiber technology, editors M. Yasin, S. W. Harun, and H. Arof, InTech, Croatia, 95-120 (2012).

[2] Cajzl, J., Peterka, P., Honzátko, P., Mrázek, J., Podrazk?, O., Todorov, F., Gladkov, P., Sahu, J.K., Nunez-Velazquez, M., Nekvindová, P., and Ka?ík, I., "Characterization of fluorescence lifetime of Tm-doped fibers with increased quantum conversion efficiency," to appear in SPIE, (2014).

[3] Peterka, P., Honzatko, P., Becker, M., Todorov, F., Pisarik, M., Podrazky, O., Kasik, I., "Monolithic Tm-Doped Fiber Laser at 1951 nm With Deep-UV Femtosecond-Induced FBG Pair," IEEE Photonics Technology Lett., 25(16), 1623-1625 (2013).

9507-26, Session 6

Transmission of red-laser radiation by using Bragg fibers

Vlastimil Matejec, Ondrej Podrazky, Ivan Kasík, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Milan Frank, Michal Jelínek M.D., Václav Kubecek, Czech Technical Univ. in Prague (Czech Republic)

This paper presents experimental results on transmission characteristics of Bragg fibers with air cores at wavelengths around 630 nm. The claddings of the fibers consist of three pairs of Bragg layers. Each pair is composed of one layer with a high and one layer with a low refractive index. Diameters of the air cores are in a range from 40 to 70 ?m. A theoretical modelling of Bragg fibers was carried out from which waveguiding characteristics of fibers were determined for the refractive-index contrast of the high- and low-index layers on a level of 0.03 and wavelengths around 630 nm.

Preforms of the Bragg fibers in the form of tubes were prepared by the MCVD method. Germanium dioxide and phosphorous pentoxide were used as silica dopants for the high-index layers. The low-index layers were fabricated of silica slightly doped with phosphorous pentoxide. The last layer applied was the high-index one. Bragg fibers were drawn from the tubes under controlled temperatures around 2000 °C in order to obtain fibers with different dimensions of Bragg claddings and air cores. Results of characterization of prepared fibers with optical microscopy are presented in the paper. The transmission and attenuation of the fibers at 630 nm were measured with a pulse He-Ne laser and with red laser diodes as light sources. Spatial distributions of output beams from the fibers were also determined.

9507-27, Session 6

Light-guidance in step-index fibers with rectangular shaped core

Jan C. Heimann, P. Raithel, Tim Tobisch, Technische Hochschule Mittelhessen (Germany); Mathias Belz, TransMIT GmbH (Germany); Karl-Friedrich Klein, Technische Hochschule Mittelhessen (Germany)

Multimode fiber with a core and step-index core/cladding profile is commonly used in a multitude of applications ranging from 185 nm (DUV) up to 2300 nm (NIR). Although the core is mainly circular, fibers with non-circular core are becoming popular and offer several interesting new optical properties.

In this work, light coupling into the core of non-circular fiber will be studied with an emphasis on selective modes or ray patterns. Observing the farfield profile at fiber output, ray-conversion can be determined, taking the azimuthal angle defined in respect to the major axis into account.

Using the inverse far-field method at two separate laser wavelengths, the numerical aperture (NA) of such specialty fibers will be determined as a function of wavelength and excitation conditions. Further, spectral ray-dependent attenuation of mode-selective illumination will be discussed. In addition, additional losses due to bending or higher-order modes will be studied in respect to core shape. Finally, the results will be compared with the illumination using uniform-mode distributions generated by a standard set-up with an LED as light-source.

9507-28, Session 6

Mode field distribution and measuring method of microstructured fiber

Guoying Feng, Sichuan Univ. (China)

A method of measuring excited modes in micro-structured fiber based on spatially and spectrally resolved measurement was adopted. According to the expression of the group delay of the micro-structured fiber modes, the derivation processing of the group delay difference of transverse modes leading to the spectral interference was given. The measurement method for a micro-structured fiber was carried out. By using the single-mode fiber and optical spectrum analyzer to measure the spectral interference signal, the spectral interference signal was analyzed, and the distributions and power fraction of transverse modes were offered. The results show that the method of measuring the micro-structured fiber modes based on spatially and spectrally resolved measurement can determine distributions of transverse modes in the fiber and their relative power level.

Conference 9508: Holography: Advances and Modern Trends

Wednesday - Thursday 15–16 April 2015

Part of Proceedings of SPIE Vol. 9508 Holography: Advances and Modern Trends IV

9508-1, Session 1

Sparse approximations of phase and amplitude for wave field reconstruction from noisy data

(Invited Paper)

Vladimir Y. Katkovnik, Tampere Univ. of Technology (Finland); Igor A. Shevkunov, Nikolay V. Petrov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Karen Egiazarian, Tampere Univ. of Technology (Finland)

The topic of sparse representations (SR) of images has attracted tremendous interest from the research community in the last ten years. This interest stems from the fundamental role that the low dimensional models play in many signal and image areas, i.e., real world images can be well approximated by a linear combination of a small number of atoms (i.e., images) taken from a large frame, often termed dictionary. The principal point is that these large dictionaries as well as the elements of these dictionaries taken for approximation are not known in advance and should be taken from given noisy observations. The sparse phase and amplitude (SPAR) algorithm has been developed in [1] for monochromatic coherent wave ?field reconstruction. This technique has been applied for phase-shifting interferometry and holography in [2, 3]. In this paper the SPAR technique is extended to off-axis holography. Pragmatically, SR representations are result in design of efficient data-adaptive fi?lters. We study different versions of the algorithms where these fi?lters are applied for denoising of phase and amplitude in object and sensor planes. Iterative algorithms are developed for optical image reconstruction from Gaussian noise and Poisson observations. In this development the SPAR ?filter is appeared from the solution of the optimization problems and built in the loop of the algorithm. The multiple simulation and real data experiments demonstrate the advance performance of the new technique.

1. V. Katkovnik and J. Astola, "High-accuracy wave fi?eld reconstruction: decoupled inverse imaging with sparse modelling of phase and amplitude," J. Opt. Soc. Am. A, vol. 29, no. 1, 44-54, 2012.V.

2. Katkovnik and J. Bioucas-Dias , ?Wavefront reconstruction in phase-shifting interferometry via sparse coding of amplitude and absolute phase,?J. Opt. Soc. Am. A, vol. 31, no. 8, 1801-1810, 2014.

3. V. Katkovnik, J. Bioucas-Dias and N. Petrov, "Digital phase-shifting holography based on sparse approximation of phase and amplitude," Proc. of 3DTV-Conference (3DTV-CON), Budapest, Hungary, 2014.

9508-2, Session 1

Real-time characterization of the neuronal response to osmotic shock by digital holographic microscopy

Maria Gomariz, Cristina Soto-Sánchez, Isabel Garcia, Gema Martinez-Navarrete, Eduardo Fernández, Antonio Fimia, Univ. Miguel Hernández de Elche (Spain)

Neuronal tissues present a significant dynamics and activity. In particular, their biophysical and morphological characteristics change in response to alterations of the external environment. These responses can be related with the variation of the common celular functions of a healthy neuron. Thus, the monitorization of the neuronal changes is quite interesting in order to study the degenarative origin of neuronal disfunctions, precursors of neurogenerative diseases 1,2.

In addition, the digital holographic microscopy (DHM) has numerous applications in biology for visualization of cells and tissues in 3D 3.4. This technique is non-invasive, non-phototoxic and where no dyes or fixing solutions for visualization of tissues and biological structures are used 5,6.

In this work, we have characterized the morphometric characteristics of neurons during a changing osmolarity process using DMH technique. With this purpose, we have studied the variation of the amplitude and frequency of oscillation of the plasmatic membrane and changes in cell volume during the diffusion of water previous to final osmotic shock. In contrast to previous works, we have used 'long-term cultures' in order to study changes related to the age of the neurons. Interestingly, we have observed a relation between neuronal cell response and age of neuronal cultures during the process of dilution of the medium.

References:

[1] Fox, N. C. and Schott, J. M. , "Imaging cerebral atrophy: normal ageing to Alzheimer's disease," The Lancet 363(9406), 392-394 (2004).

[2] Langehanenberg, P., von Bally, G. and Kemper, B. , "Application of partially coherent light in live cell imaging with digital holographic microscopy," Journal of Modern Optics 57(9), 709 (2010).

[3] Kemper, B. and von Bally, G. "Digital holographic microscopy for live cell applications and technical inspection," Appl.Opt. 47(4), A52-A61 (2008).

[4] Kou, S. S. and Sheppard, C. J. , "Imaging in digital holographic microscopy," Optics express 15(21), 13640-13648 (2007).

[5] Cuche, E., Marquet, P. and Depeursinge, C. , "Simultaneous amplitude-contrast and quantitative phase-contrast microscopy by numerical reconstruction of Fresnel off-axis holograms," Appl.Opt. 38(34), 6994-7001 (1999).

[6] Marquet, P. et al., 2005. Digital holographic microscopy: a noninvasive contrast imaging technique allowing quantitative visualization of living cells with subwavelength axial accuracy. Optics Letters, 30(5), 468–70 (2005).

9508-3, Session 1

Comparison of digital holographic interferometry and constant temperature anemometry for measurement of temperature field in fluid

Roman Dolecek, Pavel Psota, Vít Lédl, Tomás Vít, Petra Dancová, Václav Kopecky, Technical Univ. of Liberec (Czech Republic)

The presented paper shows possibility of using digital holographic interferometry (DHI) for temperature field measurement in moving fluids. This method uses a modified Twymann-Green setup having double sensitivity instead of commonly used Mach-Zehnder type of interferometer in order to obtain sufficient phases change of the field. On the other hand this setup is not light efficient as Mach-Zehnder interferometer. For measurement of the fast periodical phenomenon is not necessary to use always the high speed camera. One can consider this field to coherent phenomenon. With employing one digital camera synchronized to periodic field and external triggered one can capture whole period of the phenomenon. However the projections form one viewing direction of asymmetrical temperature field maybe misguided. Hence for sufficient examination of the asymmetrical field one should capture a large number of the phenomenon's projections from different viewing directions. This projections are later used for 3D tomographic reconstruction of the whole temperature field and its time evolution. One of the commonly used method for temperature field measurement in moving fluids is hot wire method - constant current anemometry (CCA). In contrast to whole field measurement of DHI it is a point temperature measurement method. One of the limiting factor of using CCA in moving fluids is frequency of temperature changes. This changes should not exceed 1kHz. This limitation can be overcome by using of optical methods

such as DHI. The results of temperature field measurement achieved by both method are compared in the paper.

9508-4, Session 1

Fluorescence digital holographic adaptive optics microscopy

Tianlong Man, Yuhong Wan, Dayong Wang, Beijing Univ. of Technology (China)

Fluorescence microscopy (FM) is widely used in various of practical applications now. High resolution three-dimensional sectional microscopic imaging utilized by confocal two- or three-photon FM has became an essential tool in biological applications. The resolution of the FM is highly depends on point spread function (PSF) of the scanning point source in the tissue volume. However, the nonuniform refractive index of biological tissues often introduces aberrations to the wavefront, thus distorts the PSF and the imaging quality is decreased by the distorted PSF.

Adaptive optics (AO) techniques have been successful applied in microscopy to compensate aberrations introduced by nonhomogeneity of the tissues and improve the imaging resolution. Shack-Hartmann sensor and deformable mirror are commonly used as the wavefront sensor and modulator in conventional AO system, which makes the system less robust and the spatial bandwidth of measurable aberration is limited by the subaptures of the devices. Incoherent digital holographic adaptive optics (IDHAO) is proposed as a new AO method in holographic framework, where the aberrations are compensated point by point by calculating the convolution between the extended hologram and a point source hologram. IDHAO is seen to be particularly robust and efficient with essentially unlimited dynamic range of measurable aberration. However, there are still some limitations in the method, such as the recording speed is relative slow because three or four holograms have to be captured to solve the twin image problem both in the point source and extended holograms. Furthermore, the IDHAO is still not being applied in adaptive microscopic imaging of fluorescent samples yet.

In this paper, holographic adaptive optics method is implemented to the fluorescence samples imaging by our previous proposed incoherent off-axis Fourier triangular holography (IFTH). Basing on the basic principle of IDHAO, holograms of a point source and the extended object are recorded respectively using IFTH. The aberrated complex PSF is reconstructed from the point source hologram and used to compensate the wavefront aberrations. Two single-shot holograms are sufficient to compensate the aberrations in the reconstructed images, thus the operation speed is improved. The validity of the proposed method is demonstrated in holographic microscopic imaging of fluorescent samples. This method shows great potential in biomedical imaging.

9508-5, Session 1

Dual-wavelength digital holographic microscopy for improving measurement accuracy

Jianglei Di, Teli Xi, Min Xie, Jiwei Zhang, Jianlin Zhao, Northwestern Polytechnical Univ. (China)

In DHM, the digital hologram is recorded by CCD or CMOS cameras and the complex amplitude of the object wavefront is numerical reconstructed from the hologram. The phase information can be obtained by solving the phase angle of the complex amplitude, which lie between±pi radians. These values are referred to as the wrapped phase values because the absolute phase is wrapping into the interval (-pi, pi). Then quantitative phase information of the object can be obtained directly by using phase unwrapping algorithm. However, the phase ambiguity limits the measurement range in DHM, especially for samples with steps.

Dual-wavelength technology can be introduced to solve this problem. A synthetic wavelength can be obtained by using two lasers with different wavelengths; the synthetic wavelength is longer than either of the laser wavelength and this can expand the measurement range. Meanwhile, the measurement accuracy reduces and the noise increases along with the expansion of measuring range in dual wavelength technology. In some cases, measurement accuracy is very important for samples with small phase change since sample's useful information may be submerged in the noise.

In this paper, a new dual wavelength approach is presented in DHM. A synthetic wavelength, which is only about half of laser wavelength, is obtained by using two different lasers and calculating the multiplication of the complex amplitudes. It equals to that a shorter wavelength is used for measurement. So the wrapped phase fringes will be more closed and the phase information will be smooth with this new synthetic wavelength. Therefore, higher measurement accuracy can be achieved. The numerical simulation and experimental results show the validity of this method.

9508-6, Session 2

Plasmonic spectral filters based on diffraction gratings

Alexander Y. Zherdev, Sergey B. Odinokov, Dmitry Lushnikov, Maria Ruchkina, Bauman Moscow State Technical Univ. (Russian Federation); Alexey V. Zablotskiy, Artur Azatovich Kuzin, Moscow Institute of Physics and Technology (Russian Federation); Andrey V. Smirnov, Krypten (Russian Federation)

Plasmonic spectral filters could be a new element of the design and level of protection in the security holograms. Due to its special spectral-angular characteristics of plasmonic holograms, for example, can be transmitting window in a protected document, a plastic card or banknote.

In this paper we used the Fourier modal method for the analysis of diffraction gratings with submicron period and nanometric height of relief to obtain the plasmonic spectral filters. The Fourier modal method allows us to carry out the solution of the direct problem of diffraction of electromagnetic wave at a one-dimensional periodic structure with a multilayer coating. This objective is achieved by solving Maxwell's equations for the electromagnetic radiation transmitted and reflected by the diffraction grating with a multilayer coating. Theoretical studies confirmed by obtaining of experimental samples.

The purpose of research is to achieve broadband spectral filter based on plasmonic grating with a spectral bandwidth depending on the angle of propagation of radiation.

During the research, we analyzed a lot of combinations of various materials (BK7 glass, photoresist S1813, silicon dioxide SiO_2, poly(methyl methacrylate) PMMA, polycarbonate PC, silver Ag, aluminum Al, gold Ag, chrome Cr etc.) and various configuration structures (one or few metal coating above and below the diffraction structure, the protective coating). We have considered rectangular and sinusoidal diffraction gratings. We have studied the spectral-angular characteristics of transmitting and reflected diffraction orders, including direct transmission and reflection.

Analyzed the geometrical parameters contains: the diffraction grating period from 200 nm to 1.5 mm, the grating relief height from 10 to 300 nm, the coating thickness from 10 to 100 nm.

Studies have shown that the anomalies in diffraction gratings spectral-angular characteristics appear at diffraction order existence region boundaries. Effective transmission bands are explained using plasmonic resonance effect and lead to the plasmonic spectral filters. The most efficient spectral-angular anomaly is in the zero transmitting diffraction order, i.e. in the direct transmittance.

With increasing light incidence angle the filter transmittance bandwidth shifts from the blue to the red spectral region and a simultaneous its half-width decreases. Maximum of transmittance lies in the range from 0.8 to 0.95.

Studies have shown that the change of diffraction grating period leads to a change in the shape and location of the plasmonic effect region at the spectral-angular diagram. Thus, it is possible to obtain spectral filters with variable transmittance bandwidth characteristics by changing, for example, the angle of incidence.

During the experimental studies, we have received a number of samples with a unique color behavior in transmitted light.

Changing the grating relief height and the metal coating thickness in a certain range of valid values does not lead to a qualitative change in the spectral-angular characteristics of the plasmonic filter. This allows us to create technology for the production of plasmonic spectral filters based on diffraction gratings.

9508-7, Session 2

Security hologram foil labels with a design facilitating authenticity testing:

effects of mechanical bending of the holograms

Ivo Aubrecht, Police presidium CR (Czech Republic)

Optimal design of security holograms or, better to say, diffractive optically variable image devices (DOVIDs) that would be complex enough to deter counterfeiters from attempts of mimicking but contain features readily recognizable by laymen has been addressed by many experts from the security-DOVID business.

This paper tries to discuss effects of mechanical bending of a foil DOVID glued on a flexible substrate (paper sheet, plastic card etc.) to artwork and colour appearance to be observed on defined illumination of the DOVID. Theoretical analyses and experimental results are based on recording of rainbow-type holograms, with the signal wave forming optical images in a non-planar, cylindrical-shaped surface. Recording with both the recording plane being parallel and perpendicular to the plane of curvature of the image surface is under investigation. The recorded holograms are of surface-relief kind; nickel shims are manufactured from them for the final hologram labels to be embossed to a suitable foil.

9508-8, Session 3

Volume holographic gratings: fabrication and characterization *(Invited Paper)*

Gaetano Bianco, CGS S.p.A (Italy); Maria Antonietta Ferrara, Istituto per la Microelettronica e Microsistemi (Italy); Fabio Borbone, Antonio Roviello, Univ. degli Studi di Napoli Federico II (Italy); Vito Pagliarulo, Simonetta Grilli, Pietro Ferraro, Consiglio Nazionale delle Ricerche (Italy); Valerio Striano, ANTARES S.c.a.r.l. (Italy); Giuseppe Coppola, Istituto per la Microelettronica e Microsistemi (Italy)

The fabrication and characterization of a high efficiency volume holographic transmitting grating (VHG) are reported. VHG allows an unique combination of high efficiency, controllable spectral response, and low scattering, and it is useful in many applications, such as optical elements [1].

The recording material was a photopolymer sensitive to light at wavelength of 532 nm. It was based on a sol-gel matrix formed by condensation of alkoxysilanes functionalized with organic pendant groups and they are characterized by interpenetrating organic and inorganic networks. By this approach, the low refractive index matrix of the holographic material can be formed in situ and its hybrid composition is suitable to obtain a rigid film with organic molecules (photopolymerizable monomers), involved in the hologram writing process, dissolved in it. Photopolymer was deposited by Doctor Blade method and had an average thickness of about 30µm. It shows a modulation of refractive index of about 0.02 [2]. The experimental set up used to record VHG was a typical Mach Zehnder interferometer. A laser source at 532 nm was used to modify photopolymers refractive index. A grating of 494 lines/mm was obtained.

Diffraction efficiency was measured during and after the holographic exposure by a He-Ne laser source at 632.8 nm. The diffraction efficiency ? was about 94% and it was calculated as ?=P_1/(P_inc-P_refl)), where P1 is the power of the 1st diffraction order, Pinc is the incident power and Prefl is the reflected power. A value of 2° of the grating angular selectivity, given by the FWHM of angular selectivity curve, was obtained.

A confirmation that the recorded hologram is a volume and not a surface hologram, can be obtained by evaluating the Q-factor:

Q=2ϖ?d/(n?^2) (1)

where ? is the recording wavelength, d is the photosensitive layer thickness, n is the refraction index of the material, and ? is the fringe spacing. A holographic grating is considered to be thin (surface) when $Q \leq 1$, thick (volume) when $Q \geq 10$ [3]. In our case, we obtained a $Q \approx 17$ confirming that our hologram is a VHG.

Finally, an Atomic Force Microscopy (AFM) characterization was performed on the sample in order to avoid formation of a surface grating. Results of AFM measurements shows a small sinusoidal modulation of the surface, but it is less of 5nm, then we can neglect it respect to volume grating.

In conclusion, from the results obtained, it can be concluded that the proposed photopolymer allows the fabrication of high efficiency transmitting VHG. The characterizations reported enable both the real time monitoring of the photopolymerization during the recording process, and a post characterization of VHG efficiency, angle selectivity and surface morphology.

References:

[1] J. M. Tedesco, H. Owen, D. M. Pallister, M. D. Morris, Analytical Chemistry 65, NO. 9, 441 A-449 A (1993).

[2] M. A. Ferrara, F. Borbone, V. Striano, G. Coppola, Proc. SPIE 8792, 87920Z, doi:10.1117/12.2021654 (2013).

[3] B. C. Kress, P. Meyureis, Applied Digital Optics: from micro-optics to nanophotonics, John Wiley & Sons, 638 p. (2009), ISBN: 978-0-470-02263-4.

9508-9, Session 3

Theoretical analysis of diffraction characteristics for peristrophic multiplexing with spherical reference wave

Shuhei Yoshida, Jun Mori, Manabu Yamamoto, Tokyo Univ. of Science (Japan)

Holographic data storage (HDS) can realize a large recording capacity and high data transfer rate by recording information as a volume hologram in a thick medium. Recording density of the HDS is not limited by the diffraction limit unlike conventional optical disks. Multiplexing recording is a prime determinant of the recording density in HDS. Therefore, many kinds of recording techniques have been proposed. Multiplex holographic recording techniques utilizing Bragg selectivity include angular multiplexing, wavelength division multiplexing, and shift multiplexing with spherical waves, while multiplex techniques that do not utilize Bragg selectivity include phase code multiplexing, speckle multiplexing, and co-axial shift multiplexing.

Among them, the multiplexing technique that uses spherical waves as a reference wave is characterized by its ability to enable multiplexing recording only by displacing (shifting or rotating) the recording medium. Since a spherical wave can be regarded as overlapping plane waves advancing in different directions, the shape of the diffraction grating is a function of the location in the medium. If the positional relation between the recording medium and reference wave is the same as that when the hologram was recorded, then the Bragg condition is met and the hologram can be retrieved; however, if the recording medium deviates from the reference wave, then the Bragg condition is not met and the hologram will not be retrieved. Therefore, multiplex recording is enabled in this technique by simply displacing the recording medium.

In shift multiplexing with spherical reference wave, we can find both an axis where shift selectivity suddenly occurs and an axis where shift selectivity slowly occurs. To improve recording density of this shift multiplexing technique, we worked out a technique of shift-peristrophic multiplexing with spherical reference wave that combines peristrophic (rotation) multiplexing with shift multiplexing with spherical reference waves. In this research, we analyze diffraction characteristics of peristrophic multiplexing with spherical reference wave such as rotational selectivity based on a theoretical model. Additionally, we verify the effectiveness of the model by comparing it with experimental results.

9508-10, Session 3

Humidity and temperature response of photopolymer-based holographic gratings

Tatsiana Mikulchyk, Dublin Institute of Technology (Ireland) and Centre for Industrial and Engineering Optics (Ireland); James Walshe, Dublin Institute of Technology (Ireland); Dervil Cody, Focas Research Institute, DIT (Ireland); Suzanne Martin, Izabela Naydenova, Dublin Institute of Technology (Ireland) and Centre for Industrial and Engineering Optics (Ireland)

Holographic sensors have great potential in various applications ranging from in vitro diagnostics to optical security. They are capable of providing fast, real-time, reversible or irreversible, visual colorimetric or optical readouts. The main challenge in the development of a specific holographic sensor is to create a holographic recording material responsive to a specific analyte. This material should be permeable to the analyte and its properties should change under exposure to the analyte. Specificity is also very important; responses to other analytes should be minimized.

This work explores the effects of humidity and temperature on properties of volume phase gratings recorded in photopolymers containing acrylamide and diacetone acrylamide as monomers, and triethanolamine and N-phenylglycine as photoinitiators.

Characterization of the humidity response of photopolymer-based gratings in the relative humidity range RH=20-90% was carried out by measurement of the diffraction efficiency of slanted transmission gratings and the position of the maximum intensity in the spectral response of reflection gratings. A strong dependence of the diffraction efficiency of transmission gratings recorded in diacetone acrylamide-based photopolymer on RH was observed even at low RH whereas significant changes in diffraction efficiency of acrylamide-based gratings was found to be at RH>70%. Humidity dependence of the spectral response of the reflection gratings showed that photopolymers containing triethanolamine is more hydrophilic than photopolymers containing N-phenylglycine.

Exploration of the temperature effect on properties of slanted transmission gratings recorded in photopolymers was carried out in the temperature range 20–50 ?C. Exposure to temperature was found to cause significant Bragg angle shift in case of photopolymers containing triethanolamine.

The results demonstrate an effective approach to obtaining photopolymer-based gratings with tuneable temperature and humidity sensitivity.

9508-11, Session 3

Read-out optical schemes for holographic memory system based on multiplexed computer generated 1D Fourier holograms

Sergey S. Donchenko, Sergey B. Odinokov, Vladimir I. Bobrinev, Alexandr Y. Betin, Evgenie Y. Zlokazov, Bauman Moscow State Technical Univ. (Russian Federation)

Computer synthesis of holograms allows to significantly simplify the recording scheme of microholograms in holographic memory system as the classic high precision holographic setup based on two-beam interference is removed by simple scale reduction projection scheme. Application of computer generated 1D-Fourier holograms provides the possibility of selective reconstruction of the multiplexed holograms with different orientation of data lines by corresponding rotation of anamorphic objective (cylindrical lens), used in the read-out systems. Ttwo configurations of read-out optical scheme were investigated by our team: full-page scheme and line-by-line scheme. In the present article we report the specificities of these schemes and consider their advantages and disadvantages. The results of experimental modeling of both read-out configurations are also presented.

9508-12, Session 3

Image fusion using bi-directional similarity

Chunshan Bai, Xiaoyan Luo, BeiHang Univ. (China)

In the practical application of multi source image fusion,infrared images with abundant information is in great demand,so to enhance the infrared image by the visual image become an important mode in the direction of integration of multi source image.In this paper,We propose an effective method based on the bidirectional similarity.

The proposed method aims to realize the efficient fusion of multi source images.In the process,without introducing intermediate image,only from many feasible solution according to the demand of application and some priori constraints ,we find an optimal solution which meet the requirements of image fusion,so it can preserve good characteristics in the infrared image and spatial information in the visual image.In the certain iterative step,by using the matrix that contain the square of the difference between images,we can fuse the image that retains the most information,and the image is clear and smooth.Then,we put the image fusion according to the weight.On the other hand,the method can well solve the problem of underdetermined recovery,avoid missing information about the space in the image fusion process,and support the solid theory for the recovery of image.

The infrared image and visual images generally is optical image.in order to persist the source information and improve the scope of application about the methods,image fusion in the pixel level can obtain better effect. We believe that the proposed scheme can have wide applications.

9508-27, Session PS

Design and experiments of combined diffractive optical element for virtual displays and indicators

Artem Solomashenko, Sergey B. Odinokov, Alexander Y. Zherdev, Maria Ruchkina, Gaik Sagatelyan, Bauman Moscow State Technical Univ. (Russian Federation)

Currently, diffractive optical elements (DOEs) with light guide substrates are used in miniature display systems where the display is superimposed on real imagery. By the use of these elements, the weight and size of display and visualization systems can be significantly reduced. The use of holographic indicators in different climatic conditions requires the physically protection of special photosensitive materials for DOEs or recorded directly into the glass. Also in order to project multi-colored images, DOEs need to be designed with the specified spectral and angular selectivity. The design of a new type of combined DOEs with increased diffraction efficiency and spectral-angular selectivity will facilitate the development of a new generation of signs-symbolic information displays, based on holographic optical elements and light guide substrates.

A typical scheme of a holographic display are considered and modified. The main component of such system is a signs-symbolic information output device, which can be mounted directly on the head. These devices include a glass substrate, in which radiation can propagate with total internal reflection, and diffraction gratings at the output of radiation. But in this case the combined DOE is used instead of gratings.

The combination of four-level diffractive optical elements having high diffraction efficiency with spectral transmissive filters that have a bandwidth that varies with the angle of incidence inside a single DOE is explored. To ensure high diffraction efficiency and protect gratings, DOEs must be fabricated directly in the glass, and multi-level structures of relief rather than binary structures are required for this purpose. To realize the spectral selection when the source is white or polychromatic light is the use of plasmonic effects in metal-dielectric thin films. This enables the creation of spectral filters with adjustable bandwidth by changing the

angle of incidence of the input light. The most simple meander four-layer structure “glass substrate–photoresist–silver-SiO2” is considered as plasmon filter. The meander structure can be produced in the photoresist or glass layer by lithography and ion-plasma etching technology.

To analyze these elements, Fourier modes method is used for solving Maxwell’s equations. It involves the implementation of special software to solve the direct diffraction of a plane electromagnetic wave by a multi-level rectangular and meander structure. Basic parameters of the combined DOE are calculated by this software and according to these parameters experimental samples are manufactured. The theoretical and experimental results suggest the possibility of using this combined DOE for displays, screens, and indicators showing signs-symbolic information.

9508-28, Session PS

Coping with diffraction effects in protein-based volumetric memories: a possible solution for the case of completely random data

Dragos Trinca, Piretus Prod S.R.L. (Romania); Sanguthevar Rajasekaran, Univ. of Connecticut (United States)

Much of the current research effort in biological nanotechnology is directed toward protein-based memories [1,2,3]. Previous work dealing with the diffraction effects in protein-based memories has reported that these effects can be reduced if one can reduce the differences between the refractive indices within the same page [2]. In terms of binary representations, this can be achieved if the number of 0’s is equal to the number of 1’s.

Most of the binary representations don’t have an equal number of 0’s and 1’s. One way of ensuring an equal number of 0’s and 1’s is to replace a 0 with 01 and a 1 with 10. However, this would reduce the available memory by a factor of 2 (which means that the utility factor would be 50% in this case). There are many algorithms that have been proposed and shown to achieve utility factors of 100% or even more. However, for completely random data, the best utility factor provided by previously proposed algorithms is about 99.9%, and can be obtained by using the APPROXv3 algorithm [3].

In this work-in-progress, we propose the following algorithm that could provide an utility factor of at least 100% in the case of completely random data. Let bl be the input data, in binary format.

1. Let t be an input parameter such that 1≤t< L, where L is the length of bl. In practice, t is usually chosen such that it is significantly smaller than L, the reason being that we try to compress only a small portion of bl (in step two of the algorithm), since if bl is large enough (even a few thousand bits) then common compression algorithms are not able to actually “compress” bl.

2. Compress bl_{1:t}, that is, the first t bits of bl, using a compression algorithm. Let Y be the output, also binary.

3. Apply the APPROXv3 algorithm for the binary string Ybl_{t+1:L}.

If Y is of length at most t-62, then clearly the output in the above algorithm has length at most L, which means that in such a case the above algorithm would provide an utility factor of at least 100%. However, the challenge here is to develop a compression algorithm that would compress bl_{1:t} in the second step such that Ybl_{t+1:L} is of length not greater than the length of bl.

REFERENCES:

[1] R.R. Birge, N.B. Gillespie, E.W. Izaguirre, A. Kusnetzow, A.F. Lawrence, D. Singh, Q.W. Song, E. Schmidt, J.A. Stuart, S. Seetharaman, and K.J. Wise (1999) Biomolecular Electronics:? Protein-Based Associative Processors and Volumetric Memories, Journal of Physical Chemistry B 103, 10746-10766

[2] S. Rajasekaran, V. Kumar, S. Sahni, and R. Birge (2008) Efficient algorithms for protein-based associative processors and volumetric memories, Proc. of IEEE NANO 2008, 397-400

[3] D. Trinca and S. Rajasekaran (2013) Biomolecular Electronics:? Protein-Based Associative Processors and Volumetric Memories, Journal of Computational and Theoretical Nanoscience 10, 894-897

9508-29, Session PS

Tomographic microscopic imaging with enhanced axial resolution by compressive holography

Yuhong Wan, Fan Wu, Tianlong Man, Xiaole Guo, Beijing Univ. of Technology (China)

The traditional holography can capture the amplitude and the phase of an object on a 2D surface. However, it is ill-posed to retrieve truly tomographic images from a single 2D hologram. Compressive Sensing (CS) offers a mathematical framework which allows us to reconstruct the original data from many fewer measurements than suggested by Shannon’s sampling theorem. In recent years, compressive sensing has been successfully applied in digital holography (DH) resulting in the concept of compressive holography. Compressive holography formulated holography as a compressive sensing problem and the reconstruction of original object as an inverse problem, thus it enables 3D reconstruction from a single undersampled 2D hologram by solving the minimization problem. The practical resolving power and reconstruction fidelity of compressive holography depend on the effective numerical aperture (NA) of the system. The transverse and the axial resolution of the imaging system are ?x=?/NA and ?z=?/NA? respectively. Therefore, if we want to improve the quality of tomographic image we should improve the axial resolution by increase the numerical aperture NA. Although a microscopic additional objective lens tends to increase system volume and decrease field of view, it can be used to increase the NA of a system by magnifying the field entering the objective. In this paper, we combine microscopic compressive holographic system and 4f amplifying system to enhance the axial resolution. The tomographic image of 3D biological samples are demonstrated by using 4f amplified off-axis microscopic compressive holography. The experiments are designed and implemented based on 4f amplified off-axis digital microscopic holography using Mach-Zehnder interferometric recording set-up. The reconstruction was carried out using two-step iterative shrinkage/thresholding algorithm (TwIST) to decompress. Basing on the theoretical analysis and experimental investigation, we compared the axial resolution of 4f amplifying off-axis microscopic compressive holography and off-axis microscopic compressive holography. This System enables accurately tomographic images from a single 2D undersampled hologram while improves the quality of the reconstruction and enhanced axial resolution of the compressive holography.

9508-30, Session PS

Modeling of effect of LC SLM phase fluctuations on kinoforms optical reconstruction quality

Vitaly V. Krasnov, Pavel A. Cheremkhin, Nikolay N. Evtikhiev, Vladislav G. Rodin, Sergey N. Starikov, National Research Nuclear Univ. MEPhI (Russian Federation)

Phase-only liquid crystal (LC) spatial light modulators (SLM) are actively used in various applications. However, majority of scientific applications require stable phase modulation which might be hard to achieve with commercially available SLM due to its consumer origin. The use of digital voltage addressing scheme leads to phase temporal fluctuations, which results in lower diffraction efficiency and reconstruction quality of displayed diffractive optical elements (DOE). It is often preferable to know effect of these fluctuations on DOE reconstruction quality before SLM is implemented into experimental setup. It is especially important in case of multi-level phase-only DOE such as kinoforms. Therefore we report results of modeling of effect of phase fluctuations of LC SLM “HoloEye PLUTO VIS” on kinoforms optical reconstruction quality. Modeling was conducted in the following way. First dependency of LC SLM phase shift on addressed signal level and time from frame start was measured for all signal values (0-255) with temporal resolution of 0.5 ms in time period of one frame. Then numerical simulation of effect of SLM phase fluctuations on kinoforms reconstruction quality was performed. Based on measured dependency, for each time delay new distorted kinoform was generated and then numerically reconstructed. Averaged

reconstructed image corresponds to optically reconstructed one with registration time exceeding time period of one frame (16.7 ms), while individual images correspond to momentary optical reconstruction with registration time less than 1 ms. Quality degradation of modeled optical reconstruction of several test kinoforms was analyzed. Comparison of kinoforms optical reconstruction with SLM and numerically simulated reconstruction was conducted.

9508-31, Session PS

Retractions of the gingival margins evaluated by holographic methods

Cosmin Sinescu M.D., Meda Lavinia Negrutiu M.D., Univ. of Medicine and Pharmacy Victor Babes Timisoara (Romania); Virgil-Florin Duma, Aurel Vlaicu Univ. of Arad (Romania) and Politehnica Univ. of Timisoara (Romania) and Univ. of West Timisoara (Romania)

The periodontal disease is one of the most common pathological states of the teeth and gums system. The issue is that its evaluation is a subjective one, i.e. it is based on the skills of the dental medical doctor. As for any clinical condition, a quantitative evaluation and monitoring in time of the retraction of the gingival margins is desired. This phenomenon was evaluated in this study with a holographic method by using a HeNe laser with a 1mW power. The holographic system we have utilized – adapted for dentistry applications - is described. Several patients were considered in a comparative study of their state of health – regarding their oral cavity. The impressions of the maxillary dental arch were taken from a patient during his/her first visit and after a period of six months. The hologram of the first model was superposed on the model cast after the second visit. The retractions of the gingival margins could be thus evaluated three-dimensionally in every point of interest. An evaluation of the retraction has thus been made. Conclusions can thus be drawn for the clinical evaluation of the health of the teeth and gums system of each patient.

9508-32, Session PS

Potorefractive phase-conjugation digital holographic microscopy

Chi-Ching Chang, Huang-Tian Chan, Min-Tzung Shiu, Yang-Kun Chew, MingDao Univ. (Taiwan)

In this work, we propose an innovative method for digital holographic microscopy named as photorefractive phase-conjugation digital holographic microscopy (PPCDHM) technique based on the phase conjugation dynamic holographic process in photorefractive BaTiO3 crystal and the retrieval of phase and amplitude of the object wave were performed by a reflection-type digital holographic method. Both amplitude and phase reconstruction benefit from the prior amplification by mutually pumped conjugation (MPPC) as they have an increased SNR. The interest of the PPCDHM is great, because its hologram is created by interfered the amplified phase-conjugate wave field generated from a photorefractive phase conjugator (PPC) correcting the phase aberration of the imaging system and the reference wave onto the digital CCD camera. Therefore, a precise three-dimensional description of the object with high SNR can be obtained digitally with only one hologram acquisition. The method requires the acquisition of a single hologram from which the phase distribution can be obtained simultaneously with distribution of intensity at the surface of the object.

The idea shows in this work that, for the first time to the best of our knowledge, the combination of the phase conjugation of object wave generated by a photorefractive BaTiO3 crystal and reconstruction hologram by digital holographic microscopy method that is possible to obtain the quadratic phase compensated 3D imaging of several micro-structured samples. The proposed combination of digital and photorefractive holography could open up new era and applications for digital holography for example for imaging through scattering media in biomedical applications.

9508-33, Session PS

Estimation of objects transverse parameters in off-axis and in-line Fresnel digital holography

Pavel A. Cheremkhin, Nikolay N. Evtikhiev, Vitaly V. Krasnov, Vladislav G. Rodin, Sergey N. Starikov, National Research Nuclear Univ. MEPhI (Russian Federation)

Digital holography is popular method for reconstruction of 2D and 3D scene. It is used in different fields of science and technology: interferometry, microscopy, optoelectronic information processing, and etc. Off-axis and phase-shifting inline schemes are usually used for digital holograms recording. Phase-shifting digital holography allows to record objects with bigger transverse dimensions than off-axis holography does. Usage of elements like phase plates allows to record interference patterns with different phase shifts and to separate object image from undesirable zero-order and twin images with software. Main disadvantage of phase-shifting scheme is necessity for a stable positioning of experimental setup elements during digital holograms recording. In case of off-axis digital holography there are three diffraction orders at hologram reconstruction field. In result, additional condition for obtaining of object image with low noise level is imposed: object image should not overlap with zero-order and twin images. If object and twin images are located on opposite sides relatively to zero-order under reconstruction, this is the case of preventing of cyclic shift of twin image (PCS). If twin image is located on both sides relatively zero-order under reconstruction but don't overlap with object image, this is the case of assumption of cyclic shift of twin image (ACS). The ACS case allows to register digital holograms of larger objects compared to the PCS case. However, for example, for automatic image processing, separate display of object and twin images relatively to zero-order under reconstruction is often required. Therefore both PCS and ACS are considered.

In this report transverse parameters of objects registered with inline and off-axis Fresnel digital holography schemes were estimated. Maximum transverse dimensions of objects, size and quantity of object resolution elements were evaluated. By determining allowed locations of diffraction orders under reconstruction, new expressions for estimation of objects transverse parameters were obtained. Also, earlier proposed relations were systematized both for inline and off-axis Fresnel digital holography.

Using obtained expressions, dependencies of object transverse parameters on distance between object and hologram were derived. It was found that the ACS case allows to record holograms with distance between the object and hologram 1.5 times lesser than in the PCS case. With increase of distance between object and hologram, maximum quantity of object resolvable elements becomes half of the hologram pixels quantity. This is the case of Fourier hologram of diffusely scattered object. Maximum transverse dimension of object in ACS case is always greater than in the PCS case by the half of hologram size.

For verification of obtained estimates and dependencies, off-axis digital Fresnel holograms were optically recorded. Holograms had 2048x2048 pixels with sizes of 9um x 9um. Distance between object and hologram was equal to 1040 mm. The source of light was a 50 mW frequency-doubled Nd:YAG laser with wavelength 532 nm. Contour images located behind static scatter were used as objects. Transverse size of objects can range from 1 mm to 30 mm. Confirmations of transverse object parameters estimates, satisfying ACS or PCS cases, were derived. These results demonstrate correctness of obtained quantitative estimates.

9508-34, Session PS

Study of transparent particles in the volume of optical medium using digital holography and singular-optics approach

Tatiana Y. Nikolaeva, Nikolay V. Petrov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Due to the advent of high-resolution digital image recording facilities, great progress has been achieved in the area of digital image processing

techniques. They allow measurement methods of qualitative and quantitative characteristics of particle flows or distributions of particles suspended in a volume of an optical medium to be implemented in numerical form. The necessity of study of statistics and characteristics of the particles in the volume of the medium emerges in many scientific and practical applications. For example, in atmospheric optics it is challenging to study gas-dynamic flows and fogs, and in oceanology and biology the study of small suspended particles or small organisms in the liquid such as plankton particles is one of the topical issues for a research. The study of particles that are transparent to the probing radiation but introduce a phase delay (phase objects) appears to be relevant especially in the fields of biology and medicine. In this paper, we propose an approach to the study of the distribution of transparent particles suspended in a volume of optical medium, which combines the method of digital holography and the concept of singular optics. For statistical analysis of the particle distribution we use a method, based on the obtainment and analysis of zerograms (distributions of amplitude zeros) introduced earlier for diagnostics of rough surfaces. The propagation of electromagnetic radiation through the volume of the optical medium with different statistical distributions of particles in it is numerically simulated. We consider two particle distributions: random distribution and normal distribution obtained using the Box-Muller transform. Images of particles are obtained using 4f optical imaging system. Processing of the reconstructed images of the particles involves obtaining zerograms and histograms. To obtain a distribution of amplitude zeros we determine the coordinates of points on the restored complex field where the real and imaginary parts are equal to zero. Each particle image is divided into segments, in which the local density of amplitude zeros is calculated, and a histogram characterizing the distribution of local densities is built. In this paper the density fluctuations of transparent particles in the optical medium are studied. It is shown that the increase of concentrations and/ or particle size leads to the formation of conglomerates of particles, which can be identified by analyzing the distribution of the local densities of amplitude zeros.

9508-35, Session PS

Application of fractal masks with spiral phase distribution for the determination phase discontinuities in transparent objects

Alexander A. Zinchik, Yana B. Muzychenko, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

The homogeneity of the refractive index and the phase is one of the fundamental qualitative properties of the transparent films. Methods of nondestructive checking has important role in detection of phase and refractive index discontinuities, some of them based on optical image processing.

Imaging and visualization of thin transparent phase objects such as liquid flows, biological samples, thin films, etc. are areas of considerable interest and invite extensive research. Also, the study of the phase aberrations and discontinuities in transparent optical components is important in the field of applied optics. At the present time the methods of the coherent optical image processing of the two-dimensional periodic structures photographed through researched object, allow to receive the partite information on components of a gradient of a refraction index, arbitrarily to adjust reference bands, and also to regulate sensitivity of measurements.

Application of the masks (filters) consisted of two-dimensional periodic structures has some disadvantages because of rapidly decreasing power of the spatial spectrum of the masks in radial direction.

Several years ago, was proposed to replace the periodic structure of the fractal.

The main reason of using these fractal masks instead of periodic structures is the greater power of high spatial frequencies. In this case it appears possible to register not only more precisely small refractivity gradients of the object, but also automatically to select the characteristic periods of its discontinuities.

In this paper we propose the new method of nondestructive checking, based on application of the masks with fractal amplitude part and spiral phase distribution photographed through the objects of studying.

As a result of the study it was shown, that the power of high spatial frequencies of the fractal mask with spiral phase distribution spectrum is ten times greater in comparison with spectrum of regular or amplitude fractal masks. The analysis of results of the inverse Fourier transform of the distorted spectrum of regular and fractal masks with spiral phase distribution shows that the fractal mask is more sensitive and allows obtain more precisely the value of distortion of the initial object.

9508-36, Session PS

Spectral analysis in overmodulated holographic reflection gratings recorded with BB640 ultrafine grain emulsion

Pedro Mas-Abellán, Roque Madrigal, Antonio Fimia, Univ. Miguel Hernández de Elche (Spain)

Silver halide emulsions have been considered one of the most energetic sensitive materials for holographic applications.

Nonlinear recording effects on holographic reflection gratings recorded on silver halide emulsions have been studied by different authors obtaining excellent experimental results. In this communication specifically we focused our investigation on the effects of refractive index modulation, trying to get high levels of overmodulation. We studied the influence of the grating thickness on the overmodulation and its effects on the transmission spectra for a wide exposure range by use of two different thickness ultrafine grain emulsion BB640, thin films (6 ?m) and thick films (9 ?m), exposed to single collimated beams using a red He-Ne laser (wavelength 632.8 nm) with Denisyuk configuration obtaining a spatial frequency of 4990 l/mm recorded on the emulsion. The gratings were developed with AAC developer (Ascorbic Acid 18 g/l + Sodium Carbonate 60 g/l) and bleached with reversal bleach R-9 (Potassium Dichromate 2 g/l + Sulphuric Acid 10 cc/l) and fixation-free rehalogenating bleaches R-10 (Potassium Dichromate 2 g/l + Sulphuric Acid 10 cc/l + Potassium Bromide 35 g/l) and EDTA (Sulphuric Acid 10cc/l + Potassium Bromide 30 g/l + Ferric Sulphate 30 g/l + EDTA Disodium Salt 30 g/l).

The experimental results show that high overmodulation levels of refractive index could offer some benefits such as high diffraction efficiency (reaching 90 %), increase of grating bandwidth (close to 80 nm), making lighter holograms, or diffraction spectra deformation, transforming the spectrum from sinusoidal to approximation of square shape. Based on these results, we demonstrate that holographic reflection gratings spectra recorded with overmodulation of refractive index is formed by the combination of several non-linear components due to very high overmodulation. This study is the first step to develop a new easy multiplexing technique based on the use of high index modulation reflection gratings.

9508-37, Session PS

Amplitude-phase type fractal screens and their application in phase-retrieval method

Yana B. Muzychenko, Alexander A. Zinchik, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

It was demonstrated that properties of diffractal differ essentially from properties of waves diffracted from regular geometrical objects. The principal one is that the diffraction spectrum from fractal exhibits self-similarity properties as same as initial objects. The diffraction optical elements with fractal structure have advantages over the convenient regular gratings as their diffraction spectra possess prevailing power of high spatial frequencies in comparison with two-dimensional periodic structures. This property could be applied for spatial filtering and transparent objects phase heterogeneities detection.

In this paper the analysis and comparison of diffraction spectra of amplitude-phase type fractal screens are presented. Amplitude-phase type fractal screens based on well-known fractals, possess exact or statistical self-similarity, but have managed amplitude transmittance and phase shift which are correlated with fractal spatial characteristics. Modeling and experiment results show that diffraction spectrum of amplitude-phase type fractal screens possess prevailing power of high frequencies in comparison with spectra of fractal structures with binary transmittance and phase shift. Averaging scattering indicatrixes and correlation functions for fractal screens with different parameters are presented.

The problem of phase retrieval arises in various fields of science and engineering, including electron microscopy, biology, crystallography, astronomy, and optical imaging. At presence there is a great number of phase retrieval methods based on iterative algorithms and additional intensity distribution registration. Some of existing retrieval methods without reference wave based on intensity registration at different planes, others use multispectral wavelength registration. It was described the phase retrieval and wavefront sensing method using random amplitude mask. In this paper we propose to use fractal regular or random mask with high power of high spatial frequencies in diffraction spectrum.

9508-38, Session PS

Synthesis of Fourier holograms for recognition of radiation sources with continuous spectra by dispersive correlators

Dmitriy Y. Molodtsov, Sergey N. Starikov, Vladislav G. Rodin, National Research Nuclear Univ. MEPhI (Russian Federation)

Dispersion correlators have been proposed previously for solving problems of recognition of radiating objects in real time. It is achieved using object's spatial and spectral parameters. Spectral composition of radiation, emitted or scattered by object, is also taken into account in such correlators in addition to spatial parameters of objects. Correlation signals are formed by radiation of analyzed object during its interaction with spatial filter. Fourier holograms can be used as filters. Maximum of correlation distribution parameters in correlator's output plane achieves when spatial parameters of input and reference objects coincide. Spectrum of radiation of this maximum is composed of all overlapping spectral components of input and reference spectra.

Most difficult recognition case is when spectrum of input radiation is continuous (non-line spectrum). In this work slit is used as reference object at recognition of spectral composition of radiation in such correlator. Correlation distribution for each component of radiation spectrum forms at stage of recognition. For successful recognition of spectral characteristics two conditions should be fulfilled. Firstly, localization of correlation signals for those spectral components which information is to be recorded on filter, should be achieved. Secondly, peaks of correlation signals of object's spatial parameters for all spectral components of radiation, which coincides with components presented on filter, should be formed in a single point on output plane.

Method of synthesis of Fourier holograms for its using in dispersive correlators as spatial filters is developed in this work. Spectral range, in which value of component of radiation is greater than predetermined threshold for reference spectrum, was determined. Next, spatial image of spectrum, which is a set of images of object (slit), was formed. Amount of object images and its dimensions are determined by selected wavelength ranges. Fourier hologram of this image was computer synthesized and had 2048x2048 pixels. Then this hologram was binarized and printed using laser imagesetter with 100 dots/mm resolution.

In this work the scheme of the dispersive correlator with single Fourier-objective was used. Correlation signals for different spectra were experimentally formed. LEDs, including RGB-LED with ability of dynamically changing of composition of radiation spectrum, were used as radiation sources. Correlation signals for cases of fully coinciding and partial overlapping of reference and input spectra were experimentally formed. Spectral compositions of sources radiation and correlation signals were monitored using spectrum analyzer.

Results analysis shows that for reliable recognition post-processing of registered correlation signals is required. Post-processing operations, which provide independence of recognition results from radiation source power and holograms diffraction efficiency, were defined. Three methods of normalization of correlation signal for identification signal obtaining were experimentally tested and compared. These methods are normalization to radiation power in zeroth, first, and both of these diffraction orders. Experimental results on identification of test sources with non-line radiation spectra are obtained. They show successful recognition of used LED sources of different colors. Average ratio of spectra coincidence signal to mismatch signal was 4.6 at relative spectral resolution of used setup equaled to 0.004.

9508-39, Session PS

Direct real-time measurement of shrinkage in photopolymer materials during recording of reflection gratings

Petr Vojtísek, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic); Milan Kveton, Czech Technical Univ. in Prague (Czech Republic)

Photopolymer recording materials aimed at a recording of holograms, diffraction elements for manipulation of light or storing of information received great deal of attention in recent years. For their optimal application it is desirable to characterize them and to know what to expect from them. During the recording of the diffraction gratings (or elements) into this photopolymer materials (but not exclusively) there can be some volume changes of the material itself (so-called shrinkage) which consequently alter the performance of such gratings, for example from a perspective of a color fidelity, reconstruction conditions, or diffraction efficiency. The main aim is to in advance pre-compensate for such volume changes so the resulting grating will have desired properties. In this contribution, we would like to present and discuss measurement method for direct and real-time detection of such volume changes for reflection gratings in low shrinkable photopolymer materials. This measurement method is based on a reconstruction of the grating with low intensity white light under slightly different angle than is the angle of the recording and the analysis on the idea of fringe plane rotation model. For a theoretical background the Kogelnik's Coupled Wave theory and Rigorous Coupled Wave Analysis are used. The recording of the diffraction gratings and measurement of their volume changes is experimentally done for a photopolymer material Bayfol HX.

9508-13, Session 4

3 Dimensional numerical model of holographic grating formation in photopolymer materials *(Invited Paper)*

Haoyu Li, Yue Qi, Ra'ed Malallah, 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.

9508-14, Session 4

Photorefractive amplification of dynamic light signals using photoconductive ferroelectric liquid crystals

Takeo Sasaki, Tokyo Univ. of Science (Japan)

The photorefractive effect is a phenomenon that allows for the formation of holographic images within a material; it provides the potential to realize dynamic holograms by recording holograms as a change in the refractive index of a medium. The characteristic phenomenon of the photorefractive effect is asymmetric energy exchange in two-beam coupling that can be used to coherently amplify signal beams; therefore, the photorefractive effect has the potential to be used in a wide range of optical technologies similar to a transistor in electrical circuits. Organic materials in particular have attracted significant interest in this context since 1994, because they exhibit large photorefractivity and shorter response times. The photorefractive effect in liquid crystals (LCs) has been investigated previously. LCs are basically liquid, so they can be easily driven by a low electric field. LCs are classified into several groups, the most well known of which are nematic and smectic LCs. Nematic LCs are used in liquid crystal displays (LCDs), whereas smectic LCs are very viscous and are thus seldom utilized in practical applications. Nematic LCs were first used as a photorefractive LC and large photorefractivity was obtained with the application of an electric field of only a few volts per micrometer. In this study, 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.

9508-15, Session 4

Formation of dissipative structures at hologram recording in CaF2 crystals with color centers

Alexander Shcheulin, Aleksandr Angervaks, Andrey Veniaminov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Pavel P. Fedorov, Sergey Kuznetsov, A. M. Prokhorov General Physics Institute (Russian Federation); Alexander I. Ryskin, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

The structuring of holographic planes in hologram recorded in CaF2 crystal with color centers is found. This structuring is apparent in formation of spiral bundles of Ca atoms, which pierce the holographic planes. The hologram recording in CaF2 is based on the photochromic transformation of various-type color centers introduced in the crystal at heating at 730-850 °C in the reduction atmosphere of metal-cation (“additive coloring”). At additive coloring two flows, anion vacancies and electrons diffuse from the surface into the crystal bulk. Recombination of these components results in formation of the set of color centers that may be conditionally divided into “simple” centers (F-, M-, N- and R-centers with 1–4 anion vacancies and the same quantity of electrons; and “colloidal” centers. These centers may be considered as the second phase inclusions in the crystal lattice. The recording of holograms in CaF2, crystals with color centers is possible due to photochromism of these centers, i.e., their transformation under the influence of illumination at an enhanced temperature. This process results in conversion of the center type and modification of absorption spectrum of the crystal. Hologram recording results in the increase of highly aggregated colloidal centers at the expense of simple centers. Recording mechanism is based not only on the center conversion but also on their redistribution over the crystal bulk: color centers leave the maxima of the fringe pattern and are concentrated in its minima. Nevertheless the maxima are not totally deprived of color centers due to the center thermal-decay in minima at the recording temperature T = 190 °C; in maxima this process also take place together with photo-decay of the centers. Thus, the hologram recording is accompanied by permanent formation and decay of colloidal centers, i.e., by the phase transition. Bundle formation testifies to the self-organization of color centers in holographic planes. An internal self-consistency (self-organization) arises in complex systems at interaction of various sub-systems. Their interaction occurs to be most effective near the phase transition, when the sub-system that experiences the transition becomes soft and weak external perturbation may result in the strong modification of its state, in particular, its order parameter [1]. In this case the phase transition is connected with formation and decay of colloidal centers in holographic planes and perturbations could be fluctuations of the concentration of simple centers, vacancies, and electrons. These fluctuations may trigger large-scaled stable space-inhomogeneous states in the holographic planes (dissipative structures). Just such states are the bundles. They are formed at the recording condition and are frozen at cooling the crystal after finishing the recording process. At some recording condition bundles form the regular grating. Probably, the grating is conductive; if this is the case, it means we are dealing with a meta-material.

1. G. Nicolis, I. Prigogine, Self-Organization in Nonequilibrium Systems: From Dissipative Structures to Order Through Fluctuations (Wiley, 1977).

9508-16, Session 4

Advances in photo-thermo-refractive glass composition modifications

Sergey A. Ivanov, Nikolay V. Nikonorov, Alexandr Ignatiev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

The novel photo-thermo-refractive (PTR) glass developed in National Research University of Information Technology, Mechanics and Optics (St. Petersburg, Russia) is a very promising optical material for photonic and plasmonic applications. In the present work authors make a comparison of the optical and holographic properties of the new and classic composition of glass.

The PTR glass is a photosensitive material in which nano sized crystalline phase is grown in the glass host due to the process of photo-thermo-induced (PTI) crystallization. The process of PTI crystallization is complex and includes several steps with participation of different ions. Trivalent cerium is the donor of photo-electrons and response for photosensitivity of material. Ions of silver antimony and tin at first plays role of acceptors of photo-electrons, i.e. capturing the electrons from cerium, at second, during thermal treatment process, acts role of donors, i.e. giving electrons to the silver ions, which due to the further thermal treatment creates a colloid particles. Halides, fluorides and bromides are responsible for growth of crystalline shell on the silver colloid particle and further growth of crystalline phase on the colloid particle shell.

Classic PTR glass has 2 main disadvantages such as scattering at the border of crystalline phase and optical losses in visible spectra with maximum at 450nm. This restricts the application of holograms recorded on this media. In the present work was made the optimization of concentration of halides, fluorides, bromides which are responsible for crystalline phase properties. Ions of antimony, which playing key role in catching and transferring electrons emitted during the UV exposure and subsequent heating. Also was lowered the concentration of stray impurity ions which a capable to catch photo-electrons. Optical spectra shows that new composition of PTR glass has no absorption band in visible range caused by metal Nano particles of silver. That allows recording of pure phase holograms in wide spectral range. Furthermore new PTR glass allows receiving refractive index modulation up to 1500 ppm, what is twice more than in classic composition. And the UV exposures needed to achieve maximum changes in refraction index are 6-7 times lower than in classic glass.

9508-17, Session 5

Self-Trapping of optical beams in a self-written channel in a solid bulk photopolymer material *(Invited Paper)*

Haoyu Li, Yue Qi, Ra'ed Malallah, Univ. College Dublin (Ireland); James P. Ryle, National Univ. of Ireland, Maynooth (Ireland); John T. Sheridan, Univ. College Dublin (Ireland)

We demonstrate theoretically and experimentally that the light can be self-focused and self-trapped in a self-written optical waveguide in a bulk acrylamide/polyvinyl alcohol (AA/PVA) solid photopolymer material volume. The manufacture method, i.e., how to prepare the AA/PVA photopolymer material is detailed. In our experimental observation the refractive index changes induced are permanent. The resulting optical waveguide channel has good physical stability and can be integrated with optoelectronic devices as part of integrated optical systems. The theoretical model developed predicts the formation/evolution of the observed self-written waveguides inside the bulk material. The model involves appropriately discretizing and then numerically solving the paraxial wave equation in Fourier space and the material equation in time space.

9508-18, Session 5

2nd harmonics HOE recording in Bayfol® HX

Christian Rewitz, Friedrich-Karl Bruder, Thomas Fäcke, Rainer Hagen, Dennis Hönel, Enrico Orselli, Thomas Rölle, Günther Walze, Brita Wewer, Bayer MaterialScience AG (Germany)

Volume Holographic Optical Elements (vHOEs) provide superior optical properties over DOEs (surface gratings) due to high diffraction efficiencies in the -1st order and their excellent Bragg selectivity. Bayer MaterialScience is offering a variety of customized instant-developing photopolymer films to meet the specific requirements for an optics design: at first the photopolymer film thickness is an ideal means to adjust the angular and the spectral selectivity; secondly the index modulation can be adopted with the film thickness to achieve a specific required dynamic range, which is especially helpful for transmission type holograms and in multiplex recordings. And finally a selection of different substrates is helpful to achieve the overall optical properties for a targeted application that we support in B2B-focused developments. To provide further guidance on how to record volume holograms in Bayfol® HX, we describe in this paper a new route towards the recording of substrate guided vHOEs by using optimized photopolymer films and writing conditions that are suitable to create higher 2nd harmonic intensities.

Due to total internal reflection (TIR) at the photopolymer-air interface in substrate guided vHOEs, hologram recording with those large diffraction angles cannot usually be done with two free-space beams. Edge-lit recording setups are used to circumvent this limitation. However, such setups require bulky recording blocks or liquid bathes and are complex and hard to align. A different approach that we present in this paper is to exploit 2nd harmonic grating generation in a free-space recording scheme. Those 2nd harmonic components allow replay of diffraction angles that are normally only accessible with edge-lit writing configurations. Therefore, this approach significantly simplifies master recordings for vHOEs with edge-lit functionalities, which later can be used in contact copy schemes for mass replication.

In this paper, we will discuss selected materials and recording parameters to influence 2nd harmonic efficiency and will compare experimental and simulated results.

9508-19, Session 5

Lab-level and low-cost fabrication technique of polymer based micro-optical elements and holographic structures

Maik Rahlves, Maher Rezem, Christian Kelb, Kristian Boroz, Dina Goedeke, Sebastian Schlangen, Eduard Reithmeier, Bernhard Roth, Leibniz Univ. Hannover (Germany)

Polymer based diffractive optical elements have gained increasing interest due to their large potential for application in fields as diverse as illumination technology, micro optics and holography. In addition, various high throughput production techniques are available for replication of polymer based microstructures such as injection molding or hot embossing which makes polymer optics suitable for the mass market. However, all these techniques require a master mold structure, which is either made from metal by ultra-precision machining or from silicon by using etching techniques. Alternatively, photosensitive resists can be structured by electron beam or single point laser writing followed by an electro-plating process. All these techniques are time and cost consuming due to process times of up to several hours. Especially, for optics production, a surface roughness in the lower nanometer range is required which makes the processes even more demanding with regard to process time and material. Due to high cost of master mold production, established process chains are not suitable for small series in research and development, where usually several alterations of a specific design are needed for systematic studies.

To meet these high demands in research and development, we present a novel process for master mold production based on a lab-made maskless lithography setup. We present our recent results in maskless lithography with the emphasis on low-cost techniques which are suitable to produce microstructures in photoresist and are easy to implement in a standard optical lab environment. For maskless lithography, a spatial light modulator is used, which is illuminated by either a laser source or a high power light emitting diode. The expanded beam of the light source is intensity modulated by using a spatial light modulator and projected by an optical system onto a substrate coated with a thin layer of photosensitive resist. A great advantage of spatial light modulators is that a simple binary grayscale image can be directly transferred to the modulator device using a personal computer. Hence, only a simple image is required for microstructuring of the resist. In this paper, we present two different setups utilizing a digital mirror device and a liquid crystal device as spatial light modulator. We compare both setups with respect to light efficiency as well as resolution and contrast of the microstructures obtained.

Furthermore, a copy of the microstructures is replicated into optical polymeric materials by means of a soft stamp hot embossing process. The soft stamp is made from Polydimethylsiloxan which is coated onto the microstructure in the resist. The hot embossing process is carried out by a self-made and low-cost hot embossing machine. We present confocal topography measurements to quantify the replication accuracy of the process and demonstrate the fabrication of diffractive optical elements and holographic structures.

9508-20, Session 5

Comparison of a new photosensitizer with Erythrosin B for use in a Photopolymer

Yue Qi, Haoyu Li, Univ. College Dublin (Ireland); Jean-Pierre Fouassier, Jacques Lalevée, Univ. de Haute Alsace (France); John T. Sheridan, Univ. College Dublin (Ireland)

Photosensitizers or dyes often act as the initiator in photopolymer materials and are therefore of significant interest. The properties of the photosensitizer used strongly influences grating formation when the material layer is exposed holographically. In this paper, the ability of a recently synthesized dye, D_1, to sensitise an acrylamide/

polyvinyl alcohol (AA/PVA) based photopolymer is examined and the material performance is characterised using an extended Non-local Photopolymerization Driven Diffusion (NPDD) model. The results obtained are then compared to those for the corresponding situation when using a Xanthene dye, i.e., Erythrosin B (EB), under the same experiment conditions. The results indicate that, in comparison with EB, the non-local effect is greater when this new photosensitizer is used in the material. Analysis indicates that this is the case because of the dyes weak absorptivity and the resulting slow rate of primary radical production.

9508-23, Session 5

Diffractive optical elements with an increased angular and wavelength range of operation for application in solar collectors

Hoda Akbari, Izabela Naydenova, Suzanne M. Martin, Dublin Institute of Technology (Ireland)

A holographic device characterised by a large angular and wavelength range of operation is under development. It aims to improve the efficiency of solar energy concentration in solar cells.

The aim of this study is to increase the angular and wavelength range of the gratings by stacking three layers of high efficiency Diffractive Optical Elements (DOEs) on top of each other so that light from a moving source, such as the sun, is collected from a broad range of angles.

In order to increase the angle and the wavelength range of operation of the holographic device, low spatial frequency of holographic recording is preferable. Recording at low spatial frequency requires a photopolymer material with unique properties, such as fast monomer/monomers diffusion rate/rates.

An acrylamide-based photopolymer developed at the Centre for Industrial and Engineering Optics has been used in this study. This material has fast diffusion rates and has previously demonstrated very good performance at low spatial frequency, where gratings of 90% diffraction efficiency at 300 lines/ mm spatial frequency were recorded in layers of 75 μm thickness.

This paper will study the angular selectivity of a device consisting of stacked layer of DOEs recorded at range of angles at spatial frequency of 300 lines/mm with recording intensity of 1 mW/cm2. The optical recording process and the properties of the multilayer structure are described and discussed.

9508-21, Session 6

Incoherent holography with the use of Shack-Hartmann wavefront sensor

Alina V Gorelaya, St Petersburg State Electrotechnical Univ (Russian Federation); Vladimir P Lukin, V.E. Zuev Institute of Atmospheric Optics SB RAS (IAO SB RAS) (Russian Federation); Alexander A Sevryugin, Saint Petersburg Electrotechnical Univ. “LETI” (Russian Federation); Elena V Shubenkova, St Petersburg State Electrotechnical Univ (Russian Federation); Vladimir Y. Venediktov, Saint Petersburg Electrotechnical Univ. “LETI” (Russian Federation)

Traditionally the Shack-Hartmann wavefront sensors are providing the wavefront information in various terms, including, in particular, the presentation in the form of pseudo-interferogram. We study the possibility to use such a pseudo-interferogram instead of real interferogram during the record of the hologram, which is then to be used for holographic interferometery or holographic microscopy purposes. Such an approach can be promising for the self-luminous wide spectral band objects, which are not durable in time. Also there are good prospects of such an approach in X-ray holography.

9508-22, Session 6

Holographic wavefront sensors: state-of-the-art and prospects *(Invited Paper)*

Vladimir Y. Venediktov, Saint Petersburg Electrotechnical Univ. “LETI” (Russian Federation); Maksim A Solovyev, Vavilov State Optical Institute (Russian Federation)

Holographic wavefront sensors are providing fast, robust and efficient expansion of wavefront deformations in Zernike polynomials series or in other functional series. To date there are several variants of such an approach. We present their comparative study with respect to their advantages and disadvantages and especially with respect to application in IR spectral range, whre the “traditional” Shack-Harmann wavefront sensors reveal poor performance. We also discuss some other applications of holography in wavefront sensing.

9508-24, Session 6

Chalenges in holographic measurement of aspheric and freeform optical components shape

Vít Lédl, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic); Pavel Psota, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Petr Vojtísek, Roman Dolecek, Pavel Mokry, Martin Dlask, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic)

In the measurement of finished aspherical and freeform optical elements standard methods e. g. interferometry are limited in their applicability because the deviation from best fit sphere is developing strongly with the change of spatial coordinate. Even more difficulties appears when the whole iterative production process is considered because for example the glass element surface is undergoing the change from very rough – highly diffusive to well-polished surface which is rather specularly reflecting. The measurement of complex geometries in combination with very different surfaces (from the scattering point of view) cannot be done only with one method in required precision. Interferometry cannot be applied to diffusively reflecting surface and profilometers lack the precision or the density of measurement points. We proposed and tested method which could address many of the weaknesses of previously mentioned methods because it is based on digital holographic interferometry the diffusive surfaces could be measured and the precision is fraction of the wavelength which is used. The proposed method is based on multisource multiwavelenght digital holography contouring with phase shifting principle employed. It has been proven that the method offers good enough precision for at least interoperational measurement and allows measurement of complex geometries with low slope. Recent extensive experiments which we have been working on since the last year are showing that specularly reflecting surfaces could be measured with digital holographic contouring when diffuse light is used. In this paper the measurement of prepared artefacts once having the diffusively reflecting surface illuminated with point sources and later the same surface with specularly reflecting surface illuminated with diffusive light are done. We selected for the measurement the strongly aspheric convex shape and toroidal freeform shape the diameter of the elements is approx. 60mm. The factors which are influencing strongly the precision of the measurement or the measurable geometries are analysed and the optimal solution is discussed.

9508-25, Session 6

Advanced time average holographic method for measurement in extensive vibration amplitude range with quantitative single-pixel analysis

Pavel Psota, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic); Vít Lédl, Technical Univ. of Liberec (Czech Republic); Petr Vojtí?ek, TOPTEC (Czech Republic); Jan Václavík, Roman Dolecek, Pavel Mokry, Technical Univ. of Liberec (Czech Republic)

On the market, there is a broad portfolio of vibration measurement devices, which are usually based on the Doppler phenomenon, correlation analysis, speckle ESPI (Electronic Speckle Pattern Interferometry), and other methods. Usually these methods are single point methods having precision in ranges from nanometers to micrometers. Another physical principle suited for vibration analysis is holography. The holographic-based methods are noninvasive and very precise; in addition, digital holography enables displacement measurement over the whole field.

The basic holographic method for vibration analysis is time-averaged holographic interferometry (TAHI), which was introduced by Powell and Stetson. TAHI uses a continuous laser and for the data processing, a recording of only one hologram is sufficient. Since the information about phase vibration is lost due to averaging, the evaluation of the amplitude distribution is based on processing of the reconstructed hologram intensity.

Retrieval of phase information from the intensity image is usually based on searching of extremes in the intensity field linked to well-known values of vibration amplitudes at these points. Remaining pixels are interpolated. This procedure is time consuming with considerable inaccuracy. Therefore Stetson proposed fringe-shifting technique for numerical analysis of time average holograms. The piezoelectric actuator was used to add a bias phase to argument of the Bessel function in order to use phase stepping algorithm for quantitative analysis typically using in interferometry.

However, for amplitudes smaller than approximately one tenth of the wavelength of the laser light used or for very large amplitudes, the time averaged method reaches its limit of minimum measurable amplitude. The small and large vibration amplitudes measurement fundamental problem was solved by modification of the TAHI method called frequency-shifted time average holographic interferometry (FS-TAHI) firstly introduced by Aleksoff.

In this paper we propose novel method applying the both FS-TAHI and phase modulated (fringe-shifting) time average holography (PM-TAHI) enabling us measurement of very small and large amplitudes with quantitative analysis of time average holograms. Moreover the both FM and PM are realized by acusto-optical modulators so we need no additional hardware in our experimental setup. To improve the lateral resolution and signal-to-noise ratio we also implemented phase – shifting principle for each capturing of digital hologram. The paper introduces the theoretical physical background for the method and further the method is experimentally verified. The results obtained by our method with application of quantitative analysis are presented and discussed.

9508-26, Session 6

All-optically controlled light valve assembled by photorefractive crystal and PDLC hybrid structure

Vera Marinova Gospodinova, Ren Chung Liu, Shiuan-Huei Lin, Yi-Hsin Lin, Ken-Yuh Hsu, National Chiao Tung Univ. (Taiwan); Ming Syuan Chen, National Chiao Tung University (Taiwan)

We report a near infrared sensitive hybrid device, based on excellent photoconductivity of Ru–doped $Bi_{12}SiO_{20}$ photorefractive crystal and strong birefringence of polymer dispersed liquid crystal (PDLC) layer. It is found that the space-charge field, induced by photogenerated charge carriers inside the BSO:Ru substrate can be strong enough to penetrate into the PDLC surface layer and to acts as a driving force for the LC molecules realignment inside the droplets. Thus the LCs director changed, consequently the refractive index and the transparency of the structure (from originally scattering to the highly transparent one). In addition, holographic gratings are recorded at 1064 nm in a Bragg diffraction regime, showing optical gain with prospective beam amplification values and high spatial resolution. The proposed novel BSO:Ru/PDLC structure is simple and easy to fabricate, without requirements for conductive layer deposition (ITO contacts), alignment layers and use of polarizers. Such light valve device allows all the processes to be controlled by light, thus opens further potential for real-time image processing at the near infrared spectral range.

Conference 9509: Relativistic Plasma Waves and Particle Beams as Coherent and Incoherent Radiation Sources

Wednesday - Thursday 15–16 April 2015

Part of Proceedings of SPIE Vol. 9509 Relativistic Plasma Waves and Particle Beams as Coherent and Incoherent Radiation Sources

9509-1, Session 1

Radiation emission in the transition to the radiation cooling regime *(Invited Paper)*

Joana L. Martins, Marija Vranic, Thomas Grismayer, Ricardo A. Fonseca, Luis O. Silva, Univ. de Lisboa (Portugal)

The ultra-high intensities now available with current (up to 10^21 W/cm^2) and future lasers and the simultaneous availability of laser-produced GeV-class electron bunches allow the experimental exploration of nonlinear Thomson scattering in the radiation cooling regime. Such parameters open way for the exploration of the transition from the classical regime, where the scattering is elastic, to the radiation damping regime, where quantum corrections associated with the recoil of the scattering electron need to be taken into account. The radiation modeling then needs to be corrected to accomodate these quantum effects besides the correction to the trajectory due to radiation cooling.

Lieu & Axford have proposed a way to incorporate the quantum effects associated with the recoil of the electron on the spectrum emissivity formula [ApJ vol 416, 700 (1993)]. They showed that these quantum corrections, when applied to the synchrotron radiation, reproduce the QED synchrotron spectrum and presented an emissivity formula for synchrotron radiation in a general 3D nonuniform magnetic field scenario [ApJ vol 447, 302 (1995)].

In this work we present an emissivity formula which extends that of Lieu & Axford to arbitrary observation directions and that, in the limit of no recoil, reproduces the classical emissivity formula for arbitrary angles of observation. With this quantum corrected emissivity formula, the transition of the radiation emission from the purely classical regime to the regime where radiation damping is significant (and the recoil of the emitting electron affects the radiation properties) can be explored. Numerical simulations using the OSIRIS 2.0 framework (with radiation damping) will be used to obtain the trajectories of electrons undergoing nonlinear Thomson scattering over a wide range of parameters along this transition. These will then be post-processed with the quantum corrected emissivity formula implemented in the JRad radiation diagnostic tool. Some comparisons of these spectra with the spectra obtained from a QED treatment using the OSIRIS-QED module will also be presented.

This analysis is of timely importance to understand under which combination of laser intensity and electron energy will the changes in the radiated spectrum characteristics of nonlinear Thomson scattering become significant enough to probe in experiments.

9509-2, Session 1

Femtosecond substructured electron bunches in the laser-plasma wakefield accelerator *(Invited Paper)*

Mohammad R. Islam, Enrico Brunetti, Bernhard Ersfeld, Riju C. Issac, Silvia Cipiccia, Gregor H. Welsh, S. Mark Wiggins, Adam Noble, Univ. of Strathclyde (United Kingdom); Robert A. Cairns, Univ. of St. Andrews (United Kingdom); Gaurav Raj, Dino A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

Laser-driven plasma accelerator in the bubble regime produces high quality quasi mono-energetic electron bunches with energies up to 2 GeV [1, 2], femtosecond duration gamma-rays due to wiggler-like betatron oscillations [3], compact synchronize source [4], etc. Driving a compact synchrotron source requires electron beam of low emittance [5], narrow energy spread and high peak current. These parameters are achievable when the injected electron bunch is ultra-short. The injection mechanism is crucial in determining the final bunch properties. In a restricted density range, several theoretical models (supported by PIC simulations) and experimental measurements have been performed to elucidate the injection mechanism [6], but without investigating the bunch structure. However, in this presentation we report a new injection mechanism [7], where the detailed electron bunch length (femtosecond) can be accounted for, and confirmed experimentally using coherent optical transition radiation measurements carried out on the ALPHA-X beam line [8].

References:

[1] S. P. D. Mangles, et al. Nature 431, 535538 (2004), C. G. R. Geddes, et al. Nature 431, 538-541 (2004), W. P. Leemans, et al. Nature Physics 2, 696699 (2006), J. Faure, et al. Nature 431, 541-544 (2004).

[2] X. Wang, et al. Nature Communications 4, 1988 (2013).

[3] S. Cipiccia, M. R. Islam, et al. Nature Physics 7, 867 (2011).

[4] D. A. Jaroszynski, et al. Phil. Trans. R. Soc. A 364, 689-710 (2006).

[5] E. Brunetti, et al. Phys. Rev. Lett. 105, 215007 (2010).

[6] I. Kostyukov, et al. Phys. Rev. Lett. 103, 175003 (2009), S. Kalmykov, et al. Phys. Rev. Lett. 103, 135004 (2009), S. P. D. Mangles, et al. Phys. Rev. Sp. Top.-Accelerators and Beams 15, 011302 (2012), C. Benedetti, et al. Phys. of Plasmas 20, 103108 (2013).

[7] M. R. Islam, et al. Submitted to Nature Physics for publication (2014).

[8] D. A. Jaroszynski and G. Vieux, Tenth Workshop. AIP Conference Proceedings, 647, 902 (2002).

DOI: 10.1063/1.1524946

9509-3, Session 1

Positron and electron acceleration in the wake of ultraintense exotic laser pulses *(Invited Paper)*

Jorge M. Vieira, José T. Mendonça, Luis O. Silva, Univ. Técnica de Lisboa (Portugal)

The interaction of exotic lasers with new fundamental properties and plasmas at extreme intensities has been nearly unexplored. In this talk we will describe how these beams could be used to generate plasma wakefields capable to produce energetic electron and positron beams with novel properties, providing new solutions to long-standing challenges in plasma acceleration. We will then show that exotic lasers with Orbital Angular Momentum and doughnut shaped intensity profiles can excite strongly non-linear doughnut wakefields [1] in the blowout regime, which are well suited for positron acceleration [2]. The positron focusing force is provided by a thin electron layer formed in the doughnut bubble axis, with typical densities largely exceeding background plasma ion density. Resulting focusing forces can thus be more than an order of magnitude larger than electron focusing force in a pure ion channel. As a result, the intensity of the betatron radiation produced by the accelerated positrons can be much larger than betatron radiation by relativistic electrons in a pure ion channel. In addition, we show that the extremely large wakefields present at the back of the doughtnut wakefield can self-inject ring electron bunches, which could be used as a lens for ion beams in conventional accelerators. These electrons perform betatron oscillations around the doughnut bubble centroid, which may lead to distinct radiation patterns with annular transverse profiles. Full scale 3D simulations show that these exotic laser pulses can be self-guided by their own plasma wakefield until their energy has been nearly fully depleted to the plasma, continuously diffracting after that point. Similar results can also be obtained using ring-shaped particle bunch drivers.

[1] J.T. Mendonça and J. Vieira, PoP 21 033107 (2014)
[2] J. Vieira and J.T. Mendonca, PRL 112 215001 (2014)

9509-4, Session 1

Cooling of relativistic electron beams in intense laser pulses *(Invited Paper)*

Samuel R. Yoffe, Adam Noble, Univ. of Strathclyde (United Kingdom); Yevgen Kravets, École Polytechnique (France); Dino A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

The next few years will see next-generation high-power laser facilities (such as the Extreme Light Infrastructure) become operational, for which it is important to understand how interaction with intense laser pulses affects the bulk properties of a relativistic electron beam. As we move to higher laser intensities, we expect both radiation reaction and quantum effects to play a significant role in the beam dynamics. The resulting reduction in relative energy spread (known as beam cooling) at the expense of mean beam energy predicted by classical theories of radiation reaction depends only on the energy of the laser pulse, and has been well studied in the literature. However, at the upcoming field strengths, quantum effects can no longer be neglected.

In this work, quantum effects have been incorporated in a model of radiation reaction, for which the Vlasov equation describing the evolution of a distribution of particles is intractable. To overcome this, and investigate the cooling of relativistic electron beams in a quantum regime, a novel technique for studying the evolution of a particle distribution using single particle dynamics is introduced. The distribution can be accurately reconstructed from fewer particles than in existing approaches. Comparison to the exact solution to the Vlasov equation with the classical Landau-Lifshitz model for radiation reaction is excellent.

The interaction between high-energy electron beams and N-cycle plane-wave intense laser pulses have been studied. The energy of the pulse has been kept constant, which maintains the same classical prediction for final state properties. As the laser intensity is increased, quantum effects reduce the amount of radiative damping, such that the electron beam experiences less beam cooling, and emerges from the pulse with a larger mean momentum and relative spread than predicted classically. Measurement of the skewness also indicates that the final distribution becomes more Gaussian with increased laser intensity.

Unlike the classical case, the reduction in beam cooling in the quantum model is found to depend on how the laser energy is distributed within the pulse. As an example, this is explored using chirps to modify the pulse's energy distribution. Classical predictions for final beam properties are confirmed to be insensitive to chirps, while the quantum model predicts a chirp-rate-dependent variation in beam cooling.

9509-5, Session 1

Control of self-injection in LWFA using a tailored density profile *(Invited Paper)*

Matthew P. Tooley, Dino A. Jarozsynski, Bernhard Ersfeld, Zheng-Ming Sheng, Univ. of Strathclyde (United Kingdom)

Control of bunch properties in LWFA is crucial in order to optimise beams to their intended applications. The longitudinal density profile of an electron bunch is an important property not only in terms of overall electron beam bunch, but also any structural properties of the bunch.

Stimulation and control of self-injection using density up and down-ramps has been widely studied and allows control of the energy spread of the injected electron bunch. As originally theorised by Bulanov et al. (Phys Rev. E 58, R5257) this exploits a method by which wavebreaking is induced as the wake wave phase velocity decreases down the plasma density ramp.

We have extended this work to consider the wave-breaking and self injection behaviour of more complex plasma density profiles and find that this allows design of the plasma density profile to produce tailored beam profiles. We demonstrate using PIC simulation that the properties of a self-injected electron bunch may therefore be controlled by such an appropriate choice of the longitudinal density profile.

9509-7, Session 2

Characterization of the in-line X-ray phase contrast imaging beam line developed at ALLS and based on laser-driven betatron radiation *(Invited Paper)*

Jean-Claude Kieffer, Sylvain Fourmaux, Steve MacLean, Institut National de la Recherche Scientifique (Canada); Emil L. Hallin, Canadian Light Source Inc. (Canada); Andrzej Krol, SUNY Upstate Medical Univ. (United States)

The plasma wakefield generating the betatron radiation is obtained by focusing a linearly polarized 800nm laser pulse with energy of 2.5 J and pulse duration of 30fs onto a gas jet target with an f/17 off axis parabola. The FWHM of the optical focal spot is 20µm and the peak intensity is around 8x1018 W/cm2. A side view interferometer is employed to probe the plasma formation and density. He gas target is used with a 10mm diameter supersonic conical nozzle. A cylindrical plasma is produced along the laser propagation axis and the plasma density was measured to be approximately 1.5x1019cm-3. The generated electron beam was measured by an electron spectrometer made with two dipole magnets. Results show that electrons are accelerated up to approximately 400 MeV.

The x rays produced by the accelerated electrons were measured by several diagnostics. The x-ray angular profiles were measured using a GdOS:Tb phosphor screen located on the laser propagation axis (the total collection angle was 44 mrad) and recorded using a visible CCD. The measured angular spreads of the x-ray beams were 25 and 31 mrad (FWHM) in the horizontal and the vertical directions (averaged over 10 successive laser shots). The x-ray spectra were measured with an x-ray photon counting technique using a deep-depletion x-ray CCD and with a technique of Reflection off a Grazing incidence Miror. The measurements of electron spectra, x-ray angular profiles, and x-ray spectra were obtained simultaneously for every single laser shot. We currently have 2.2x108 photons/0:1% bandwidth/sr/shot at 10 keV. A fit to a synchrotron distribution provides a critical energy Ec=12.3 keV with 2.5 keV precision. The total number of photons over the whole spectrum, obtained from the synchrotron fit distribution, is N=109ph. The x-ray spot size was measured to be 1.7 µm (FWHM) with a knife-edge technique.

In this in-line geometry, the standard transmission geometry with a divergent beam is used. The object to be imaged is positioned between the X-ray source and the detection system. R1 and R2 are respectively the source to object and the object to detector distances. The magnification is thus given by (R1+R2)/R1. Two sets of experiments with respectively R1=70cm and R1=110cm have been realized in order to obtain images with two different coherence lengths, calculated using the Cittert-Zernike theorem. In the first case, R2 has been varied between 70cm (M=2) and 280cm (M=5). In the second case, R2 was fixed at 200cm (M=2,8). A series of nylon fibers having diameter ranging from 10µm to 400µm have been used for the characterization of the imaging beam line. In these conditions, imaging is thus realized in the near field Fresnel regime, except for the smallest fiber diameters (10µm) with the largest magnification (M=5) for which imaging is done in the Fresnel and in the Fraunhofer regimes. The length corresponding to the optimized spatial frequencies is in the 50-60µm range with our parameters when magnification is large.

Imaging in the detection plane is realized with two different detection systems having respectively 20µm and 40µm pixel size. The first detection system includes an X-ray CCD camera having 20µm pixel. The second system includes a CCD camera coupled to a GdOS:Tb phosphor with a fiber-optic faceplate. The pixel size for this detection system is 40µm. The imaging beam line spatial resolution depends on the source diameter and on the pixel size and changes with the magnification. In the present geometry the projected source size in the detection plane remains lower than the pixel size. The resolution is thus given by the size of the pixel in the object plane. The best resolution achieved with our system is 7µm.

The model used in this work has been described in our previous papers. The Fresnel–Kirchoff integral is used in the Fresnel approximation to calculate the diffraction pattern of the various nylon wires taking into account the imaging geometry and the source size (1.7μm in diameter). The fitted synchrotron spectrum, multiplied by the spectral transmission of the absorption filters and the spectral response of the detector is included in the calculations.

The contrast and the phase interface lengths are measured as a function of the imaging parameters (magnification, resolution, coherence length) for cylindrical fibbers and more complex objects. Phase is retrieved with different techniques and the results will be compared to the calculation model.

The method described in this paper provides key information in guiding the future design of betatron imaging beam lines. We will discuss the design and the potential of a betatron beam line for a 500TW driving laser system.

9509-8, Session 2

High-energy gamma-ray beams from nonlinear Thomson and Compton scattering in the ultra-intense regime *(Invited Paper)*

Christopher N. Harvey, Mattias Marklund, Chalmers Univ. of Technology (Sweden); Erik Wallin, Umeå Univ. (Sweden)

The new generation of ultra-intense lasers, combined with the energetic electron beams now obtainable via laser-wakefield processes, will allow for the possibility of very compact, all-optical Compton scattering radiation sources of very high energies. However, as we move to towards these higher intensity regimes, radiation reaction effects will begin to play an important role in the particle dynamics. The electrons will experience significant energy loss which will impact on the resulting spectra. In addition, as we approach ultra-high intensities, quantum effects will start to become important both for electron acceleration and Compton scattering. We find that the electron bunches will spread out as a result of discrete photon emission. We present a discussion of the modelling of these effects and assess their impact on both the electron bunch dynamics and the resulting Thomson/Compton spectra in different intensity regimes.

9509-9, Session 2

Nonlinear effects in relativistic all-optical Thomson-backscattering *(Invited Paper)*

Stefan Karsch, Konstantin Khrennikov, Johannes Wenz, Ludwig-Maximilians-Univ. München (Germany); Alexander Buck, Jiancai Xu, Laszlo Veisz, Max-Planck-Institut für Quantenoptik (Germany)

A tunable, reproducible, quasi-monochromatic, all-optical Thomson source was created by colliding a 28 fs, 10 TW laser pulse with a narrow-energy spread electron beam. The latter was produced in a laser-wakefield accelerator with controlled injection in a shock front, and its energy was tunable from 15 to 70 MeV at a nearly constant FWHM bandwidth of 5 MeV. We observe the electron and X-ray spectra on a single-shot basis with high resolution and good statistics, as well as the beam divergence and photon number. Together with independent measurements of the pulse duration and source size we give brilliance figures. The spectra show evidence of the nonlinear photon wavelength increase due to the fact that the amplitude of the scattering beam approaches the relativistic regime ($a_0=0.9$), as well as the onset of 2nd harmonic radiation. To our knowledge, this is the first direct observation in the X-ray spectrum of nonlinear effects in relativistic Thomson backscattering.

9509-10, Session 2

Narrowbandwidth and tunable hard X-rays from an all-laser-driven Thomson light source *(Invited Paper)*

Donald P. Umstadter, Sudeep Banerjee, Shouyuan Chen, Baozhen Zhao, Cheng Liu, Grigory Golovin, Jun Zhang, Univ. of Nebraska-Lincoln (United States); Nathan Powers, KLA-Tencor Corp. (United States); Shaun Clarke, Sara A. Pozzi, Univ. of Michigan (United States)

We report the results of experiments in which a single laser system is used to both accelerate electrons (0.5 GeV) and generate hard x-rays, by means of inverse Compton scattering. The x-rays are shown to have narrow-bandwidth (50%) over a wide range of photon energies (50 keV -- 9 MeV). Results on the application of this novel source to x-ray radiography with high-resolution (< 5 micron) are also discussed.

9509-11, Session 2

Laser-plasma undulator for an ultracompact synchrotron radiation source *(Invited Paper)*

Igor A. Andriyash, Remi Lehe, Agustin Liftshitz, Cédric Thaury, Jean-Marcel Rax, Ecole Nationale Supérieure de Techniques Avancées (France); Karl M. Krushelnick, Univ. of Michigan (United States); Victor Malka, Ecole Nationale Supérieure de Techniques Avancées (France)

The capability of plasmas to sustain ultra-high electric fields has attracted considerable interest over the last decades and has given rise to laser-plasma engineering. Today, laser plasmas are commonly used for accelerating [1-3] and collimating [4] relativistic electrons, or to manipulate intense laser pulses [5]. The applications of the laser plasmas are now widely discussed in the context of a next generation of the compact synchrotron radiation (SR) sources.

One important application is a laser plasma accelerator (LPA), where an ultrashort laser pulse is focused into a gas and drives a plasma wave to trap and accelerate electrons of the produced plasma. State-of-the-art LPA now deliver reproducible and quasi-monoenergetic electron beams with energies from dozens MeVs to GeVs. This technology has potential to reduce the size of electron accelerators down to few millimeters. To take advantage of the extremely intense but rather divergent LPA electron beams, the undulator in a future light source should also operate on a very short length. The concepts of short magnetostatic [6,7] and optical [8] undulators are explored, and promise interesting prospects.

We propose and discuss an alternative ultra-compact plasma undulator which combines plasma technology and nano-engineering [9]. When coupled with a laser-plasma accelerator, this undulator constitutes a millimeter-size synchrotron radiation source of X-rays and is driven by a single terrawatt laser pulse. The undulator consists of an array of nano-wires, which are ionized by the laser pulse exiting from the accelerator. The strong charge-separation field, arising around the wires, efficiently wiggles the laser-accelerated electrons. With help of numerical simulations we demonstrate that this system can produce bright, collimated, and tunable beams of photons with 10-100 keV energies. This concept opens a path towards a new generation of compact synchrotron sources based on nano-structured plasmas.

References

[1] J.Faure et al, Nature 444, 737 (2006)

[2] C.Joshi, Phys. Plasmas 14, 055501 (2007)

[3] E.Esarey et al, Rev. Mod. Phys. 81, 1229 (2009)

[4] R.Kodama et al, Nature 432, 1005 (2004)

[5] J.Faure et al, Phys. Rev. Lett. 95, 205003 (2005)

[6] H.-P. Schlenvoigt et al, Nat. Phys. 4, 130 (2008)

[7] M. Fuchs et al, Nat. Phys. 5, 826 (2009)

[8] K. Ta Phuoc et al, Nat. Phot. 6, 308 (2012)

[9] I.A. Andriyash et al, Nat. Commun. 5, 4736 (2014)

9509-6, Session PS

Single photon spectrometry of laser-plasma x-ray sources, using a Timepix detector *(Invited Paper)*

Karel Bohacek, Antonin Fajstavr, Miroslav Krus, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Laser-plasma sources represent a promising way of a hard X-ray or gamma ray pulse generation (betatron radiation, nonlinear Thomson scattering, inverse Compton scattering, K_{alpha}, bremsstrahlung). One of the sensors that can be considered for the detection of such radiation is a Timepix pixel detector (Medipix2 family). Timepix is a 65kpx (256x256), 13-bit pixel detector consisting of square pixels of 55 mum side length. Devices with two different types of semiconductor sensor were tested a Si sensor with a typical thickness of 300 mum (suitable for the energy range up to 80 keV) and a CdTe sensor with a typical thickness of 1000 mum (allowing detection in the energy range up to 500 keV). The calibration curve and resolution dependences on fundamental parameters of the read-out electronics were studied for both types of the Timepix sensor (bias voltage, threshold, discharging current (I_{krum}), clock frequency). Calibration curves for single-pixel and multi-pixel events were created with measured data of known radiation source lines (gamma + K_{alpha}). The calibration and the spectrometry itself was performed in the time over threshold (ToT) mode. The calibrated devices were tested using betatron X-ray radiation or bremsstrahlung in electron laser wakefield acceleration experiments at (sub)PW class laser facilities.

9509-12, Session 3

Betatron radiation from density tailored plasma *(Invited Paper)*

Kim Ta Phuoc, Andreas Döpp, Cédric Thaury, Emilien Guillaume, Julien Gautier, Pascal Rousseau, Jean-Philippe Goddet, Fabien Tissandier, Amar Tafzi, Antoine Rousse, Ecole Nationale Supérieure de Techniques Avancées (France)

Betatron radiation is naturally produced in most types of laser plasma accelerators. This mechanism emultates in a millimeter scale the princple of a synchrotron. The radiation is the consequence of the oscillating motion of relativistic electrons in the wakefield cavity which acts as a wiggler. A typical laser-produced Betatron source produces femtosecond x-ray beams in the keV range and collimated within a few tens mrad.

The features of the radiation are directly linked to the electrons orbits in the wakefield cavity. In particular, the larger is the amplitude of the Betatron oscillation and the brighter is the radiation. However, so far, the Betatron amplitude of motion was defined by the injection conditions in the cavity and electrons were confined in the vicinity of the cavity axis. This is inefficient and much more energy from the plasma could be converted into radiation if electrons could have a larger transverse amplitude of motion.

Here we demonstrate a method that allows to increase this amplitude of motion. We experimentally show that the flux and energy of the Betatron radiation can be significantly increased. This method opens perspectives toward Betatron sources much brighter and energetic than present Betatron sources.

9509-13, Session 3

Laser-wakefield betatron radiation for biological imaging *(Invited Paper)*

Nelson C. Lopes, Imperial College London (United Kingdom) and Univ. Técnica de Lisboa (Portugal)

Laser-wakefield accelerators have been proven as a compact source of ultra-short bunches of relativistic electrons. A short laser pulse can be focused to a diameter close to its longitudinal size (e.g. 20 micron FWHM) reaching an intensity of 1019 W/cm2. When this “light bullet” hits a plasma with the adequate electron density to sustain electron waves with wavelength matching the laser spot diameter a relativistic cavitation bubble with almost no electrons is formed in the plasma. This bubble like plasma structure surrounds the laser pulse and guides it until the laser pulse energy is consumed or the gas finishes. Electrons can be trapped by this structure and accelerated to energies above 500 MeV in less than one centimeter. Those electrons oscillate in the radial field of the plasma structure resulting in the emission of betatron radiation with a few milliradian divergence and broadband photon energies with a synchrotron like spectra with critical energies typically in the 1- 50 KeV range. This radiation has a source size of a few microns and is bright enough for single shot imaging (typically > 109 photons with 5 – 9 KeV).

A betatron imaging setup was built at Astra-Gemini laser facility for an experiment dedicated to demonstrate the adequacy of this light source for biological imaging. Electron bunches with energies of 1 GeV where produced in a 1 cm long helium gas target by laser pulses with energy of 10 J and duration of 45 fs focused to a spot size of 25 micron by a F/20 off-axis-parabola. The experimental parameters where optimized to produce a small source size bright x-ray betatron beam. We have performed two imaging modalities: phase-contrast imaging of soft-tissue samples (millimeter thick prostate slices) using radiation in the range 5-9 KeV and absorption-contrast imaging of trabecular bone samples using radiation in the range 5-50 KeV. The phase-contrast result in images of the prostate tissues where the architecture of the tissues is clearly visible with resolution comparable to what is possible using histology techniques. The absorption-contrast imaging of the bone sample with different angles made possible the tomographic high-resolution reconstruction of the sample. These studies indicate the usefulness of these sources for biological research and clinical applications. They also show that 3D imaging can be made possible with this source in a fraction of the time that it would take with a x-ray tube.

9509-14, Session 3

Resonant betatron radiation in bubble regime *(Invited Paper)*

Silvia Cipiccia, Bernhard Ersfeld, Mohammad R. Islam, Enrico Brunetti, Gregor H. Welsh, Gregory Vieux, Xue Yang, S. Mark Wiggins, David Reboredo-Gil, Peter A. Grant, David W. Grant, Dino A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

In a laser plasma wakefield accelerator, the ponderomotive force of the laser expels the plasma electrons from the laser axis while the heavy ions form a bubble-like structure following the laser pulse. Plasma electrons trapped in the bubble experience a longitudinal accelerating field in excess of 100 GV/m while oscillating transversally due to the non-zero initial transverse momentum due to the electrostatic field of the ions. The transverse motion results in emission of X-rays with a synchrotron-like spectrum. When electrons reach the part of the bubble filled by the laser pulse, their oscillatory motion can be driven in resonance with the Doppler downshifted oscillating laser field. At resonance, the amplitude of oscillation and the transverse momentum are strongly increased which results in enhancement of the emission of photons, increase of the critical energy and direct laser acceleration. The resonant motion results in a spatial structure that can be observed in the electron energy spectrum.

9509-15, Session 3

High harmonic generation from relativistic plasma surfaces in ultrasteep plasma density gradients *(Invited Paper)*

Christian Roedel, Friedrich-Schiller-Univ. Jena (Germany) and SLAC National Accelerator Lab. (United States); Erich Eckner, Friedrich-Schiller-Univ. Jena (Germany);

Jana Bierbach, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz Institute Jena (Germany); Mark Yeung, Helmholtz Institute Jena (Germany); Brendan H. Dromey, Queen's Univ. Belfast (United Kingdom); Thomas Hahn, Dirk Hemmers, Georg Pretzler, Heinrich-Heine-Univ. Düsseldorf (Germany); Matthew Zepf, Helmholtz Institute Jena (Germany) and Queen's Univ. Belfast (United Kingdom); Gerhard G. Paulus, Friedrich-Schiller-Univ. Jena (Germany) and Helmholtz Institute Jena (Germany)

High harmonic generation from relativistic plasma surfaces is discussed which marks one of the most promising ways for generating attosecond pulses of unprecedented intensity. The recent experimental progress will be presented with a special emphasis on the optimization of the harmonic yield by using defined plasma density gradients. Our observations reveal that efficient generation requires steep plasma density scale lengths. However, the harmonic efficiency declines for the steepest plasma density scale lengths demonstrating that near-steplike density gradients can be achieved using high-contrast high intensity laser pulses.

We have further observed a strong influence of the plasma scale length on the spectral fine structure of the high harmonics. While sharp harmonic lines are obtained for short plasma scale lengths, an extended plasma profile leads to strongly modulated harmonic spectra. These modulations are explained by an unequal pulse spacing of attosecond pulses generated at the laser-driven surface plasma and can be used for determining the plasma scale length in the experiment.

Moreover, we have observed an enhanced emission of particular harmonics when the plasma density gradient is extremely steep. The enhancement of these harmonic frequencies can be explained by the relativistic oscillating mirror (ROM) model when an additional surface oscillation at the plasma frequency is included.

The observed effects are supported by particle-in-cell simulations and can be explained by a simple model of a relativistically oscillating mirror. As an outlook, experiments utilizing x-ray femtosecond pulses are proposed.

9509-16, Session 4

High intensity regimes for resonant Raman compression *(Invited Paper)*

Nathaniel J. Fisch, Vladimir M. Malkin, Princeton Univ. (United States); Zeev Toroker, Technion-Israel Institute of Technology (Israel)

The largest laser intensities to date are achieved through the technique of chirped pulse amplification, which is subject to the material limits of conventional materials.

At high laser intensity and fluence, these materials fail, limiting the intensity of the output pulses. These material limits may be overcome through the use of plasma as a medium mediating resonant backward Raman amplification in plasma, wherein a short counter-propagating seed pulse, with frequency downshifted from a long pump pulse by the plasma frequency, absorbs the pump energy through a resonant decay interaction. In the pump-depletion regime, the counter-propagating seed pulse assumes a self-contracting self-similar form, capturing the pump energy in a pulse, of far shorter duration [1]. Absent non-ideal effects, the so-called pi-pulse regime is attained, wherein the amplified seed pulse comprises a series of spikes, with most of the energy contained in the leading spike.

Robust amplification, avoiding deleterious effects such as premature backscatter from noise or precursors to the amplified pulse, requires careful selection of plasma and wave parameters [2], including techniques of chirping the seed and pump pulses [3]. There are limiting effects that enter at both high seed output intensities and at high pump intensities. At high seed output intensities, relativistic effects tend to saturate the pulse, particularly the largest, leading spike, limiting the compression effect [4]. However, it turns out that after the saturation of the leading spike, subsequent spikes can in fact reach higher intensity yet [5]. At high pump intensities, which can be useful in achieving the compression effect with less plasma, the plasma wave can be broken, limiting the efficiency. However, even at moderate wavebreaking, the compression can still be efficient, only becoming inefficient in the deep wavebreaking regime [6].

Through an understanding of these limiting effects, new regimes for Raman compression may now be identified that are capable of efficient processing of light at the highest intensities.

[1] V. M., Malkin, G. Shvets, and N. J., Fisch, "Fast compression of laser beams to highly overcritical powers," Phys. Rev. Lett. 82, 4448 (1999).

[2] V. M. Malkin and N. J Fisch, "Key plasma parameters for resonant backward Raman amplification in plasma, " Eur. Phys. J. Special Topics 223, 1157 (2014).

[3] Z. Toroker, V. M. Malkin and N. J Fisch, "Seed laser chirping for enhanced backward Raman amplification in plasmas,"Phys. Rev. Lett. 109, 085003 (2012).

[4] V. M. Malkin, Z. Toroker, and N. J Fisch, "Saturation of the leading spike growth in backward Raman amplifiers," Phys. Plasmas 21, 093112 (2014).

[5] V. M. Malkin, Z. Toroker, and N. J Fisch, "Exceeding the leading spike intensity and fluence limits in backward Raman amplifiers," arXiv:1409.5407 (to appear in PRE).

[6] Z. Toroker, V. M. Malkin and N. J Fisch, Backward Raman amplification in the Langmuir wavebreaking regime," Phys. Plasmas 21, 113110 (2014).

9509-17, Session 4

Raman amplification in the strong wavebreaking regime *(Invited Paper)*

John P. Farmer, Alexander Pukhov, Heinrich-Heine-Univ. Düsseldorf (Germany)

Raman amplification in plasma has been suggested as a possible mechanism for the creation of the next generation of ultrashort, ultraintense laser pulses. However, experiments to date show a much lower efficiency than simulations (~4% compared to ~40%). One possible mechanism limiting the efficiency is plasma wave breaking, which limits energy transfer between the pump and probe. We investigate Raman amplification in the strong wavebreaking regime, which has applications in both understanding existing experimental results and in planning future experimental works.

9509-19, Session 4

Study of saturation mechanisms in short laser pulse amplification by stimulated Raman backscattering in warm plasma *(Invited Paper)*

Gregory Vieux, Xue Yang, Enrico Brunetti, Bernhard Ersfeld, Univ. of Strathclyde (United Kingdom); John P. Farmer, Heinrich-Heine-Univ. Düsseldorf (Germany); Min Sup Hur, Ulsan National Institute of Science and Technology (Korea, Republic of); Riju C. Issac, Mar Athanasius College (India); Gaurav Raj, S. Mark Wiggins, Gregor H. Welsh, Samuel R. Yoffe, Dino A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

For almost 20 years, stimulated Raman back-scattering in plasma has been extensively studied as a promising method to develop the next generation of ultra high energy laser systems. The interest of this method relies on the possibility to directly amplify and compress laser pulses without the need to use diffraction gratings. However, to date, measured energy transfer efficiencies are limited to a few percent, with seed energies only reaching 10s of mJ before onset of saturation. In this talk we present an experimental and numerical investigation of the saturation mechanisms. We identify electron trapping and wavebreaking as the main processes that prevent accessing efficient gain regimes. Chirped-pulse Raman amplification is experimentally studied using a short seed pulse interacting with a counter-propagating chirped long pump pulse in a preformed plasma waveguide. We analyse and interpret the experimental results using averaged particle-in-cell simulations and propose methods of achieving higher amplification efficiency.

9509-20, Session 5

A realizable optical free-electron laser with Traveling-wave Thomson-scattering *(Invited Paper)*

Klaus Steiniger, Richard Pausch, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany) and Technische Univ. Dresden (Germany); Alexander Debus, Fabian Röser, Michael Bussmann, Ulrich Schramm, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

Traveling-Wave Thomson-Scattering (TWTS) is a scheme for the realization of optical free-electron lasers (OFELs) from the interaction of ultra-short, high-power laser pulses with relativistic electrons. The laser pulse thereby provides the undulator field which typically needs to include a few 100 to several 1000 undulator periods for OFEL operation. Such long optical undulators are realized in TWTS by the combination of a side-scattering geometry where electron and laser pulse propagation directions enclose an interaction angle and a laser pulse-front tilt of half the interaction angle. This combination of side-scattering and pulse-front tilt ensures continuous overlap of electrons and laser pulse during the passage of the electrons through the laser beam. Laser beam diameters of a few centimeter in the interaction plane are required for OFEL operation and are available with multi-hundred terawatt to petawatt laser systems at laser intensities required for optical undulators. Optimum spatial overlap of electrons and laser pulse is provided by focusing the laser pulse in the plane perpendicular to both propagation directions with a cylindrical mirror which focal line is on the electron trajectory. Then all of the available laser photons interact with the electrons contrary to head-on Thomson scattering where laser defocusing reduces the overlap of laser and electrons ultimately limiting the available interaction distance. Thus much longer interaction distances can be provided in TWTS setups increasing the photon output and reducing the radiation bandwidth leading to orders of magnitude higher brilliance of TWTS OFELs compared to standard head-on Thomson scattering OFELs. Furthermore the variability of TWTS with respect to the interaction angle grants control over the scattered wavelength even if the electron energy is fixed by tuning the interaction angle and thereby changing the effective undulator period.

In a 1.5D FEL theory we show analytically that the electron and radiation field dynamics in TWTS OFELs can be described equivalently to standard magnetic FELs. Consequently, microbunching and exponential gain is present in TWTS OFELs as in standard magnetic FELs. Within our theory we take into account that electrons are interacting with the electric and magnetic field of the laser and that laser, radiation and electrons have different propagation directions. Consistent with the slowly varying envelope and phase approximation commonly done in FEL physics we separate the laser and radiation field in an amplitude and a plane wave term.

Beyond the justification of this approximation it is vital for TWTS OFEL operation that the field of the laser pulse is a monochromatic plane wave along the electron trajectory. For this condition to hold it is necessary to provide compensation for angular dispersion introduced at the grating tilting the laser pulse-front. Angular dispersion increases the laser pulse duration and spatially separates the frequencies contained in the pulse during the propagation from this grating to the interaction point and during the interaction. Dispersion compensation can be accomplished with an additional grating.

We present a complete experimental TWTS OFEL setup giving electron parameters, specifications of the gratings and arrangement of the required element.

9509-21, Session 5

Undulator radiation driven by laser-wakefield accelerator electron beams *(Invited Paper)*

S. Mark Wiggins, Maria Pia Anania, Gregor H. Welsh, Enrico Brunetti, Silvia Cipiccia, Peter A. Grant, David Reboredo-Gil, Univ. of Strathclyde (United Kingdom); Grace Manahan, Univ of Strathclyde (United Kingdom); David W. Grant, Dino A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

The Advanced Laser-Plasma High-Energy Accelerators towards X-rays (ALPHA-X) programme is developing laser-plasma accelerators for the production of ultra-short electron bunches with subsequent generation of coherent, bright, short-wavelength radiation pulses. The new Scottish Centre for the Application of Plasma-based Accelerators (SCAPA) will develop a wide range of applications utilising such light sources. Electron bunches can be propagated through a magnetic undulator with the aim of generating fully coherent free-electron laser (FEL) radiation in the ultra-violet and X-rays spectral ranges. Demonstration experiments producing spontaneous undulator radiation have been conducted at visible and XUV wavelengths but it is an on-going challenge to generate and maintain electron bunches of sufficient quality in order to stimulate FEL behaviour.

In a laser-plasma wakefield accelerator, a high intensity ultra-short laser is focused into a gas or plasma medium in order to create a miniature accelerating cavity for electrons that travel behind the laser pulse. The rate of energy gain is about 1000 times that of conventional radio frequency (RF) or microwave accelerators, hence, the infrastructure requirements for a high-energy synchrotron or FEL light source would be substantially reduced from km-scale to 10's of metre-scale. In addition, due to the inherently short nature of the laser-plasma interaction, the electron bunches are ultra-short in length which, in turn, leads to very short duration radiation pulses.

In the ALPHA-X beam line experiments, a Ti:sapphire femtosecond laser system with peak power 20 TW has been used to generate electron bunches of energy 100-150 MeV in a 2 mm gas jet laser-plasma wakefield accelerator and these bunches have been transported through a 100 period planar undulator. High peak brilliance, narrow band spontaneous radiation pulses in the vacuum ultra-violet wavelength range have been generated. Analysis is provided with respect to the magnetic quadrupole beam transport system and subsequent effect on beam emittance and duration. Requirements for coherent spontaneous emission and FEL operation are presented.

9509-22, Session 5

Practical considerations for the ion channel free-electron laser *(Invited Paper)*

Bernhard Ersfeld, Sijia Chen, Rodolfo Bonifacio, Mohammad R. Islam, Dino A. Jaroszynski, Univ. of Strathclyde (United Kingdom) and Scottish Univ. Physics Alliance (United Kingdom)

The ion-channel laser (ICL) has been proposed as an alternative to the free-electron laser (FEL), replacing the deflection of electrons by the periodic magnetic field of an undulator with the periodic betatron motion in an ion channel. Ion channels can be generated by passing dense energetic electron bunches or intense laser pulses through plasma. The ICL has potential to replace FELs based on magnetic undulators, leading to very compact coherent X-ray sources. In particular, coupling the ICL with a laser plasma wakefield accelerator would reduce the size of a coherent light source by several orders of magnitude.

An important difference between FEL and ICL is the wavelength of transverse oscillations: In the former it is fixed by the undulator period, whereas in the latter it depends on the betatron amplitude, which therefore has to be treated as variable. Even so, the resulting equations for the ICL are formally similar to those for the FEL with space charge taken into account, so that the well-developed formalism for the FEL can be applied.

The amplitude dependence leads to additional requirements compared to the FEL, e.g. a small spread of betatron amplitudes. We shall address these requirements and the resulting practical considerations for realizing an ICL.

9509-23, Session 5

Coherent X-ray sources based on a laser wakefield accelerator *(Invited Paper)*

Dino A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

No Abstract Available

9509-24, Session 6

Quasi-continuous, high-power terahertz emission from colliding laser pulses in a magnetized plasma *(Invited Paper)*

Min Sup Hur, Myung-Hoon Cho, Young-Kuk Kim, Ulsan National Institute of Science and Technology (Korea, Republic of); Hyyong Suk, Gwangju Institute of Science and Technology (Korea, Republic of); Bernhard Ersfeld, Dino A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

A novel method of intense terahertz (THz) radiation from a laser-driven magnetized plasma was studied by theory and simulations. In this newly suggested scheme, two counter-propagating laser pulses collide in a magnetized plasma, leaving a non-linear current which acts as a radiation antenna. The resulting power of the THz emission was found to be enhanced by more than hundreds of times compared to the single-pulse-driven Cherenkov wake scheme. The emission amplitude reaches tens of MV/m for 10 THz even with a low amplitude of the driving laser pulse such as a0 ? 0.05, and has a quasi-continuous feature with a monochromatic frequency spectrum. Two factors of the enhanced THz emission are discussed. One is the stronger ponderomotive force by the beat of counter-pulses than that of a single pulse. The other is the diffusion-like behavior of the electromagnetic field near cutoff. We theoretically found that when an electromagnetic radiation is driven near cut-off by a constant current, as in our case, the field exhibits a diffusion-like behavior with the field amplitude growing with time. As the growing field hits the plasma-vacuum boundary by the diffusion, it comes as an enhanced THz radiation in free space. This phenomenon was modeled by a constantly driven, complex diffusion equation, which was deduced from the slowly varying envelope model.

9509-25, Session 6

Intense terahertz pulses from SPARC LAB coherent radiation source

Flavio Giorgianni, Istituto Nazionale di Fisica Nucleare (Italy) and Univ. degli Studi di Roma La Sapienza (Italy); Enrica Chiadroni, Istituto Nazionale di Fisica Nucleare (Italy); Stefano Lupi, Univ. degli Studi di Roma La Sapienza (Italy); Alessandro Cianchi, Riccardo Pompili, Fabio Villa, Domenico Di Giovenale, Marco Bellaveglia, Massimo Ferrario, Istituto Nazionale di Fisica Nucleare (Italy); Andrea Mostacci, Massimo Petrarca, INFN and SBAI Department, "Sapienza" University of Rome (Italy); Maddalena Daniele, Michele Castellano, Vladimir Shpakov, Giampiero Di Pirro, INFN-LNF (Italy)

Highly intense THz radiation is routinely produced at SPARC_LAB as Coherent Transition Radiation (CTR) and Coherent Diffraction Radiation (CDR) emitted by ultra-short (≈100 fs) high-brightness electron bunches. By proper tailoring the longitudinal electron beam distribution, either broadband or narrowband tunable THz radiation be generated. We report a complete spatial and spectral characterization in different machine conditions and a application in condensed matter physics.

9509-26, Session 6

New opportunities for strong-field LPI studies in mid-IR spectral domain

Igor V. Pogorelsky, Ilan Ben-Zvi, John Skaritka, Markus Babzien, Mikhail N. Polyanskiy, Brookhaven National Lab. (United States); Zulfikar Najmudin, Nicholas Dover, Imperial College (United Kingdom); Wei Lu, Tsinghua Univ. (China)

The last two decades, the BNL ATF pioneers high-peak power CO2 lasers for doing research in advanced accelerators and radiation sources. Our recent developments in ion acceleration, Compton scattering and IFEL research further underscore benefits from expanding studies of strong-field laser interactions deeper into the mid-infrared (MIR) wavelength range. This validates our ongoing efforts of advancing multi-Terawatt CO2 laser technology discussed here alongside with newly opportunities of studying ultra-relativistic laser interactions with plasma and free electrons in MIR spectral domain. We will address new regimes in particle acceleration of ions and electrons, as well as in radiations sources ranging from gamma-rays to T-rays, enabled by the emerging ultra-fast CO2 lasers."

9509-27, Session 6

Coherent effects in backward EUV and X-Ray transition radiation of a bunch of electrons from thin wires

Alexey Tishchenko, Daria Sergeeva, Mikhail Strikhanov, National Research Nuclear Univ. MEPhI (Russian Federation)

Transition radiation is a well-known scheme for generation of X-ray radiation. In high frequency region (X-Ray, EUV), where the wavelength of radiation is less than length of a beam, the main part of radiation is incoherent. In this case the radiation from an electron bunches is described by the so called incoherent form-factor. It was mentioned about in [1, 2], and described analytically and analysed in detail in [3] for uniform distribution of the particle in the bunch and in [4] for Gaussian distribution. In present work we show that incoherent form-factor arises always when the size of a target is finite and it depends on ratio between this size and the transversal size of the bunch, wavelength and Lorentz-factor of the charged particles. We consider X-Ray and EUV Transition radiation propagating in backward direction which is generated by the ultrarelativistic electron bunch crossing the target. The target consists of periodical set of wires with thickness narrower than the transversal beam size. We give analytical expressions for the spectral-angular distribution of transition radiation. Besides, we obtain and analysed the expressions for coherent and incoherent form-factors. The coherent effects of target and the electron bunch play an important role not only in increasing the intensity of radiation, but also change the picture of radiation. When coherent radiation is suppressed, the incoherent form factor plays an important role. For restricted transversally target the phenomenon of incoherent form-factor has been investigated for the first time.

References

[1] G. Doucas et al., "Determination of longitudinal bunch shape by means of coherent Smith-Purcell radiation," Phys. Rev. ST AB, vol. 5, p. 072802, 2002.

[2] J. H. Brownell et al., "Spontaneous Smith-Purcell radiation described through induced surface currents," Phys. Rev. E, vol. 57, p. 1075, 1998.

[3] D.Yu. Sergeeva, A.A. Tishchenko, M.N. Strikhanov, UV and X-ray diffraction and transition radiation from charged particles bunches, NIM B 309 (2013) 189.

[4] A.A. Tishchenko, D.Yu. Sergeeva, X-Ray Smith-Purcell radiation from a beam skimming a grating surface, Proc. of FEL 2014, TUPO13, Basel, 2014.

9509-28, Session 6

XUV Cherenkov and diffraction radiation from femtosecond electron bunch

Daria Sergeeva, Alexey Tishchenko, Mikhail Strikhanov, National Research Nuclear Univ. MEPhI (Russian Federation)

Absorption of the medium, i.e. an imaginary part of dielectric permittivity, can lead to arising the Cherenkov radiation at high frequencies – X-Ray and XUV. Experimentally it was observed by W. Knulst and others [1, 2]. They considered this radiation to develop compact, narrowband, high-brightness X-ray sources. In work [3] X-Ray Diffraction radiation from ultra-relativistic electron moving near an absorbing target was investigated theoretically. In these conditions the Cherenkov radiation arises even when trajectory of the particle does not cross the target. The spatial distribution represents the cone with the axis in forward direction with thickness proportional to the imaginary part of dielectric permittivity. However, as it was shown in [4, 5], allowing for the refraction and reflection of the waves on the face of the target leads to essential changes in spatial distribution of radiation. In present work we supplement the investigation of the work [3] by more accurate allowing for the refraction and reflection effects. In terms of approach described in [4, 6], we give analytical description of the XUV Cherenkov and diffraction radiation from the bunch of charged particles. We show that the spatial distribution of radiation is not symmetrical in relation to the top face of the target. Spectral and angular characteristics of radiation from a femtosecond electron bunch are discussed from point of view noninvasive diagnostics of electron bunches and creating the powerful source of XUV radiation.

References

[1] W. Knulst, O.J. Luiten, M.J. van der Wiel, J. Verhoeven, Appl. Phys. Lett. 79 (2001) 2999.

[2] W. Knulst, M.J. van der Wiel, O.J. Luiten, J. Verhoeven, Appl. Phys. Lett. 83 (2003) 4050.

[3] A.A. Tishchenko, A.P. Potylitsyn, M.N. Strikhanov, X-ray diffraction radiation in conditions of Cherenkov effect, Physics Letters A 359 (2006) 509–511.

[4] D.Yu. Sergeeva, A.A. Tishchenko, M.N. Strikhanov, UV and X-ray diffraction and transition radiation from charged particles bunches, NIM B 309 (2013) 189.

[5] A.A. Tishchenko, D.Yu. Sergeeva, Forward X-Ray and ultraviolet Smith-Purcell radiation for FEL, Proc. of FEL 2014, TUPO14, Basel, 2014.

[6] A.P. Potylitsyn, M.I. Ryazanov, M.N. Strikhanov, A.A. Tishchenko, Diffraction Radiation from Relativistic Particles, Springer, 2011.

9509-29, Session 6

X-ray transition, parametric and Cherenkov radiation sources driven by ultrashort laser pulses

Alexey Tishchenko, National Research Nuclear Univ. MEPhI (Russian Federation); Karo Ispirian, Yerevan Research Institute (Armenia)

Transition radiation of charged particles is a well-known source of X-rays, and used in TRD (transition radiation based detectors) in most of big experiments with high-energy particles over the entire world [1]. X-ray parametric radiation (radiation of charged particle moving in a crystal) and X-ray Cherenkov radiation (CR) (occurring near the lines of absorption in UV, X-ray and gamma- frequency regions) are also known, but less experimentally investigated. At this, X-ray CR is proved to be a good source of radiation in the water window [2,3]. All these kinds of radiation are collected by the same physical mechanism – polarization radiation arising owing to the dynamically changed current density created by the Coulomb field of moving charged particles [4].

However, the propagation in medium of laser pulses also polarizes the electrons bonded in the medium and should lead to the polarization radiation.

In the works [5] G.A. Askarian predicted and theoretically studied the production of long wave Cherenkov radiation by electromagnetic waves passing through linear and nonlinear optic (elecro-optic) media due to gradient force and nonlinear polarization, respectively. Without serious consideration he also noted that at the interface of two media transition radiation can be produced in the same way, and, moreover, the radiation can take place in the region of X-ray frequencies. After that his theoretical predictions was confirmed experimentally [6-8] in infrared range, but for X-rays there are only few theoretical considerations of the polarization radiation from short laser pulses.

The main goal of this research is to explore the possibility to have brilliant, ultra-short X-ray beams for multidisciplinary applications. We managed to generalize the theory of polarization radiation [9-11] for the case of interaction ultrashort laser pulse with matter of target. Different processes X-ray Transition at intersection by the laser pulse boundary between two media; X-ray Parametric radiation at propagating of laser pulse in crystal; Cherenkov radiation at from laser pulse in amorphous medium – all these processes is investigated theoretically as sources of radiation. Spectral-angular characteristics of radiation is obtained and compared.

1. Dolgoshein B. Nucl. Instr. and Methods. A. 326 (1993) 434.

2. Knulst W., Luiten O.J., van der Wiel M.J., Verhoeven J. Appl. Phys. Lett. 79 (2001) 2999.

3. Knulst W., van der Wiel M.J., Luiten O.J., Verhoeven J. Appl. Phys. Lett. 83 (2003) 4050.

4. A.P. Potylitsyn, M.I. Ryazanov, M.N. Strikhanov, A.A. Tishchenko, Diffraction Radiation from Relativistic Particles, Springer-Verlag, 2011, 276.

5. G.A. Askarian, Zh. Eksp. Teor. Fiz. 42 (1962) 1360; Phys. Rev. Lett. 57 (1986) 2470.

6. K.H. Yang, P.L. Richards, Y.R. Shen, Appl. Phys. Lett. 19, 320, 1971.

7. D.A. Bagdasarian, A.O. Makarian, P.S. Pogosian, Pisma Zh.Eksp. Teor. Fiz. 37 (1983) 498.

8. D.N. Auston, K.P. Cheung, J.A. Valdmanis, D.A. Kleiman, Phys. Rev. Lett. 53 (1984) 1555.

9. A.A. Tishchenko, A.P. Potylitsyn, M.N. Strikhanov, Phys. Rev. E 70 (2004) 066501.

10. A.A. Tishchenko, M.N. Strikhanov, A.P. Potylitsyn, Nucl. Instr. and Meth. B 227 (2005) 63.

11. A.A. Tishchenko, A.P. Potylitsyn, M.N. Strikhanov, Phys. Lett. A. 359 (2006) 509.

Conference 9510: EUV and X-ray Optics: Synergy between Laboratory and Space

Monday - Tuesday 13–14 April 2015

Part of Proceedings of SPIE Vol. 9510 EUV and X-ray Optics: Synergy between Laboratory and Space IV

9510-1, Session 1

Beyond Chandra: the future for high-resolution X-ray astronomy *(Invited Paper)*

Martin C. Weisskopf, Jessica A. Gaskin, NASA Marshall Space Flight Ctr. (United States); Harvey D. Tananbaum, Alexey A. Vikhlinin, Harvard-Smithsonian Ctr. for Astrophysics (United States)

Over the past 15 years, NASA's Chandra X-ray Observatory has provided an unparalleled means for exploring the high energy universe because of its half-arcsec angular resolution. Chandra studies have deepened our understanding of objects from galaxy clusters, AGNs, galaxies, supernova remnants, planets, and solar system objects addressing most, if not all, areas of current interest in astronomy and astrophysics. Despite this outstanding progress, it is also clear that many Chandra observations are extremely photon-limited, leaving one with driving scientific questions which eventually will require angular resolution at least as good as Chandra's with much higher photon throughput. Such a mission would also benefit from utilization of the next generation of X-ray instrumentation. Such an observatory will be capable of addressing and studying the formation and subsequent growth of black hole seeds at very high redshifts; the emergence of the first galaxy groups; and details of feedback over a large range of scales from galaxies to galaxy clusters to mention a few topics. There are a number of technical approaches currently under development including adjustable X-ray optics, differential deposition, and modern polishing techniques applied to a variety of innovative substrates. All of these efforts lead one to believe that a major X-ray mission is scientifically and technically well suited to be a major contender in the next American National Academy of Sciences Decadal Survey for Astronomy and Astrophysics.

9510-2, Session 1

X-ray optics at NASA Marshall Space Flight Center

Stephen L. O'Dell, NASA Marshall Space Flight Ctr. (United States); Carolyn Atkins, The Univ. of Alabama in Huntsville (United States); David M. Broadway, Ronald F. Elsner, Jessica A. Gaskin, Mikhail V. Gubarev, NASA Marshall Space Flight Ctr. (United States); Kiranmayee Kilaru, Universities Space Research Association (United States); Jeffery J. Kolodziejczak, Brian D. Ramsey, Jacqueline M. Roche, NASA Marshall Space Flight Ctr. (United States); Douglas A. Swartz, Universities Space Research Association (United States); Allyn F. Tennant, Martin C. Weisskopf, NASA Marshall Space Flight Ctr. (United States); Vyacheslav E. Zavlin, Universities Space Research Association (United States)

NASA's Marshall Space Flight Center (MSFC) engages in research, development, design, fabrication, coating, assembly, and testing of grazing-incidence optics (primarily) for x-ray telescope systems. Over the past two decades, MSFC has refined processes for electroformed-nickel replication of grazing-incidence optics, in order to produce high-strength thin-walled full-cylinder x-ray mirrors. In recent years, MSFC has used this technology to fabricate numerous x-ray mirror assemblies for several flight (balloon, rocket, and satellite) programs. This paper will identify and describe the properties of these mirror assemblies.

While this mature technology enables the production of moderate-cost x-ray telescopes with good (≈20 arcsecond) angular resolution, achieving arcsecond imaging likely requires development of other technologies. Accordingly, MSFC is conducting a multi-faceted research program toward enabling cost-effective production of lightweight high-resolution x-ray mirror assemblies. Relevant research topics currently under investigation include differential deposition for post-fabrication figure correction, in-situ monitoring and control of coating stress, and direct fabrication of thin-walled full-cylinder grazing-incidence mirrors. This paper will report the current status of these three research investigations.

9510-3, Session 1

Alternative technologies and arrangements for future space X-ray telescopes

René Hudec, Astronomical Institute of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Ladislav Pina, Adolf J. Inneman, Czech Technical Univ. in Prague (Czech Republic)

Novel and alternative technologies and arrangements for future space X ray telecopes will be presented and discussed.

9510-5, Session 2

X-ray monitoring for astrophysical applications on Cubesat

Ladislav Pina, Czech Technical Univ. in Prague (Czech Republic); René Hudec, Astronomical Institute of the ASCR, v.v.i. (Czech Republic); Adolf J. Inneman, Rigaku Innovative Technologies Europe (Czech Republic); Jan Jakubek, V. Daniel, Czech Technical Univ. in Prague (Czech Republic); Daniela Cerna, Rigaku Innovative Technologies Europe (Czech Republic); L. Sieger, Czech Technical Univ. in Prague (Czech Republic)

This work addresses the issue of X-ray monitoring for astrophysical applications. The proposed wide-field optical system has not been used in space yet. The proposed novel approach is based on the use of 1D "Lobster eye" optics in combination with Timepix X-ray detector in the energy range 3 - 40 keV. The proposed project includes theoretical study and a functional sample of the Timepix X-ray detector with multifoil wide-field X-ray "Lobster eye" optics. Using optics to focus X-rays on a detector is the only solution in cases the intensity of impinging 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.

9510-6, Session 2

X-ray characterization of curved crystals for hard x-ray astronomy

Elisa Buffagni, Consiglio Nazionale delle Ricerche (Italy) and MIST E-R S.C.R.L. (Italy); Elisa Bonnini, Claudio Ferrari, Consiglio Nazionale delle Ricerche (Italy); Enrico Virgilli, Filippo Frontera, Univ. degli Studi di Ferrara (Italy)

The efficient focalization of hard x- and gamma-rays is essential for a large variety of fields of applications, such as gamma-ray astronomy and nuclear medicine.

Among the methods to focus photons the crystal diffraction results as one of the most effective for high energy photons. An assembling of properly oriented crystals can form a lens able to focus x-rays at high energy via Laue diffraction in transmission geometry; this is a Laue lens.

Several approaches are considered to maximize the diffracted intensity; for instance crystals with high atomic number (such as Au, Ag, Cu) have been proposed. However according to x-ray diffraction theory, the maximum diffraction efficiency is achieved in ideal mosaic crystals, that are ideally imperfect crystals made of small misoriented domains. Unfortunately real mosaic crystals are not ideal ones, due to the uncontrolled size of crystalline tiles which form the crystal itself. This technological difficulty in controlling the mosaicity of the crystals leads to a diffraction efficiency several times lower than the ideal case.

An alternative and convenient approach is the use of curved crystals. We have recently optimized a method based on the surface damage of crystals to produce self-standing uniformly curved Si, GaAs, and Ge tiles of thickness up to 2-3 mm and curvature radius R up to a few meters.

We show that perfect crystals with permanent curved diffracting planes (obtained with our surface damage method) have a diffraction efficiency two orders of magnitude higher than perfect similar flat crystals, thus very close to that of ideal mosaic crystals.

Moreover, in a configuration with diffracting planes perpendicular to the curved crystal surface, a significant focussing effect is demonstrated.

These results were obtained for several energies between 17 and 210 keV with lab sources and at high energy facilities such as LARIX at Ferrara (Italy), ESRF at Grenoble (France), and ANKA at Karlsruhe (Germany).

This makes self-standing curved crystals excellent candidates as optical elements to form efficient lenses for gamma ray focussing at energies of several hundreds keV.

9510-7, Session 2

ISS-Lobster: a low-cost wide-field X-ray transient detector on the ISS

Jordan Camp, NASA Goddard Space Flight Ctr. (United States)

This talk presents ISS-Lobster, a wide-field X-ray transient detector proposed to be deployed on the International Space Station. Through its unique imaging X-ray optics (known as Lobster optics) that allow a 30 deg by 30 deg FoV, a 1 arc min position resolution and a 10-11 erg/(sec cm2) sensitivity in 2000 sec, ISS-Lobster will observe numerous events per year of X-ray transients related to compact objects, including: tidal disruptions of stars, supernova shock breakouts, neutron star bursts and superbursts, high redshift Gamma-Ray Bursts, and perhaps most exciting, X-ray counterparts of gravitational wave detections involving stellar mass and possibly supermassive black holes. The mission includes a 3-axis gimbal system that allows fast Target of Opportunity pointing, and a small gamma-ray burst monitor.

9510-8, Session 2

Polarizers for a spectral range centered at 121.6 nm operating by reflectance or by transmittance

Juan I. Larruquert, Consejo Superior de Investigaciones Científicas (Spain); A. Marco Malvezzi, Univ. degli Studi di Pavia (Italy); Angelo Giglia, Consiglio Nazionale delle Ricerche (Italy); José A. Aznárez, Luis Rodríguez-de Marcos, José A. Méndez, Consejo Superior de Investigaciones Científicas (Spain); Paolo Miotti, Fabio Frassetto, CNR-Istituto di Fotonica e Nanotecnologie (Italy); Giuseppe Massone, Gerardo Capobianco, Silvano Fineschi, INAF - Osservatorio Astronomico di Torino (Italy); Stefano Nannarone, Consiglio Nazionale delle Ricerche (Italy)

Polarimetry is a powerful tool to interpret how the coronal plasma is involved in the energy transfer processes from the Sun's inner parts to the outer space. Space polarimetry in the far ultraviolet (FUV) provides essential information of processes governed by the Doppler and Hanle resonant electron scattering effects. Among the key FUV spectral lines to observe these processes, H I Lyman alpha (121.6 nm) is the strongest one. Some developing or proposed solar physics missions, such as CLASP, SolmeX, and COMPASS, plan to perform polarimetry at 121.6 nm. Hence there is an interest to develop efficient linear polarizers at this wavelength. Classical solutions, such as a parallel plate of a transparent material, either MgF2 or LiF, result in a modest efficiency of the passing polarization component. A significant efficiency increase can be obtained with the use of coatings.

A research has been conducted to develop polarizers based on (Al/MgF2) n multilayer coatings in a band containing 121.6 nm. Coatings operating by reflectance result in a high efficiency after approximately one year of storage under nitrogen. Coatings following various designs with good polarizing performance in a 7-to-8-nm wide FUV range were prepared. In parallel, coating polarizers operating by transmittance have been prepared for the first time. Transmissive polarizers have the advantage that they involve no deviation of the beam. As a further benefit, the developed transmittance polarizers additionally incorporate filtering properties to help reject wavelengths both shortwards and longwards of a band containing 121.6 nm. These filtering properties, properly enhanced, could enable a polarimeter for solar physics with an improved global figure of merit if they make unnecessary the use of a filter to isolate the H I Lyman alpha line.

9510-9, Session 2

Transverse X-ray scattering on random rough surfaces

Ping Zhao, Harvard-Smithsonian Ctr. for Astrophysics (United States)

The study of wave scattering from random rough surfaces has been a subject of investigation in physics and engineering for a very long time. The modeling of X-ray scattering at grazing incident angles is difficult because of the short wavelength (compared to the scale of the surface roughness) and the small angle between the wave propagating direction and the surface. Most traditional approaches make the approximation that the scattering angle is much smaller than the incident grazing angle. This approximation is not practical for many of the applications involving X-ray mirrors.

In year 2002, we presented a SPIE paper entitled "A new method to model X-ray scattering from random rough surfaces" (SPIE Proceedings Vol. 4851, 124). This new method uses a novel approach to solve this century old problem. It provides the exact solution to scattering angles of any size, not limited to small scattering angles.

However, the above paper only gives the solution for scatterings in the plane of incidence. For actual two dimensional random rough surfaces, the outgoing rays can also be scattered out of the incident plan, i.e. the transverse scattering. Traditionally, the transverse scattering was approximated by multiplying the in-plane scattering by a factor of $sinalpha$, where $alpha$ is the incident grazing angle.

This treatment is adequate with the traditional method of small angle approximation. With our new method, which is not limited to the small angle, this treatment is no longer valid.

This paper presents a new solution to the transverse scattering. It uses the same approach as we presented in our 2002 paper, but consider the scattering in the direction perpendicular to the incident plane.

For a given Power Spectral Densities (PSD), a model surface is constructed by assigning a random phase to each spectral component. The incident wave is reflected from the model rough surface and then projected to an outgoing wavefront. The outgoing wave then is redistributed onto an even grid in the transverse direction, with corrections for the wave densities and the phase shifts. Fast Fourier transforms are then performed to calculate the transverse scattering. The process is repeated with different model surfaces which are generated using different sets of random phases. This method provides the exact solution to transverse scattering angles of any size. This solution is generally applicable to any transverse wave scatterings on random rough

surfaces and is not limited to small scattering angles.

This paper together with our 2002 SPIE paper give the complete solution for the wave scattering on the random rough surfaces, for rays scattered in any directions. Examples are given by applying this new method to the Chandra X-ray Observatory optics. This method is also useful for the next generation X-ray observatory missions.

9510-10, Session 3

Applications of lobster eye optics

René Hudec, Astronomical Institute of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic)

We will review recent status of Lobster Eye X-ray optics developments with emphasis on various application areas such as astrophysical, space, laboratory, atmoshperic science etc.

9510-11, Session 3

He+ ions damage on optical coatings for solar missions

Sara Zuccon, IFN-CNR LUXOR Lab. (Italy); Enrico Napolitani, CNR - IMM (Italy); Enrico Tessarolo, Paola Zuppella, Alain J. Corso, Francesca Gerlin, Marco Nardello, Maria G. Pelizzo, IFN-CNR Padova (Italy)

Optical components in solar missions are continuously exposed to the solar wind, i.e. to low energy ions irradiation. It is important to deeply investigate the effects of this irradiation on different metals in order to predict the expected damage on the optical coatings and so to select the best ones for future solar missions. The effects on different metals are shown at different fluences. The main effect is a change in reflectivity, it is explained in terms of modulation of the refractive index of the metal as a result of ions inplantation and metal density local decrease. The synergy between TRIM simulations and SIMS experimental results gives a reliable depth profile for the composition of the implanted region. A local variation of the refractive index, modeled with an Effective Madium Approximation (EMA) theory, can be associated at each depth. By integrating along the whole profile, the expected variation of the optical constants is retrieved. The results are compared with experimental reflectivity measurements in the visible and EUV region.

9510-12, Session 3

Mathematical modeling of multifoil optical systems

Vladimir Tichy, Czech Technical Univ. in Prague (Czech Republic)

First, method simplifying the common ray-tracing procedure is presented. In specific cases, to perform numerical simulations of reflective optical system, not traces of all rays are necessary to simulate but only of few ones.

Therefore, the presented method is extremely effective. Moreover, to simplify the equations, the specific mathematical formalism is used. Because only few simple equations are used only, the program code can be simple as well. At next, analytical model of lobster eye optics is presented. The method allows to determine optical performance on dependence on geometrical parameters. Negative effects like non-ideal mirror reflectivity and non-zero mirror thickness are included to the model.

9510-13, Session 3

Optical study of nanosatellite X-Ray monitor

Vladimir Tichy, Czech Technical Univ. in Prague (Czech Republic); David N. Burrows, The Pennsylvania State Univ. (United States); René Hudec, Czech Technical Univ. in Prague (Czech Republic); Zachary R. Prieskorn, The Pennsylvania State Univ. (United States)

The Schmidt lobster eye design for a grazing incidence X-ray optics provides wide field of view of the order of many degrees, for this reason it can be a convenient approach for the construction of space X-ray monitors. Schmidt lobster eye is possible to assemble in various scales of dimensions and also dimensions and focal lengths acceptable for nano-class satellites are possible.

Draft of nano-class space mission providing monitoring of specific sky area is presented. Preliminary optical design study for such mission is performed. Two of possible opticle designs are presented. For those designs, field of view, effective input area and other basic optical parameters are calculated.

9510-28, Session 3

Techniques for achieving zero stress in thin films of iridium, chromium, and nickel

David M. Broadway, Stephen L. O'Dell, Brian D. Ramsey, NASA Marshall Space Flight Ctr. (United States); Jeffrey J. Weimer, The Univ. of Alabama in Huntsville (United States)

We report on techniques to achieve zero intrinsic stress in thin films of iridium, chromium, and nickel deposited by magnetron sputter deposition. The intrinsic stress is further correlated to the microstructural features and physical properties such as surface roughness and optical density at a scale appropriate to soft x-ray wavelengths. An analysis of surface topography of films in various states of intrinsic stress from images obtained using atomic force microscopy is reported. The examination of the stress in these materials is motivated by efforts to advance the optical performance of light-weight x-ray space telescopes into the regime of sub-arcsecond resolution through various deposition techniques that rely on control of the film stress to values within 10-100 MPa. A characteristic feature of the intrinsic stress behavior in chromium and nickel is their sensitivity to the magnitude and sign of the intrinsic stress with argon gas pressure and deposition rate, including the existence of a critical argon process pressure that results in zero film stress which scales linearly with the atomic mass of the sputtered species. Stress reversal with argon pressure has been previously reported by Hoffman[1] and others for nickel and chromium, and we find the same for iridium. In addition to stress reversal, we identify zero stress in the optical functioning iridium layer shortly after island coalescence for low process pressures at a film thickness of approximately 35nm. The measurement of the low values of stress during deposition was achieved with the aid of a sensitive in-situ instrument capable of a minimum detectable level of stress, assuming a 35nm thick film, in the range of 0.40-6.0 MPa for <111> oriented crystalline silicon substrate thicknesses of 70-280 microns, respectively.

1 John A. Thornton, David W. Hoffman, "Internal stresses in titanium, nickel, molybdenum, and tantalum films deposited by cylindrical magnetron sputtering" J. Vacuum Science Technology., Vol. 14, No.1, Jan/Feb. 1977

9510-15, Session 4

Does X-ray flux data variation reciprocate to the H component and proportionate to D components of geomagnetism observed by airborne magneto-gram and characterize for the seismic event?

Umesh P. Verma, Madhurendra N. Sinha, Patna Science College (India)

TEC stay at regional basis most of time does not signify pessimistic signature,But it isXray flux variation in ionospheric pruturbance symptomies interesting feature with the H component and D component of geomagnetism of airborne magneto-gram data.Continuous observation on Real time basis through NOAA Goes15 and 13 satellite link of satellite Env section provided remarkable fact prior to most of important(greater Earthquakes)on global map.Xray flux variation mostly reciprocate to the variation of H component and Proportionate to D component of Geomagnetism data released on hourly basis by NOAA Immediate prior the Indonesia with6.7Mw14NOV2014 and recently new Zealand with 6.5Mw on 17nov'2014 have evidenced the fact.Ionospheric and LIA pruterbance are the normal phenomena taking place as pre-seismic features. In the Dynamic behavior of earth does not ascertain and fix of geophysical and geochemical characters to fix certain rule to the forecasting and predicting solution. But the induced EM radiation due to stress within the Crustal subsurface transmit various signals and sets relationship prior to most of significant seismic events.entire observations can be explained by Maxwell theory of EM radiation.

Xray flux variation are indicative of negative charge emission developed either from solar activity or of stress developed at Sub-crustal level, we get affirm by works of Dimitar Ozunov and F,T,Freidemann2004-12) EM radiations have mainly two components electric and magnetic.D components of geomagnetism are the generation in vertical direction whereas h horizontal one.At certain crustal spot geomagnetism or magnetic component rise in proportion to Xray flux or negative charge development assures the pre-seismic phenomena

9510-16, Session 5

Self standing curved crystals for gamma ray focusing

Claudio Ferrari, Consiglio Nazionale delle Ricerche (Italy); Elisa Bonnini, Consiglio Nazionale delle Ricerche (Italy) and Univ. degli Studi di Parma (Italy); Elisa Buffagni, Consiglio Nazionale delle Ricerche (Italy); Stephen Doyle, Karlsruher Institut für Technologie (Germany)

Laue lens is an innovative approach to focus x and gamma ray in the energy range from ~60 keV to 1 MeV through Laue diffraction by a properly arranged array of crystals. The best candidates as optical elements for such lenses are self-standing bent crystals, in which crystals with curved diffracting planes allow to achieve the maximum diffraction efficiency, corresponding to the integrated intensity of the diffraction profile.

Mosaic crystals of high Z elements such as Cu, Ag, Au [1-2] were proposed as elements for a gamma ray lens to diffract radiation with high efficiency in an angular range dependent on the desired resolution.

We present a study on diffraction efficiency of bent crystals of Si, Ge and GaAs crystals providing optimized parameters, such as curvature, thickness and diffraction geometries, in which we demonstrate that these relatively light crystals may diffract with the same or even better efficiency than crystal with higher Z number , such as Cu, Ag and Au.

The calculation is based on the dynamical theory of the diffraction. It is found that in 220 Laue diffraction Si and GaAs crystals may exhibit a higher efficiency than heavier materials in an energy range up to 400 keV.

Moreover, we demonstrate that surface damaged bent Si and GaAs crystals exhibit a diffraction efficiency- equivalent or better than equivalent Si and GaAs elastically bent crystals at 17, 19, 22.5 and 60 keV indicating a negligible detrimental effect of the damage process on the crystal diffraction efficiency [3].

Thus, the use of low-Z and perfect curved crystals in Laue lenses may permit an increase of the lens performances. This opens up important opportunities for use in x-ray astronomy for space telescopes and in nuclear medicine for the localization of cancers in the human body.

[1] Courtois P et al (2005). Exp. Astron. 20, 195.

[2] Barriere N et a. (2009). J. Appl. Cryst. 42, 834.

[3] Buffagni E et al (2012). Opt. Eng. 51, 056501.

9510-17, Session 5

Dynamical diffraction approach of deformed crystals using FEM

Vito Mocella, Istituto per la Microelettronica e Microsistemi (Italy); Claudio Ferrero, Jean-Pierre Guigay, ESRF - The European Synchrotron (France)

In classical dynamical diffraction theory for X-ray or neutron [1], the theory does not allow dealing directly with crystals of arbitrary shape; in fact, the crystal surface is usually regarded as a planar surface.

Dynamical diffraction in a deformed crystal is described by the Takagi equations which, in general, have to be solved numerically [2]. With some small differences all available approaches, are based on a Finite Difference (FD) scheme which can be easily implemented on a Cartesian regular mesh, but cannot be easily implemented in a deformed mesh reproducing the real shape of a crystal [9,12]. In practice, in all the numerical studies of diffraction in a deformed crystal, the crystal surface is considered as flat [9-12]. The internal deformation of the crystal structure is taken into account in the numerical scheme, but not the eventual curvature of the crystal surface. Conversely, finite element method (FEM) can be easily applied to a deformed mesh and serves very well to the purpose of modelling an arbitrary incident wave on an arbitrarily deformed surface.

For instance, the cylindrical shape of the surface of a bent crystal plate in symmetrical Bragg geometry can easily be taken into account in a FEM calculation; this is of importance for instance when a bent crystal acts as a focussing device.

FEM has also others advantages: the flexibility in handling complex geometries, like for instance crystal shapes designed to avoid back reflection of incident neutrons and, more generally, an automatic inclusion of boundary conditions in the integral, weak formulation of FEM problems.

References

[1] A. Authier, Dynamical Theory of X-Ray Diffraction (Oxford University Press on Demand, 2004).

[2] Y. Epelboin, Materials Science and Engineering 73, 1 (1985).

[3] J. Gronkowski, Propagation of X-Rays in Distorted Crystals Under Dynamical Diffraction (Physics Report, 1991), pp. 1–41.

[4] V. Mocella, Y. Epelboin, and J. P. Guigay, Acta Crystallogr a Found Crystallogr 56, 308 (2000).

[5] V. Mocella, J. P. Guigay, Y. Epelboin, J. Härtwig, J. Baruchel, and A. Mazuelas, J. Phys. D: Appl. Phys. 32, A88 (1999).

[6] V. Mocella, J. P. Guigay, J. Hrdy, C. Ferrero, and J. Hoszowska, J Appl Crystallogr 37, 941 (2004).

[7] S. Lagomarsino, A. Cedola, S. Di Fonzo, and W. Jark, Crystal Research and Technology 37, 758 (2002).

9510-18, Session 5

3-dimensional profiling for diffraction optical elements

Anatoly Firsov, Alexander Firsov, Heike Loechel, Jürgen Probst, Panagiotis Loukas, Frank Siewert, Alexei Erko, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany)

The modern types of diffractive optical elements (DOE) such as variable line space (VLS) gratings with a large period variation as well as reflection zone plates (RZP) required fabrication of a real 3-dimensional structure profile. The depth variation is dependent on an energy range and lateral period and can be as high as 10 times and more. At the same time the absolute values of the depth profile vary from several nm to several hundred nm.

In this work we report the development of a new technology for the 3-D DOE based on an ion milling process. The examples of VLS gratings and RZPs with lateral periods from 20 µm down to 0.25 µm with a profile depth variation from 8 to 120 nm on the same substrate are presented. This approach allows a precise fabrication of large-area gratings on substrates up to 30 mm x 100 mm with a lateral resolution of the depth variation process of about 0.1 mm. An accuracy of a depth profiling is better than 1 nm.

9510-19, Session 5

Transmittance filters for the FUV range

Luis Rodríguez-de Marcos, Juan I. Larruquert, José A. Méndez, José A. Aznárez, Consejo Superior de Investigaciones Científicas (Spain); Liping Fu, Ctr. for Space Science and Applied Research (China)

Imaging at key spectral lines or bands in the far ultraviolet (FUV) range will provide important information for fields like Astrophysics, Solar Physics, Atmosphere Physics or Plasma Diagnostics. Examples of fundamental FUV spectral lines are H I Lyman ? (121.57 nm), O I (130.4 and 135.6 nm), N I (149.3 nm), and the N2 Lyman-Birge-Hopfield band (LBH, 127-240 nm).

In many applications the intensity of the ultraviolet, visible, and infrared background is higher than the intensity of the target FUV lines; therefore, one of the most important requirements for imaging instruments is to strongly reject (either through reflection or absorption) the visible and adjacent regions. (Al/MgF2)n transmittance filters is the most common device to isolate an FUV spectral band. These materials present unique properties in this range: MgF2 is transparent down to ~115 nm and Al has a very low refractive index in the FUV that contrasts well with MgF2. This sort of filters provides a narrow band at the desired FUV wavelength above 120 nm with very low transmittance at long wavelengths.

Even though transmittance filters based on Al/MgF2 have been used since the 1960`s, their design and fabrication involve difficulties and still nowadays there exist few laboratories or companies that can prepare efficient FUV transmittance filters. Furthermore, little information can be found in the literature about filter designs and optimized deposition procedures.

At Grupo de Óptica de Láminas Delgadas (GOLD) we have developed transmittance filters peaked at some of the FUV key wavelengths mentioned above. We will present data on filters of 3 and 4 Al/MgF2 bilayers peaked either at 135.6 nm or at the center of the LBH band (~160 nm). A transmittance in the visible range below 4•10-6 was obtained for filters peaked at 135.6 nm and below 2•10-5 for the filters peaked at 160 nm, with a transmittance peak of ~0.085. Further research is underway to try to improve filter performance.

9510-20, Session 5

Hard X-ray iterferometer based on parallel micromirrors

Mikhail Lyubomirskiy, Anatoly A. Snigirev, Irina Snigireva, ESRF - The European Synchrotron (France); Sergey Kuznetsov, Vyacheslav Yunkin, Institute of Microelectronics Technology and High Purity Materials (Russian Federation)

Recently mirror interferometers have been proposed for hard X-rays [1, 2]. The main idea of the interferometers is based on the interference of beams reflected by the mirrors at the angle of incidence below the critical angle of total external reflection. It took advantage of the strong demagnification of the projected length of mirrors at small incident angles making this scheme equivalent to the Young interferometer with narrow slits of micrometer size.

Modern microfabrication technologies allow profiling of Si crystals to a significant depth with a high quality of sidewalls offering manufacturing of planar refractive lenses and interferometers [3-5]. In the current work we propose a new design of the mirror interferometer using a parallel scheme, where mirrors located one under another in the beam. The use of sidewalls as reflecting mirrors allows to realize bi- and multi-mirror systems with reflecting surfaces at any split distances including very compact collocation. It opens up the possibility to use such interferometers under low spatial coherence conditions, such as laboratory sources.

We studied optical properties of mirror interferometers in the near- and far- field geometries. The experiments were performed at the micro optics test bench of the ESRF ID6 beamline in the energy range of 12 - 16 keV. The observation distance of interference pattern varied from 1.5 meter to 15 meters. The interference patterns have been registered with the different incidence angles of X-ray beam.

The proposed interferometers based on parallel micro-mirrors can be used for coherence characterization, for an optics and beam metrology and diagnostics in the wide energy range . The strong advantage of planar Si technologies is the ability to create integrated optical systems consisting of refractive optics, lens- and mirror-based interferometers.

[1] K. Fezzaa, et al. (1997). J Xray Sci Technol 7, 12-23

[2] W. Leitenberger, U. Pietsch (2007). J Synchrotron Radiat. 14, 196-203.

[3] A. Snigirev, et al. (2007). Proc SPIE 6705, 670506.

[4] A. Snigirev, et al. (2009). Phys. Rev. Lett. 103, 064801.

[5] A. Snigirev, et al. (2014). Opt. Express. 22, 25842-25852.

9510-21, Session 5

Low-stress coatings for sputtered-sliced Fresnel zone plates and multilayer Laue lenses

Stefan Braun, Adam Kubec, Maik Menzel, Peter Gawlitza, Andreas Leson, Fraunhofer IWS Dresden (Germany)

The application of thin film coating processes for the fabrication of diffractive X-ray optical elements like sputtered-sliced zone plates or multilayer Laue lenses (MLL) is a very promising approach for X-ray focusing down to spot sizes of < 10 nm. However, for practical useful focal length in the order of millimeters or decimeters, multilayer thicknesses of several 10 µm up to a few 100 µm are necessary in order to have large enough numerical apertures of the optical systems.

Currently one of the main challenges is to coat low-stress multilayers with large total thickness in the order of 100 µm. Usually sputter deposition results in thin films with significant compressive stress [1,2]. With increasing thickness of the coatings the risk for delamination, micro cracks and geometric deformation steeply rises. In order to avoid these problems, a new silicon-based multilayer system has been developed that shows low stress with absolute values < 50 MPa. This has been obtained in a broad bilayer thickness range between 5 and 50 nm necessary for multilayer Laue lens designs with focal length of about 10 mm. Additionally, the thermal stability, the change of the internal stress with temperature and the microroughness have been characterized for these multilayers.

[1] C. Liu et al.: „Film stress studies and the multilayer Laue lens project“, Proc. SPIE 63170J-1 (2006)

[2] K. MacArthur et al.: „Periodic variation of stress in sputter deposited Si/WSi2 multilayers“, Appl. Phys. Lett. 99, 081905 (2011)

9510-22, Session 6

A compact "water-window" microscope with 60nm spatial resolution based on a double stream gas-puff target and Fresnel zone plate optics

Przemyslaw W. Wachulak, Alfio L. Torrisi, Andrzej S. Bartnik, Daniel Adjei, Jerzy Kostecki, Lukasz Wegrzynski, Tomasz Fok, Roman Jarocki, Miroslaw Szczurek, Henryk Fiedorowicz, Military Univ. of Technology (Poland)

Shorter illumination wavelength allows for extension of the diffraction limit towards nanometer scale, thus significantly improving a spatial resolution in photon based microscopes. Radiation, particularly suitable for biological imaging due to natural optical contrast, is from so called "water window" spectral range, ?=2.3-4.4 nm, because of selective absorption of radiation by carbon and water, being constituents of the biological samples.

Much effort and time have been already devoted to develop soft X-ray (SXR) microscopes, capable of visualizing features smaller than ~100 nm in size, using both large scale facilities and compact sources. The tradeoff, which can be seen between the exposure time and the size of the microscope is very difficult to deal with, demonstrating often compact systems with very long exposure times [1], or, on the other hand, systems that can obtain very high spatial resolution, short exposure times, however, employing quite large and complicated sources [2].

We present a desk-top system, which is capable of resolving 60 nm features, requires a few seconds exposure time and has a desk-top footprint. We exploit the advantages of a compact, laser-plasma SXR source, based on a double stream nitrogen gas puff target, developed at the Institute of Optoelectronics, Military University of Technology. The source, emitting quasi-monochromatic, incoherent radiation, in the "water widow" spectral range at ? = 2.88 nm, is coupled with ellipsoidal, grazing incidence condenser (RITE s.r.o., Czech Republic) and Fresnel zone plate objective [3]. Details about the source and the microscope, as well as some recent images of test and real samples will be presented.

Such system, in our opinion, represents an interesting solution for high resolution imaging for biomedical applications, material science and nanotechnology.

Acknowledgements

This work is supported by the National Centre for Science, award number DEC-2011/03/D/ST2/00296 and the National Centre for Research and Development, Lider programme, award # LIDER/004/410/L-4/12/NCBR/2013. The authors acknowledge also financial support from the EU FP7 Erasmus Mundus Joint Doctorate Program EXTATIC under framework partnership agreement FPA-2012-0033 and from the 7th Framework Programme's Laserlab Europe project (No. 284464).

Literature:

[1] M. Müller, T. Mey, J. Niemeyer and K. Mann, Opt. Express 22, 19, 23489 (2014).,

[2] H. Legall, G. Blobel, H. Stiel, W. Sandner, C. Seim, P. Takman, D. H. Martz, M. Selin, U. Vogt, H. M. Hertz, D. Esser, H. Sipma, J. Luttmann, M. Höfer, H. D. Hoffmann, S. Yulin, T. Feigl, S. Rehbein, P. Guttmann, G. Schneider, U. Wiesemann, M. Wirtz, and W. Diete, Opt. Express 20, 16, 18362–18369 (2012).

[3] P. W. Wachulak, A. Torrisi, A. Bartnik, D. Adjei, J. Kostecki, L. Wegrzynski, R. Jarocki, M. Szczurek and H. Fiedorowicz, "Desk-top water window microscope using a double stream gas puff target source", Optics Letters 2014 - submitted

9510-23, Session 6

Nanoscale imaging and optimization of a compact "water window" SXR microscope

Alfio L. Torrisi, Przemyslaw W. Wachulak, Military Univ. of Technology (Poland); Muhammad Fahad Nawaz, Czech Technical Univ. in Prague (Czech Republic); Andrzej S. Bartnik, Jerzy Kostecki, Lukasz Wegrzynski, Roman Jarocki, Miroslaw Szczurek, Henryk Fiedorowicz, Military Univ. of Technology (Poland)

One way to extend the diffraction limit is to reduce the wavelength. This allows smaller features can be resolved and improves the spatial resolution in the extreme ultraviolet and soft X-ray (SXR) imaging systems.

Soft X-ray wavelength is about two orders of magnitude shorter than the visible light; additionally, radiation from the "water window" spectral range, which extends between K-absorption edges of carbon (photon energy of 280 eV) and oxygen (540 eV), is very attractive for high-contrast biological imaging, due to natural optical contrast.

It was already demonstrated that a laser-plasma double stream gas puff target source is suitable for SXR microscopy in the "water window" spectral range. SXR microscopy has been successfully employed in transmission mode using a Wolter type-I objective [1,2] and - more recently - diffractive optics such as Fresnel zone-plates [3]. Such a system, operating at He-like nitrogen spectral line ?=2.88nm, is capable of imaging with half pitch spatial resolution approaching 60 nm..

Herein we would like to present measurements on the signal-to-noise ratio in the obtained images for various acquisition conditions. The goal of those measurements is to characterize in more details such compact microscopy system, based on double stream gas puff target and Fresnel zone plate objective.

This system represents an important alternative for high resolution imaging for biomedical applications, material science and nanotechnology.

Acknowledgements

This work is supported by the National Centre for Science, award number DEC-2011/03/D/ST2/00296 and the National Centre for Research and Development, Lider programme, award # LIDER/004/410/L-4/12/NCBR/2013. The authors acknowledge also financial support from the EU FP7 Erasmus Mundus Joint Doctorate Program EXTATIC under framework partnership agreement FPA-2012-0033 and from the 7th Framework Programme's Laserlab Europe project (No. 284464).

[1] P. W. Wachulak, A. Bartnik, M. Skorupka, J. Kostecki, R. Jarocki, M. Szczurek, L. Wegrzynski, T. Fok and H. Fiedorowicz, Applied Physics B 111, 2, 239-247 (2013),

[2] P. W. Wachulak, A. Bartnik, L. Wegrzynski, J. Kostecki, R. Jarocki, T. Fok, M. Szczurek and H. Fiedorowicz, Nuclear Instruments and Methods in Physics B 311, 42–46 (2013)

[3] P. W. Wachulak, A. Torrisi, A. Bartnik, D. Adjei, J. Kostecki, L. Wegrzynski, R. Jarocki, M. Szczurek and H. Fiedorowicz, "Desk-top water window microscope using a double stream gas puff target source", Optics Letters 2014 - submitted

9510-37, Session 6

Performance testing of a novel off-plane reflection grating and silicon pore optic spectrograph at Panter

Hannah R. Marlowe, The Univ. of Iowa (United States); Ryan Allured, Harvard-Smithsonian Ctr. for Astrophysics (United States); Casey T. DeRoo, Benjamin D Donovan, Drew M. Miles, James H. Tutt, The Univ. of Iowa (United States); Vadim Burwitz, Benedikt Menz, Gisela Hartner, Max-Planck-Institut für extraterrestrische Physik (Germany); Randall L. McEntaffer, The Univ. of Iowa (United States)

An X-ray spectrograph consisting of radially profiled off-plane reflection gratings and silicon pore optics was tested at the Max Planck Institute for Extraterrestrial Physics Panter beamline. For the first time, two gratings were aligned within an active alignment module in 3 degrees of freedom. We report the line spread function and efficiency of the telescope, and plans for future development.

9510-24, Session 7

Photoionized plasmas in laboratory: a connection to astrophysics and planetary sciences

Andrzej S. Bartnik, Military Univ. of Technology (Poland); Tadeusz Pisarczyk, Institute of Plasma Physics and Laser Microfusion (Poland); Przemyslaw W. Wachulak, Military Univ. of Technology (Poland); Tomasz Chodukowski, Institute of Plasma Physics and Laser Microfusion (Poland); Tomasz Fok, Lukasz Wegrzynski, Military Univ. of Technology (Poland); Zofia Kalinowska, Institute of Plasma Physics and Laser Microfusion (Poland); Henryk Fiedorowicz, Roman Jarocki, Miroslaw Szczurek, Military Univ. of Technology (Poland); Edward Krousky, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic); Miroslav Pfeifer, Jiri Skala, Institute of Physics (Czech Republic); Jiri Ullschmied, Jan Dostal, Roman Dudzak, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic); Jan Hrebícek, Tomas Medrik, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Jakub Cikhardt, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Balzima Cikhardtova, Czech Technical Univ. in Prague (Czech Republic); Daniel Klir, Karel Rezac, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Ladislav Pina, Czech Technical Univ. in Prague (Czech Republic)

Photoionized plasmas are not produced in normal conditions on Earth, but are common in Space. Most of the matter in the Universe is ionized due to heating by gravitational compression or exposure to intense EUV or X-ray radiation. Photoionization of gases is a key process in formation of different kinds of astrophysical plasmas, especially located close to strongly radiating compact objects. Spectral investigations of these plasmas can provide information about astrophysical objects emitting X-ray radiation that irradiate surrounding gases. Interpretation of the observed spectra require constructing of physical models and performing laboratory experiments that support the accuracy of the models.

Photoionization of gases is also an important process for planetary science. Photoionization of atoms and molecules is one of the dominant processes that occur in upper atmospheres. In the case of molecules, ionization can result in further dissociation to ionic and neutral species. Ionization of O2, N2 and other simple molecules by solar radiation is one of the most important ion production channels on Earth's and Titan's upper atmospheres. Modelling of the upper atmosphere requires knowledge of the composition and reactions that occur among its constituents.

In this work investigations of photoionized plasmas were performed using using laser-produced plasma (LPP) extreme ultraviolet (EUV) or soft X-ray (SXR) sources with different parameters. The sources were based on three different laser systems with pulse energies ranging from 0.8 J to 500J and pulse duration 0.2 10 ns. Laser plasmas were produced by irradiation of double stream gas puff targets with Xe or KrXe mixture as the working gas. EUV or SXR radiation was focused using grazing incidence collectors of different types. The collectors were based on multifoil, ellipsoidal or paraboloidal mirrors optimized for specific wavelength ranges.

Different gases were injected into the interaction region, perpendicularly to an optical axis of the irradiation system, using an auxilary gas puff valve. Irradiation of the gases resulted in ionization and excitation of atoms and molecules forming photoionized plasmas. Spectra in SXR/EUV range were measured using a grazing incidence, flat-field spectrograph (McPherson Model 251), equipped with a 450 lines/mm toroidal grating and a home made spectrograph based on free standing transmission grating 5000l/mm. Density distribution of photoionized plasmas was measured using laser interferometry. In all cases the most intense emission lines were assigned to singly charged ions. Other spectral lines corresponding to doubly, triply and even quadruply charged ions were also recorded.

9510-25, Session 7

Laser plasma sources of soft X-rays and extreme ultraviolet (EUV) for application in science and technology

Henryk Fiedorowicz, Military Univ. of Technology (Poland)

Laser plasma sources of soft X-rays and extreme ultraviolet (EUV) developed in our laboratory for application in various areas of technology and science are presented. The sources are based on a laser-irradiated gas puff target approach. The targets formed by pulsed injection of gas under high-pressure are irradiated with nanosecond laser pulses from Nd:YAG lasers. We use commercial lasers generating pulses with time duration from 1ns to 10ns and energies from 0.5J to 10J at 10Hz repetition rate. The targets are produced with the use of a double valve system equipped with a special nozzle to form a double-stream gas puff target which secures high conversion efficiency without degradation of the nozzle. The use of a gas puff target instead of a solid target makes possible to generate plasmas emitting soft X-ray and EUV radiation without target debris production. The sources are equipped with optical systems to collect soft X-ray and EUV radiation and form the radiation beam. We use various optical systems, including grazing incidence axisymmetrical ellipsoid mirrors, the "lobster eye" type grazing incidence multifoil mirror, and the ellipsoidal mirror with Mo/Si multilayer coating as the collectors. The source equipped with the ellipsoidal mirror with Mo/Si multilayer coating has been used for imaging with nanometer resolution using a Fresnel zone plate as an objective. Quasi-monochromatic EUV emission at 13.8nm is obtained by selection of a single spectral line from the argon plasma emission using the ellipsoidal mirror. EUV imaging with the spatial resolution of about 50nm has been demonstrated for the first time with the use of a very compact desk-top device. The source equipped with the grazing incidence ellipsoid mirror as a condenser and the grazing incidence hyperboloid/ellipsoid (Wolter I type) mirror as an objective was used for imaging in the "water window" wavelength range with sub-micrometer resolution and the source with a Fresnel zone plate was used for imaging in the soft X-ray region with resolution of about 60nm.

The EUV source with the grazing incidence ellipsoid mirror has been used for processing of materials by direct photoetching with EUV photons. Efficient micro- and nanoprocessing of various polymers was demonstrated. Modification of polymer surface by nano- and microstructuring with EUV radiation for biocompatibility control has been investigated. It was shown that CHO cells seeded on PET polymer surfaces irradiated with EUV show more pronounced adhesion and alignment as compared with polymer surfaces irradiated with UV lasers. EUV radiation has been also used for efficient micromachining of PVDF, material which is known to have an extremely high chemical stability and electrical resistivity. Results on processing polymers and modification of polymer surfaces with EUV photons will be shown and discussed. The compact soft X-ray source operating in the 'water window' range has been used for the first time in X-ray contact microscopy and DNA damage for radiobiology studies. The EUV sources have been also used in experimental research of photoionization processes of gases. Various gases injected into the interaction region were irradiated with the focused EUV beam. Spectra in the EUV/VUV region from photoionized plasmas have been measured. Results of the studies will be presented and discussed.

9510-26, Session 7

Problems and prospects of laboratory reflectometry in soft X-ray and EUV ranges

Nikolay Chkhalo, Nikolay N. Salashchenko, Alexander Scherbakov, Sergei Y. Zuev, Institute for Physics of

Microstructures (Russian Federation)

Current status, real opportunities and the main problems of the laboratory reflectometry in soft X-ray (SXR) and extreme ultraviolet (EUV) ranges are analyzed. A new reflectometer based on Czerny-Turner monochromator and a laser-plasma source SXR and EUV radiation developed in IPM is reported about. Seven–axes goniometer allows to study samples with arbitrary shape of the surface, with a numerical aperture up to NA=0.5 and with a diameter up to 300 mm with high spatial (better than 0.1 mm) and angular (at the level of 0.01 °) resolution. The main advantages of this device are: high intensity of the light source, dynamic range of the intensity is about 105-106 ; high spectral resolution, ??~0.01 nm and the possibility of a smooth change in the wavelength of the probe beam. These advantages: firstly, to expand the list of traditional metrology problems solved with the help of laboratory reflectometry, in particular, add the study of the polarization properties of X-ray optical elements; secondly, to develop new methods, such as resonant X-ray reflectometry (measurements in the vicinity of absorption edges of materials that make up the objects under study), absorption spectroscopy EXAFS and NEXAFS; thirdly, possible to study the optical activity materials in the soft X-ray range. The report presents the results of testing the performances of the reflectometer and examples of its application to the study the surfaces, multilayer mirror's reflectivity and diffusion scattering, and polarizers based on free-standing multilayer structures.

9510-27, Session 8

Diffraction gratings based on asymmetric-cut multilayers

Mauro Prasciolu, Deutsches Elektronen-Synchrotron (Germany); Henry N. Chapman, Deutsches Elektronen-Synchrotron (Germany) and Univ. Hamburg (Germany); Sa?a Bajt, Deutsches Elektronen-Synchrotron (Germany)

Asymmetric-cut multilayers are volume diffraction elements that show high efficiency and high angular dispersing behaviour due to the asymmetric truncation of the multilayer stack [1-3]. They can be prepared by cutting a multilayer coating under an angle. For a multilayer with a period d cut at an angle of ? the cut surface exhibits layers with a period of D = d / sin ?. The cut multilayer can be thought of as a blazed grating of period D and blaze angle ? with an over-coated multilayer structure that satisfies the Bragg condition for reflection from the facets of the blaze.

Multilayers can be deposited with Ångstrom thickness precision, which enables fabrication of practically perfect blazed gratings. However, to make highly efficient, viable structure one has to overcome several limitations. One of them is the final size of the grating, which is determined by the maximum multilayer thickness deposited in a single run. Here, we will present a new design that overcomes this limitation and is based on using specially prepared substrates combined with post-deposition planarization. So prepared asymmetrically-cut multilayer gratings are highly dispersive and very efficient and can be used as monochromators, spectrometers and pulse compressors with novel x-ray sources. Recent results including fabrication and characterization of such diffraction gratings optimized for extreme ultraviolet (EUV) regime (~13 nm) will be presented.

[1] V. E. Levashov and A. V. Vinogradov, "Resonance diffraction efficiency enhancement in sliced multilayers", Appl. Opt. 32, 1130–1135 (1993)

[2] R. M. Fechtchenko, A. V. Vinogradov, D. L. Voronov, "Optical properties of sliced multilayer gratings," Opt. Comm. 210, 179-186 (2002)

[3]S. Bajt, H. N. Chapman, A. Aquila, E. Gullikson, "High-efficiency x-ray gratings with asymmetric-cut multilayers", J. Opt. Soc. Am. A (3), 216-230 (2012)

9510-29, Session 8

Optical and structural characterization of CeO2/B4C multilayers near the Boron absorption edge

Mewael Giday Sertsu, Univ. degli Studi di Padova (Italy) and RWTH Aachen Univ. (Germany); Angelo Giglia, Consiglio Nazionale delle Ricerche (Italy); Sascha Brose, RWTH Aachen (Germany); Antonela Comisso, Univ. degli Studi di Padova (Italy); Zhanshan Wang, Tongji Univ. (China); Larissa Juschkin, RWTH Aachen Univ. (Germany); Piergiorgio Nicolosi, Univ. degli Studi di Padova (Italy)

Multilayers are key components of EUV and X-ray optics. Si/Mo MLs for EUVL applications , Cr/Sc MLs for X-ray microscopy in the 2 - 4nm wavelength ranges , Si/Mo , Si/Ir and Si/Mg MLs for building imaging components of space telescopes in the 17 -30.5 nm wavelength ranges, and polarization control in HHG for studying magnetic properties of materials are some of the application areas of MLs. Other group of material combinations sought for the next generation EUV lithography (BEUV lithography) include Mo/B4C, La/B4C, W/B4C and LaN/B4C. Now, we want to add another group to the list, B4C/CeO2. This combination gives comparable theoretical reflectivity with La/B4C ML (which is the best theoretically) at about 6.7nm. For N < 70, the CeO2/B4C ML gives even higher theoretical reflectivity.

Having 9% more in theoretical reflectivity for N < 70, and comparable theoretical reflectivity (with some design modifications) for large bi-layer periods (N>150) seem to be another opportunity for the BEUV lithography.

Several reports on thin film growth of CeO2 indicated its importance as a buffer layer between Silicon substrate and superconductors mainly because of its small lattice mismatch with Si, excellent thermal stability at high growth temperature, and as effective diffusion barrier . Thus, the interface situation of the CeO2/B4C MLs is not expected to be worse than the La/B4C, a chance to enhance reflectivity. However, detail study of the surface and interface roughness, interface diffusion, and thickness determinations are required to exploit the potentiality of the CeO2/B4C combination.

In this work, we provide a preliminary analysis of CeO2/B4C MLs grown by RF magnetron sputtering facility. Reflectivity performance at the working wavelengths of 6.x (near the boron edge), period and layer thicknesses, and surface roughness analysis will be presented.

9510-30, Session 8

Combined EUV and X-ray analysis of periodic multilayer structures

Igor A. Makhotkin, Konstantin Nikolaev, Univ. Twente (Netherlands); Sergey N. Yakunin, Russian Research Ctr. Kurchatov Institute (Russian Federation); Robbert W. E. van de Kruijs, Fred Bijkerk, Univ. Twente (Netherlands)

Accurate information about the atomic scale structure of periodic multilayer mirrors is essential for the optimization of deposition process and modelling of the performance of these mirrors. Here we present a way to analyze the chemical composition of multilayers used as optics in the short-wavelength X-ray and XUV range. We use the combined analysis of grazing incidence hard X-Ray reflectivity (GIXR) and normal incidence extreme ultraviolet reflectance (EUVR). This allows to combine the high sensitivity of GIXR data to layer and interface thicknesses with the high sensitivity of EUVR to layer densities and atomic compositions. This method was applied for the reconstruction of the layered structure of LaN/B multilayer mirrors with 3.5 nm periodicity. We have compared profiles obtained by simultaneous EUVR and GIXR and GIXR-only data analysis, and both reconstructed profiles result in a similar description of the layered structure. However, our new, combined EUVR/GIXR analysis leads to a ~2x increased accuracy of the reconstructed layered model, and a more narrow range of solutions, as compared to the GIXR analysis only. It also explains the inherent difficulty of accurately predicting EUV reflectivity from a GIXR-only analysis.

9510-31, Session 8

Multilayer optical elements based on beryllium

Vladimir N. Polkovnikov, Nikolay N. Salashchenko, Nikolay Chkhalo, Nikolay N. Tsybin, Sergei Y. Zuev, Institute for Physics of Microstructures (Russian Federation)

The development of multilayer structures, designed as efficient reflective coatings and absorption filters in the soft X-ray and extreme ultraviolet (EUV), is subject to continuous improvement of the optical properties of elements: the reflection characteristics for multilayer mirrors MLM and transmission, combined with the strength, for absorption filters AF. The limit values of the optical properties were nearly achieved. Of course, this statement refers to the well-known and used in practice combinations of materials. Improve the performance of structures through the use of some additional methods (barrier layers, ion polishing, ion assisting) is possible, but it can hardly give a substantial effect. It is, in particular, the increment of reflection coefficient for a few percent. Of course, even such a gain is very important for many applications. But most of the increase, obviously, give greater effect.

As a rule, high reflection and transmission coefficients are achieved near the absorption edges of chemical elements of which are synthesized structure. For example, in the soft X-ray is allocated a limited set of absorption edges: Sc (? = 3.14 nm), C (? = 4.47 nm), B (? = 6.63 nm). In intermediate ranges we need effective MLM. There is a problem of creating highly reflective MLM with stable over time characteristics for EUV astronomy (line HeI 58.4 nm and HeII 30.4 nm). Even more acute for this range is the problem of creating AF. Thus the design and synthesis of effective MLM and AF for a range of 2-60 nm remains an urgent task.

Typically, the transition to a qualitatively new level occurs when introducing new pairs of elements. In this work as a basis for design effective MLM and AF are encouraged to apply beryllium. In the vicinity of the wavelength of 11.2 nm, 17.1 nm and 30.4 nm, the MLM based on beryllium theoretically easy to overcome the bar at 70%, which makes them likely candidates for the role of structures for optical scheme lithographers new generation of orbiting solar telescopes.

In this work we focus primarily on the performance of EUV multilayers based on beryllium for use in solar physics, specifically in high-angular-resolution or high-spectral-resolution instruments employing normal-incidence mirrors.

9510-32, Session 8

Periodic Co/C, Cr/C, and CoCr/C soft X-ray multilayers prepared by N reactive sputtering

Mingwu Wen, Li Jiang, Zhong Zhang, Qiushi Huang, Zhanshan Wang, Tongji Univ. (China); Hongchang Wang, Diamond light source (United Kingdom); Mingqi Cui, Beijing Synchrotron Radiation Facility (China); Rongqing Yi, China Academy of Engineering Physics (China)

There are many soft X-ray sources in the sky, such as puslars, active galactic, black hole binaries and so on which can emit polarized radiation. A project named Lightweight Asymmetry and Magnetism Probe (LAMP) was proposed in China and the polarized radiation at 250 eV will be observed for check some radiation mechanism in the soft X-ray celestial sources. We have deposited periodic Co/C, Cr/C, CoCr/C X-ray multilayers with and without reactive sputtering with nitrogen. We have also studied the properties of single-layer Co, Cr, CoCr and C coatings, in order to understand specifically how the roughness, chemical composition and microstructure in these materials change with reactive sputtering. In comparison to the multilayers deposited nonreactively, reactively-sputtered multilayers show high reflectivity at 250 eV and lower interfacial roughness. Consequently we have been able to make Co/C, Cr/C, CoCr/C multilayers that have much smaller periods relative to what can be achieved using non-reactive sputtering. The multilayers made by reactive sputtering show excellent X-ray performance and excellent temporal stability.

9510-33, Session 8

Development of XUV multilayer gratings with high resolution and high efficiency

Xiaowei Yang, Qiushi Huang, Tongji Univ. (China); Igor V. Kozhevnikov, A.V. Shubnikov Institute of Crystallography (Russian Federation); Zhanshan Wang, Tongji Univ. (China); Jun Zhao, Yanqing Wu, Shanghai Institute of Applied Physics (China)

High resolution XUV diffraction optics with high efficiency are the key components to probe the structure and dynamics of matters in laboratory and space. Combing XUV multilayers with high quality gratings can further improve the spectral resolution and efficiency/throughput of the diffraction optics to serve the advanced applications like normal incidence astronomy telescopes and high precision x-ray spectroscopy techniques. Different types of multilayer gratings are under development in our lab, particularly the multilayer coated blazed grating. The blazed grating substrate is produced by wet anisotropic etching of a single crystalline silicon. This method can generate sharp triangular profile with atomically smooth surface which is very important for achieving the high efficiency in theory. Different multilayers were tested on the blazed gratings while the related design and fabrication results will be presented in here.

9510-38, Session 8

Overview of the multilayer-Fresnel zone plate and the kinoform lens development at MPI for Intelligent Systems

Umut Tunca Sanli, Kahraman Keskinbora, Corinne Grévent, Gisela Schütz, Max-Planck Institut für Intelligente Systeme (Germany)

The ultimate goal of our research is to develop novel fabrication methods for high efficiency and high resolution X-ray optics. To this end, we have been pursuing the fabrication of several un-conventional diffractive/refractive optics designs. One such optic is the multilayer type (ML) Fresnel zone plate (FZP). Despite the long standing idea, high resolution imaging with such optics has not been possible until recently. Our fabrication process relies on the atomic layer deposition (ALD) of two materials on a smooth glass fiber followed by focused ion beam (FIB) based slicing and polishing [1]. Recently, we demonstrated 21 [2] to 15 nm half-pitch resolutions in the soft X-ray range. The advantages of this type of optic are two-fold; first it can, in principle, have a much smaller outermost zone width than industry standard electron beam lithography based FZPs, meaning a potentially higher resolution and second it can have a very high optical thickness, i.e. high aspect ratio, to be able to focus hard X-rays as well as soft X-rays [3]. Another optic with a long history of stagnating development is the kinoform lens. A kinoform lens is a refractive/diffractive optic with a 100 % theoretical focusing efficiency. Their fabrication is usually realized by using some approximate models which limit their success. Recently the fabrication of real kinoform lenses has been successfully realized in our lab via gray-scale direct-write ion beam lithography without any approximations. The lenses have been tested in the soft X-ray range with up to 14 % and 89 %, absolute and relative focusing efficiencies, respectively [4]. The high focusing efficiency relative to the theoretical value demonstrates the successful replication of the designed 3D surface relief profile of the lens. The above mentioned two types of lenses can be utilized for a wide range of photon energies ranging from extreme UV to possibly gamma ray energies.

Literature:

[1] M. Mayer, C. Grévent, A. Szeghalmi et al., Ultramicroscopy, 111(12), 1706-1711 (2011).

[2] K. Keskinbora, A.-L. Robisch, M. Mayer et al., Optics Express, 22(15), 18440-18453 (2014).

[3] M. Mayer, K. Keskinbora, C. Grévent et al., J Synchrotron Radiat, (2013).

[4] K. Keskinbora, C. Grévent, M. Hirscher et al., Adv. Opt. Materials (2015). doi: 10.1002/adom.201400411

9510-34, Session PS

Characterization of TiO2 thin films in the EUV and soft X-ray region

Antonela Comisso, Piergiorgio Nicolosi, Univ. degli Studi di Padova (Italy); Angelo Giglia, CNR- Istituto Officina Materiali (Italy); Laura Calvillo, Department of Chemical Sciences, University of Padova (Italy); Marco Nardello, Enrico Tessarolo, Mewael Sertsu, Univ. degli Studi di Padova (Italy); Gaetano Granozzi, Department of Chemical Sciences, University of Padova (Italy); Francesca Gerlin, Laura Brigo, Univ. degli Studi di Padova (Italy)

Recent research, has output oxide compounds such us TiO2, as very promising and important materials for EUV and SX applications, highlighted as effective capping layers for Mo/Si multilayer (ML) mirrors, beam splitter (BS) for high-order harmonics and as a component on novel MLs for “water window” wavelength, to name a few. Furthermore, traditionally, chromium (Cr) is the “scattering” material for the creation of multilayers for the “water window” in combination with scandium (Sc), however, a Cr/Sc pair has never reached it´s theoretical reflectivity, and has a series of drawbacks [1]. Considering the fact that oxide multilayer can prevent the formation of an alloy at the interface without any buffer layer, with absorption of oxygen in oxides negligible at water-window wavelengths [2], TiO2 can be very promising as the “scattering” material to improve perfomrances of such MLs. Sc/TiO2 multilayer show theoretical reflectivity of 69% in the soft x-ray wavelength range, for normal incidence.

In order to design, predict performance and improve optical devices used in the EUV and SX, it is vital to have knowledge and accurate information on the refractive index of these materials in this wavelength spectrum, as well as the way they grow when coupled with other materials. Thus, a full characterization of these materials and an analysis of interfaces are of great interest for development of new high performance components.

In this context, we´ve deposited TiO2 thin films using e-beam evaporation technique, studying their reflectivity in the Soft X-ray and EUV range, their surface roughness, thickness and optical constants. Structures of a few Sc/TiO2 layers have also been analyzed.

References:

[1] “Multilayer Structures for the WaterWindow Spectral Range on the Basis of Scandium” S. S. Andreev, M. M. Barysheva, P. K. Gaikovich, D. E. Par’ev, and N. I. Chkhalo. Journal of Surface Investigation. Xray, Synchrotron and Neutron Techniques, 2012, Vol. 6, No. 4, pp. 598–600.

[2] “Novel TiO2/ZnO multilayer mirrors at ‘water-window’ wavelengths fabricated by atomic layer epitaxy”, H Kumagai1, Y Tanaka1, M Murata 1, Y Masuda1 and T Shinagawa2, J. Phys. Condens. Matter 22 (2010)

9510-35, Session PS

Radiometric modelling of a space optical instrument: an example of application to PHEBUS

Alain J. Corso, Paola Zuppella, IFN-CNR LUXOR Lab. (Italy); Enrico Tessarolo, Univ. degli Studi di Padova (Italy) and IFN-CNR LUXOR Lab. (Italy); Francesca Gerlin, Sara Zuccon, IFN-CNR LUXOR Lab. (Italy); Davide Bacco, Marco Nardello, Univ. degli Studi di Padova (Italy) and IFN-CNR LUXOR Lab. (Italy); Piergiorgio Nicolosi, Univ. degli Studi di Padova (Italy); Jean Francois Mariscal, Nicolas Rouanet, Eric Quémerais, LATMOS (France); Maria G. Pelizzo, IFN-CNR LUXOR Lab. (Italy)

Probing of Hermean Exosphere By Ultraviolet Spectroscopy (PHEBUS) is a dual channels spectrometer working in the Extreme UltraViolet (EUV) and Far UltraViolet (FUV) range. It will be on board of ESA BepiColombo cornerstone mission and it will be devoted to investigate the composition, the dynamic, the formation and the feeding mechanisms of Mercury’s exosphere system.

A consistent interpretation of the observational data collected by PHEBUS requires a deeply knowledge of its radiometric behavior. The Mueller’s Matrix formalism can be adopted to derive an accurate radiometric model able to takes into account also the polarization state of the source observed by PHEBUS. Moreover, this theoretical model can be further verified and refined during an experimental ground calibration campaign. In this work we present the radiometric model derived for PHEBUS spectrometer together with some results obtained during the Flight Model (FM) ground calibration which is still ongoing. In particular, the results obtained employing this approach show that this is a complete and versatile method to perform the radiometric calibration of a generic space instrument.

9510-36, Session PS

EUV ablation: a study of the process

Chiara Liberatore, HiLASE Ctr. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Andrzej S. Bartnik, Inam Ul Ahad, Military Univ. of Technology (Poland); Martina Toufarová, Irena Matulkova, Vera Hájková, Ludek Vysín, Tomás Burian, Libor Juha, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Ladislav Pina, Czech Technical Univ. in Prague (Czech Republic); Akira Endo, Tomás Mocek, HiLASE Ctr. (Czech Republic)

An investigation on short-wavelength ablation mechanism of poly(1,4-phenylene ether ether-sulfune) PPEES by EUV radiation is presented.

The goal of this work is to evaluate the ablation behaviour with respect to the influence of wavelength, fluence and quantum efficiency.

Because there is no yet a general EUV ablation theory, data are analyzed in order to underline regularity of the process which can be used in future to detect the scaling laws of the process. The differences with longer wavelengths ablation and EUV one are pointed out and possible applications of EUV ablation are proposed.

Conference 9511: Damage to VUV, EUV, and X-ray Optics V (XDam5)

Wednesday - Thursday 15–16 April 2015

Part of Proceedings of SPIE Vol. 9511 Damage to VUV, EUV, and X-ray Optics V

9511-1, Session 1

The hard x-ray optics for the study on matter in extreme conditions at LCLS *(Invited Paper)*

Hae Ja Lee, Robert Nagler, Eric C. Galtier, Eduardo Granados, Brice Arnold, SLAC National Accelerator Lab. (United States); R. Curiel, SLAC (United States); Justin A. Garofoli, Western Washington Univ. (United States); Jerome B. Hastings, Greg R. Hays, Philip A. Heimann, Richard W. Lee, Despina Milathianaki, Andreas Schropp, SLAC National Accelerator Lab. (United States); Franz Tavella, Deutsches Elektronen-Synchrotron (Germany); Marc Welch, Jing Yin, SLAC National Accelerator Lab. (United States); Ulf Zastrau, Friedrich-Schiller-Univ. Jena (Germany)

No Abstract Available

9511-2, Session 1

The PADReS optical transport and focusing system at FERMI: design, performance, applications, and multi-approach focal characterization *(Invited Paper)*

Cristian Svetina, Nicola Mahne, Lorenzo Raimondi, Marco Zangrando, Elettra-Sincrotrone Trieste S.C.p.A. (Italy)

FERMI is the first operative SXR/XUV FEL user facility relying upon the High-Gain Harmonic Generation (HGHG) scheme, in which an external UV laser is used to trigger the emission process. It is composed by two undulator chains: the low energy branch (FEL-1) covering the wavelength range from 20 nm up to 100 nm, and the the high energy branch (FEL-2, employing a double stage cascade), covering the wavelength range from 4 nm up to 20 nm. The radiation emitted by both sources has been thoroughly characterized: high intensity, very high coherence, narrow single-peak spectrum, being almost transform limited, and full polarization are among the most important features that have been demonstrated. As a consequence, a brand new class of experiments is now possible in the energy range covered by FERMI. The Photon Analysis Delivery and Reduction System (PADReS) is used to provide online and pulse-resolved information about the photon beam quality (intensity, spatial distribution and position, spectral content, transverse and longitudinal coherence, etc.) as well as to deliver and focus the FEL radiation inside the experimental end-stations. In this presentation we will discuss PADReS design of both transport and focusing optics as well as the characterization of the focal spot by means of different techniques, such as direct imaging from screens, wavefront sensing, and PMMA ablation. We will also present some unique machine configurations allowing to perform two-color pump-probe experiments with FEL light as well as most recent results of FEL-matter interaction study in the frame of 4-wave mixing: the transient grating spectroscopy.

9511-3, Session 1

Damage limitations to scientific experiments at the European XFEL *(Invited Paper)*

Viktor Lyamayev, European XFEL GmbH (Germany)

No Abstract Available

9511-4, Session 1

ARAMIS beamline at SwissFEL: optics and photon diagnostics *(Invited Paper)*

Luc Patthey, Uwe Flechsig, Rolf Follath, Pavle Juranic, Christian David, Milan Radovic, Claude Pradervand, Bruce D. Patterson, Rafael Abela, Paul Scherrer Institut (Switzerland)

X-ray Free Electron Lasers are the new generation of X-ray radiation sources. They provide unprecedented radiation properties, exceeding by orders of magnitude the synchrotron sources, in terms of peak intensity/brilliance, coherence and pulse length. These characteristics provide opportunities for new experiments in chemistry, solid state physics, biochemistry and materials science. However, the X-ray FEL radiation suffers from the stochastic nature of the called Self Amplified Spontaneous Emission (SASE). The ultra high peak intensity/brilliance as well the stochastic nature of the X-ray FEL lead to new challenges for the X-ray optics and photon diagnostics of the beamline.

The presentation will focus on novel optical scheme and photon diagnostic systems used at the hard X-ray (ARAMIS) beamline from the new X-ray Free Electron Laser (SwissFEL) facility currently under construction at the Paul Scherrer Institute. The beam transport offers pink and monochromatic beams to tree different end-stations in the energy range from 2 KeV to 12.4 KeV. The beamline is equipped with non-invasive intensity/position monitors, single shot spectrometer and pulse arrival/length monitors.

9511-5, Session 1

Towards compact high-repetition free-electron lasers: basic principles, potential schemes, expected output parameters, and optics requirements *(Invited Paper)*

Sandra G. Biedron, Colorado State Univ. (United States); Stephen V. Milton, Element Aero, LLC (United States)

No Abstract Available

9511-19, Session PS

Irradiation of low energy ions damage analysis on multilayers

Mewael Giday Sertsu, Univ. degli Studi di Padova (Italy) and RWTH Aachen Univ. (Germany); Angelo Giglia, IOM - CNR (Italy); Larissa Juschkin, RWTH Aachen Univ. (Germany); Piergiorgio Nicolosi, Univ. degli Studi di Padova (Italy)

Optical multilayer coatings for Space and Solar applications have been under thorough study recently as the need for detail study of Sun's atmosphere is increasing. Multilayers are proposed to be part of the Multi-Element Telescope for Imaging and Spectroscopy (METIS). METIS is a Solar remote-sensing instrument of SoLO (Solar Orbiter) satellite whose launch is expected by 2017 [ESA]. As one of the payload instruments for SoLO mission, original METIS design was expected to image the Solar-corona with unprecedented resolution simultaneously in the UV (17 nm, 30.4 nm and 121.6 nm) and polarized visible spectra [ESA].

The solar corona composition is the same as the one in the Sun's interior, mainly hydrogen, but completely ionized, thus protons and electrons, and a small fraction of the other atoms in the same percentages, as they are present in the photosphere [1]. Such low energy ions and electrons (mainly protons and ?-particles), thermal loads, continuous irradiations of ions and radicals, and natural aging processes affect the performances of optical multilayers severely. Thus, detail study of the MLs before they make it on board to the solar satellite mission is indispensable. Previous studies have experimentally demonstrated degradation of reflectivity performances for Si/Mo MLs at working wavelength of 30.4nm (He alpha-Lyman series) because of proton and Alpha particles irradiations [2]. In this piece of work, innovative experimental methods are implemented to perform more detail analysis of optical and structural changes of Si/Mo MLs beyond merely reporting performance degradation.

Synchrotron based grazing incidence EUV reflectivity (GEUVR) near the resonance edges of the spacer element (Si in this work) and XRR measurements are implemented in order to come up with reliable structural, optical and interface characterizations of MLs. The EUV near resonance edge reflectivity gives higher sensitivity to fluctuations in optical constants, layer thicknesses, and potentially promising technique in determining phases and optical constants of interlayers formed at the interfaces [4, 5] in a non-destructive and non-imaging mode. Possible structural changes (mainly periodicity) of MLs are derived from the XRR measurements. Reference sample of Si/Mo ML is analyzed against ion-bombarded sample to substantiate the experimental work.

9511-20, Session PS

Material properties of lithium fluoride for predicting XUV laser ablation rate and threshold fluence

Tomáš Blejchar, Václav Nevrlý, VŠB-Technical Univ. of Ostrava (Czech Republic); Michal Dostál, VŠB-Technical Univ. of Ostrava (Czech Republic) and J. Heyrovský Institute of Physical Chemistry AS CR (Czech Republic); Michal Vašinek, VŠB-Technical Univ. of Ostrava (Czech Republic); Lukaš Pecinka, VŠB-Technical Univ. of Ostrava (Czech Republic) and J. Heyrovský Institute of Physical Chemistry of the ASCR, v.v.i. (Czech Republic); Jakub Dlabka, Martin Stachoň, VŠB-Technical Univ. of Ostrava (Czech Republic); Libor Juha, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Petr Bitala, VŠB-Technical Univ. of Ostrava (Czech Republic); Zdenek Zelinger, J. Heyrovský Institute of Physical Chemistry of the ASCR, v.v.i. (Czech Republic); Peter Pira, Charles Univ. in Prague (Czech Republic) and Institute of Physics of the ASCR, v.v.i. (Czech Republic); Jan Wild, Charles Univ. in Prague (Czech Republic)

This paper deals with prediction of extreme ultraviolet (XUV) laser ablation of lithium fluoride at nanosecond timescales. Material properties of lithium fluoride were determined based on bibliographic survey.

These data are necessary for theoretical estimation of surface removal rate in relevance to XUV laser desorption/ablation process. Parameters of XUV radiation pulses generated by the Prague cavity-discharge laser (CDL) tabletop system were assumed in this context. Prediction of ablation curve and threshold laser fluence for lithium fluoride was performed employing XUV-ABLATOR code.

Quasi-random sampling approach was used for evaluating its predictive capabilities in the means of variance and stability of model outputs in expected range of uncertainties. These data were compared with previously observed experimental values. Temporal profiles of relevant output quantities predicted by one-dimensional model were implemented into the multidimensional unsteady hydrodynamic solver in order to study spatially-resolved formation and morphology of laser plume. This information is essential for supporting ongoing experimental activities.

9511-22, Session PS

Compact laser plasma soft X-ray source for contact microscopy experiments

Mesfin G. Ayele, Military Univ. of Technology (Poland)

Recent advancements in soft X-ray contact microscopy (SXCM) have improved the ability to visualize fine cellular structures and their elemental distribution [1-3]. The improvements in design and performance of soft X-ray (SXR) sources have increased the resolution up to a few tens of nanometers to visualize living biological samples. SXRs ranging from 1 nm to 10 nm wavelengths can be produced by synchrotron radiation (SR) sources or laser-plasma based sources. SR sources are able to produce high intensity radiations with reduced exposure time and can be tuned for elemental mapping. However, the limited access to SR sources encouraged development of laboratory scale laser produced plasma SXRs sources, which produce burst of SXRs that can be used to image living cells.

Laser plasma SXR sources that have been used so far in the studies with SXCM technique are based on a solid target; however, it creates serious problems with the source operation due to an inevitable target debris production [4-5].To avoid this, a compact laser-plasma SXR source based on a double-stream gas puff target has been developed for contact microscopy application. The gas puff target composed of argon encapsulated by helium gas has been irradiated employing a nanosecond Nd:YAG laser pulse operating at 10 Hz repetition rate. Characterisation of the source, including spectral and soft X-ray yield measurements have been performed using transmission grating spectrograph (TGS) and silicon PIN photodiode, respectively. From the characterisation measurements it has been observed that strong emission of SXRs in the 'water window' spectral range (2.3 nm-4.4 nm) can be obtained from argon/helium gas puff target.The source described in this work has been used to irradiate test samples such as rectangular mesh and plasmid DNA at a distance of 7 mm from the source in preliminary experiments. The atomic force microscope analysis of the resulting image revealed, the laser plasma source that has been developed in this study is quite promising for contact microscopy experiments of living biological samples.

Acknowledge:

The authors acknowledge financial support from the EU FP7 Erasmus Mundus Joint Doctorate Programme EXTATIC under framework partnership agreement FPA-2012-0003. With the support from the 7th Framework Programme's Laserlab Eorpoe project (No. 284464).

References

1.Cheng, P. C., R. Feder, D. M. Shinozaki, K. H. Tan, R. W. Eason, A. Michette, and R. J. Rosser. "Soft x-ray contact microscopy." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 246, no. 1 (1986): 668-674.

2. Michette, A., P., Cheng, R., Easons, R., Feder, F., O'Neill, Y., Owadano, R., Rosser, P., Rumsby and M. J., Shaw, "Soft x-ray contact microscopy using laser plasma sources," J phy 19(3), 363 (1986).

3. Batani, D., C.,Botto, M., Moret, M., Milani, G., Lucchini, K., Eidmann, F., Cotelli, C., C., Lora Lamia Donin, G., Poletti, T., Ford, and Stead, A., "The

use of high energy laser-plasma sources in soft X-ray contact microscopy of living biological samples." Eur Phys J D 21(2), 167-179 (2002).

4. Fiedorowicz, H., A., Bartnik, Z., Patron and Parys, P., "X?ray emission from laser?irradiated gas puff targets," Appl phys lett 62(22), 2778-2780 (1993).

5. Fiedorowicz, H., A., Bartnik, J., Kostecki and Szczurek, M., "Debrisless laser-produced X-ray source with a gas puff target," SPIE 2723, 310-316 (1996).

9511-23, Session PS

X-ray-induced electron cascades in dielectrics modeled with XCASCADE code: effect of impact ionization cross sections

Nikita A. Medvedev, Ctr. for Free-Electron Laser Science (Germany)

Modern X-ray free-electron lasers (FEL) provide femtosecond pulses with photon energies up to a few tens of keV. Their durations can be as short as just a few femtoseconds. Such extreme pulse parameters opened new regimes of nonequilibrium electron kinetics in solids, not accessible before. Recently developed experimental pump-probe scheme with an FEL pump and a visible light probe of a solid-state target [1,2] can be used for the pulse duration monitor on a shot-to-shot basis.

Photoabsorbtion excites electrons into high-energy states. Such highly energetic electrons produce electron cascades of impact ionizations and Auger-decay of deep atomic shell holes. To study the electron cascading in different materials, XCASCADE, a Monte Carlo model of the transient electron kinetics within an irradiated target, was developed [3]. With this tool it was shown that the electron cascading duration is sensitive to material properties. A carefully selected target can significantly shorten the electron relaxation times. XCASCADE simulated performance of a FEL-timing tool [3]. The obtained results suggested that with the choice of an appropriate material one could achieve direct monitoring of the pulse duration on a few-femtosecond time scale. For photon energies as high as of 24 keV that will be produced by the European XFEL, 40-fs-timescales can be achieved. Moreover, deconvolution of the electron density into the contribution from the pulse itself and from the secondary cascading can increase the resolution up to a scale of a femtosecond.

[1] M. Harmand et al., Nature Photonics 7, 215 (2013)

[2] R. Riedel et al., Nature communications 4, 173 (2013)

[3] N. Medvedev, "Femtosecond X-ray induced electron kinetics in dielectrics: application for FEL-pulse-duration monitor", submitted to Appl. Phys. B (2014)

9511-24, Session PS

X-ray free-electron laser induced ablation of lead iodide

Vera Hájková, Institute of Physics of the ASCR vvi (Czech Republic)

The contribution describes behavior of X-ray-irradiated lead iodide coatings on silicon and poly(methyl methacrylate) substrates. Damage thresholds of PbI2 were determined at x-ray free-electron laser facilities. The results are compared to findings presented for lead tungstate reported earlier [1]. Possible utilization of lead iodide for revealing the FEL beam properties from an ablation imprint of the beam will be disscused.

[1] V. Hajkova, L. Juha, P. Bohacek, T. Burian, J. Chalupsky, L. Vysin, J. Gaudin, P.A. Heimann, S.P. Hau-Riege, M. Jurek, D. Klinger, J. Pelka, R. Sobierajski, J. Krzywinski, M. Messerschmidt, S.P. Moeller, B. Nagler, M. Rowen, W.F. Schlotter, M.L. Swiggers, J.J. Turner, S.M. Vinko, T. Whitcher, M. Matuchova, S. Bajt, H. Chapman, T. Dzelzainis, D. Riley, J. Andreasson, J. Hajdu, B. Iwan, N. Timneanu, K. Saksl, R. Faeustlin, A. Singer, K. Tiedtke, S. Toleikis, I. Vartaniants, H. Wabnitz, "X-ray laser-induced ablation of lead compounds," Proc. SPIE 8077, 807718 (2011).

9511-25, Session PS

Responses of molecular and covalent carbonaceous solids to a single ultra-shot pulse of extreme ultraviolet and soft x-ray radiation

Martina Toufarova, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Carbonaceous materials, e.g., amorphous carbon (a-C) coatings and C60 fullerene, play an important role in the short-wavelength free-electron laser (FEL) research motivated by FEL optics development and FEL applications in nanotechnology. In this contribution, a response of a-C (890-nm layer on Si) and C60 (220 nm thin film on Si) samples to extreme ultraviolet (SCSS: SPring-8 Compact SASE Source in Japan) and soft X-ray (FLASH: Free-electron LASer in Hamburg, Germany) free-electron laser radiation is investigated by Raman spectroscopy, Nomarski (DIC=differential interference contrast) and atomic force (AFM) microscopy. Both material removal (i.e., erosion, ablation) and expansion (i.e., extrusion) were registered in C60 and a-C materials irradiated by SCSS and FLASH ultra-short laser pulses. The expansion behavior is more frequent in a-C than in C60 fullerene solids. Raman spectroscopy confirms the expansion due to graphitization in a-C while C60 fullerene remains at the crater edge chemically unchanged. Single-shot damage thresholds are 4-fold and 6-fold lower in fullerene exposed to SCSS and FLASH radiation, respectively, than in a-C irradiated at the same wavelength and pulse duration. This behavior can be explained by the fact that a-C represents covalent carbonaceous solids while C60 fullerene is a typical example of molecular solids, where C60 clusters are bound together only by weak intermolecular interactions, i.e., van der Waals forces. Just a small amount of energy should be needed for evaporating C60 clusters, especially if a possible non-thermal mechamism based on cluster charging and cluster-ion repulsion should be taken into account. C60 fullerene seems to be a promising material for an efficient and clean surface nanopatterning induced by short-wavelength lasers.

9511-26, Session PS

Development and preliminary application of a desktop laser-produced plasma soft X-ray to induce single- and double strand breaks in plasmid DNA irradiated in vacuum

Daniel Adjei, Military Univ. of Technology (Poland) and Ghana Atomic Energy Commission (Ghana); Mesfin G. Ayele, Military Univ. of Technology (Poland); Ludek Vy?ín, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Przemyslaw W. Wachulak, Military Univ. of Technology (Poland); Libor Juha, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Andrzej S. Bartnik, Henryk Fiedorowicz, Lukasz Wegrzynski, Military Univ. of Technology (Poland); Anna Wiechec, Janusz Lekki, Wojciech M. Kwiatek, Institute of Nuclear Physics (Poland); Marie Davídková, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

During the past several years many sources of ionizing radiation have become available and enabled the understanding of the effects of these radiations on matter. It is now possible to study the effects of different radiation qualities on cells, cellular components and tissues. They have been useful in the studies of radiation induced cancers. The biological damage produced by SXR radiation was found very often (but not always) more effective as compared with much harder X-rays and gamma rays.

There are numerous sources of SXR including X-ray tubes (electron beam interacting with a solid target), synchrotrons, free-electron lasers, hot plasmas, both discharge and laser-produced, among others. Currently, biological effects of low-energy X-rays are studied using, mainly, monochromatized synchrotron radiation . It has, therefore, become important to have laboratory based facilities with almost similar characteristics for widespread of applications. Experimental laboratory sources of SXR radiation based on micro-focus X-ray tubes, delivering broadband radiation at energies up to 15 keV, or quasi-monochromatic radiation at 284 eV, 1.5 keV, 4.5 keV or 5.4 keV, have been useful for radiobiology studies. However, these sources deliver radiation to the sample at a low dose rate, and thus a relatively long irradiation time is needed to induce measurable biological effects. Higher dose rates can be achieved with laser-produced plasma sources emitting high-intensity pulses of X-ray radiation.

Laser produced plasma sources provide pulses of high photon yield thus can be complementary to the synchrotron based sources. Currently we may count few of such sources of X-rays dedicated for radiobiology experiments. We have, therefore, developed a desk-top laser produced plasma soft X-ray source based on a double-stream gas puff target irradiated with a commercial Nd:YAG laser dedicated for radiobiology research. The source has been optimized for maximum emission in the X-ray “water window” spectral wavelength range from 2.3 nm to 4.4 nm wavelength (280 - 540 eV) by using argon gas puff target and spectral filtering. The source delivers nanosecond pulses of soft X-rays with fluence of about 4.20x10^3 photon/(μm^2 pulse) to sample placed in the vacuum and about 7.48x10^2 photon/(μm^2 pulse) at a sample outside the chamber. The design and characterization measurements of the source will be discussed.

For the first time, the source has been used to induce single- and double-strand breaks in supercoiled plasmid pBR322 DNA when irradiated in vacuum chamber. Remarkable strand breaks were observed in the irradiated DNA by gel electrophoresis and the results will be presented. The fractions of the different forms of the plasmid after irradiation were fitted by a known model in order to characterize the behaviour of the damage with respect to increase in photon flux. The cross-sections for single-strand breaks induction was estimated to be ~9.40x10^-18 m^2 and for double-strand breaks was ~4.61x10^-19 m^2. The combination of the SXR source and the radiobiology irradiation layout, that will be discussed, will make possible investigation of prospective radiobiology studies in the X-ray “water window” spectral range.

9511-6, Session 2

Damage to inorganic materials illuminated by the focused beam of X-ray free-electron laser radiation *(Invited Paper)*

Takahisa Koyama, Hirokatsu Yumoto, Kensuke Tono, Tadashi Togashi, Yuichi Inubushi, Tetsuo Katayama, Japan Synchrotron Radiation Research Institute (Japan); Jangwoo Kim, Satoshi Matsuyama, Osaka Univ. (Japan); Makina Yabashi, RIKEN (Japan); Kazuto Yamauchi, Osaka Univ. (Japan); Haruhiko Ohashi, Japan Synchrotron Radiation Research Institute (Japan)

With the emergence of the X-ray free electron laser (XFEL) facilities, intense ultra-short pulse and fully transverse coherent X-ray pulses have been available in the hard X-ray region. Such intense X-ray pulses possibly induce damage of optical elements, which can be a serious problem of degradation in beam quality. In order to investigate damage thresholds of optical elements, we used focused XFEL pulses that have sufficient power density for inducing ablation phenomena.

The experiments performed at the XFEL facility SACLA (SPring-8 Angstrom Compact free electron LAser) in Japan. The test samples were bare silicon, fused silica, and metal (Mo, Ru, Rh, Pt, etc.) coated substrates, which are often used as X-ray mirror materials. Experimentally determined damage threshold of metal coatings is useful for enlarging acceptance aperture of mirror optics for high throughput and tight focusing. We designed and installed a test chamber for irradiation experiments [1]. The test chamber is equipped with precise scan stages for positioning the test sample and measuring the beam profile, optical microscopes for online monitoring, and a rotation stage for grazing incidence irradiation. Focused XFEL pulses were produced by a pair of elliptical mirrors arranged in Kirkpatrick-Baez geometry. The size of focused XFEL pulses was measured to approximately 1 μm by a knife edge scanning method. X-ray photon energy was chosen to be 5.5 and 10 keV. Single and/or multiple focused XFEL pulses were irradiated to test samples under normal and/or grazing incidence condition. Shot by shot irradiation intensities and reflection intensities (in the case of grazing incidence condition) were monitored to determine the fluence and the reflectivity. In the normal incidence condition, the damage thresholds were evaluated by measuring surface morphology measurement with a scanning probe microscope and scanning electron microscope [1]. In the grazing incidence condition, the damage thresholds were evaluated by measuring X-ray reflectivity degradation [2].

We found that obtained damage fluence thresholds of rhodium coating under grazing incidence condition were about 1-2 order of magnitude larger than the unfocused beam fluence of the SACLA. These results suggest that metal coatings possibly usable in mirror optics at the SACLA.

References

[1] T. Koyama, et al., Opt. Express 21 (2013) 15382.

[2] T. Koyama, et al., Proc. SPIE 8848 (2013) 88480T.

9511-7, Session 2

Electronic energy transport in c-Si irradiated with X-ray beam under grazing incidence angles *(Invited Paper)*

Ryszard Sobierajski, Institute of Physics (Poland); Andrew Aquila, European XFEL GmbH (Germany); Dorota Klinger, I. Jacyna, Piotr Dluzewski, Marcin Klepka, The Institute of Physics (Poland); Tomás Burian, Jaromír Chalupsky, Vera Hájková, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Yuichi Inubushi, Japan Synchrotron Radiation Research Institute (Japan); Libor Juha, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Adrian P. Mancuso, European XFEL GmbH (Germany); Haruhiko Ohashi, Japan Synchrotron Radiation Research Institute (Japan); Cigdem Ozkan, Harald Sinn, European XFEL GmbH (Germany); Takahisa Koyama, Kensuke Tono, Japan Synchrotron Radiation Research Institute (Japan); Kai Tiedtke, Sven Toleikis, Deutsches Elektronen-Synchrotron (Germany); Thomas Tschentscher, European XFEL GmbH (Germany); Makina Yabashi, RIKEN SPring-8 Ctr. (Japan); Jérôme Gaudin, European XFEL GmbH (Germany)

The rapid development of a new generation of X-ray radiation sources providing ultrashort (from atto- to femtoseconds) pulses creates unique possibilities for generating high energy density states of matter. Instruments, like free-electron lasers (FELs) produce pulses of very high intensity and allow to extend the optical studies of radiation induced phase transitions of solids. The excitation of solid materials with x-ray femtosecond pulses offers a number of advantages over irradiation with femtosecond optical lasers. First of all the energy deposition process is not influenced by optical nonlinearities i.e. multiphoton absorption and free carrier absorption. Moreover the absorption depth can be varied over many orders of magnitude. E.g. for silicon it changes from a few nanometres up to hundreds of microns. Therefore, ultrashort X-ray pulses allow the preparation of well-defined excitation conditions in variable sample volumes and thus to study the energy transport processes.

Single shot irradiations of the Si flat mirror were performed at SACLA FEL facilities in the range of 5.5 – 12 keV photon energies, at normal and grazing incidence angles. Observed radiation induced structural modification of materials is related to melting of silicon and its resolidification and a have threshold nature. The experimental damage thresholds are the highest in case of the irradiations below the critical angles. In these cases the energy density of the radiation absorbed at the sample's surface can reach above a melting threshold (approx. 1eV/atom) without any structural modification. This may be explained by

the transport of the energy out of the excitation volume (limited to the absorption skin depth) by hot electrons on the time scales shorter than the one typical for the electron-phonon coupling (~2 ps for Si). Modelling of the energy transport by ballistic electrons has been performed by means of the PENELOPE simulation code.

Acknowledgments: The authors wish to thank the staff of SACLA, Japan for all the help during experimental beam time. This work was partly supported by the Polish National Science Center (Grant No. DEC-2011/03/B/ST3/02453)

9511-8, Session 2

Mass spectra of ions emitted from monocrystalline lithium fluoride irradiated by focused 46.9-nm laser radiation

Tomá? Burian, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Ilya Kuznetsov, Carmen S. Menoni, Jorge J. Rocca, Colorado State Univ. (United States); Libor Juha, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

No Abstract Available

9511-9, Session 2

Nanosecond pulse EUV irradiation of Pt/Co/Pt trilayers: structural, morphological and magnetic changes *(Invited Paper)*

Iosif Sveklo, Univ. of Bialystok (Poland); Andrzej S. Bartnik, Military Univ. of Technology (Poland); Ivanna Yatsyna, Dorota Klinger, Jerzy B. Pelka, Ryszard Sobierajski, Marcin Klepka, Piotr Dluzewski, Andrzej Wawro, Institute of Physics (Poland); Jan Kisielewski, Zbigniew Kurant, Andrzej Maziewski, Univ. of Bialystok (Poland)

Magnetic anisotropy in thin films is very sensitive to various external factors and of great importance for industrial applications. Transition from in-plane to out-of-plane state (PMA) of magnetic anisotropy in Pt/Co/Pt thin trilayers upon femtosecond pulse laser irradiation has been recently reported [1]. We have also very recently shown induction of PMA by application of extreme ultraviolet EUV pulses. A study of morphological and magnetic changes in Pt/Co/Pt under EUV pulse light irradiation is the purpose of the current work.

The epitaxial MBE grown trilayers have the following structure: substrate-Al2O3(00.1))/(Pt(111) 5nm)/(Co(00.1) 3nm)/(Pt(111) 5 nm. As grown samples exhibit smooth surface and in-plane magnetic anisotropy.

A laser-plasma extreme ultraviolet (EUV) source is based on a double-stream gas puff target formed in a vacuum [2]. The target is formed by pulse-injected mixture of Kr and Xe into a hollow stream of helium. The gas puff target is irradiated with 3ns Nd:YAG (?=1.06 ?m) laser pulses with energy of 0.8 J and repetition rate of 10 Hz. The EUV radiation is focused by means of a grazing incidence gold-coated ellipsoidal mirror. Spectrum of the reflected radiation consists of a narrow peak with intensity maximum at wavelength of 10–11 nm. This EUV source is capable to irradiate in vacuum a sample with single/multiple pulses with energy density up to 100 mJ/cm2 and duration about 3 ns. Using this technique spots of modified magnetic properties, about 1mm diameter, were created.

Pt/Co/Pt samples were exposed to a single and multiple EUV pulse(s). Depending on the value of maximum irradiation energy density, either circular or ring-shape spots of characterized by out-of-plane magnetization were observed on remanence polar magneto-optical Kerr (PMOKE) images. In case of the single shot exposures the formation of PMA state corresponds to radiation fluence in the range of 60 to 75 mJ/cm2. Above this value magnetization returns to in-plane state. Detailed atomic force microscopy study of the center of the irradiated spot revealed the appearance of micrometer range holes. These holes penetrate entire metallic trilayers down to the substrate. Magnetic force microscopy revealed a tiny domain structure in PMA induced areas with periodicity depending on the irradiation energy density. Using PMOKE we have determined the dependence of magnetic parameters as a function of a distance from the spot center. Structural modifications of the EUV irradiated Pt/Co/Pt trilayers were also studied by Transmission Electron Microscopy. Atomic interlayer diffusion and modifications of the lattice parameters were observed.

Acknowledgments: This work was supported by: NCN project HARMONIA Nr 2012/06/M/ST3/00475 and SYMPHONY project (Polish Science Team Programme, European Regional Development Fund, OPIE 2007–2013.

Reference

[1] J. Kisielewski et al., JAP 115, 053906 (2014)

[2] A. Bartnik et.al, Nuclear Instruments and Methods in Physics Research A 647 (2011) 125

9511-10, Session 3

Response of polydimethylsiloxane (PDMS) to extreme ultraviolet light emitted from laser produced plasma *(Invited Paper)*

Tetsuya Makimura, Shuichi Torii, Univ. of Tsukuba (Japan); Daisuke Nakamura, Akihiko Takahashi, Kyushu Univ. (Japan); Hiroyuki Niino, National Institute of Advanced Industrial Science and Technology (Japan); Tatsuo Okada, Kyushu Univ. (Japan)

Polydimethylsiloxane (PDMS) is a material used for micro total analysis systems / lab-on-chips due to its flexibility, chemical / thermo-dynamic stability, bio-compatibility and moldability. For further development, it is inevitable to find a technique to fabricate three dimensional structures in micrometer-scale at high aspect ratio. We have investigated a technique for micromachining of PDMS by means of photo direct machining using laser plasma EUV light. The EUV radiations were generated by irradiation of Ta, Sn and Xe targets with Nd:YAG (10 ns) and pulsed TEA CO2 laser (50 ns) light. The generated EUV light around 100 eV (10 nm) were focused on PDMS surfaces up to a power density of 1X10^8 W/cm2, using an ellipsoidal mirror. Applying the technique, we demonstrated microfabrication of a through hole with a diameter of 1 micrometer in a PDMS sheet. We measured ablation depth using the EUV sources and found that ablation depth is governed by power density of EUV light on PDMS surfaces. At EUV power density around the ablation threshold, the surfaces is swelled after EUV irradiation. At power densities sufficiently higher than the threshold, the surfaces are ablated at a rate up to 200 nm/shot. From the threshold, the accumulated EUV energy is estimated to be comparable to that to decompose a PDMS surface into small fragments. X-ray photoelectron spectroscopy has revealed that there is no chemical modification induced by the EUV irradiation. All these properties are suitable for micromachining of PDMS elastomers at high aspect ratios. Thus, we have developed a practical micromachining technique free from chemical modification.

9511-11, Session 3

Damage formation on fused silica illuminated with ultraviolet-infrared femtosecond pulse pairs *(Invited Paper)*

Xiaoming Yu, Kansas State Univ. (United States); Zenghu Chang, Univ. of Central Florida (United States); Paul B. Corkum, National Research Council Canada (Canada) and Univ. of Ottawa (Canada); Shuting Lei, Kansas State Univ. (United States)

We investigate damage formation on the surface of fused silica by two

femtosecond laser pulses, a tightly focused 266 nm (UV)pulse followed by a loosely focused 800 nm (IR)pulse. We show that the damage size is determined by the UV pulse, and only a small fraction of the normal UV damage threshold energy is needed to cause damage when combined with the properly delayedIR pulse. Our results, analyzed with a rate equation model, suggest that the UV pulse generates seed electrons through multiphoton absorption and the IR pulse utilizes these electrons to cause damage by avalanche ionization. By tuning such parameters like pulse energy, time delay, IR pulse duration and polarization, we further demonstrate that damage profile can be controlled.

9511-12, Session 4

Physics of corrosion-resistant Mg/SiC multilayer coatings for EUV sources *(Invited Paper)*

Regina Soufli, Lawrence Livermore National Lab. (United States); Monica Fernandez-Perea, Consejo Superior de Investigaciones Científicas (Spain); Christopher C. Walton, Lawrence Livermore National Lab. (United States); Manuela Vidal-Dasilva, Consejo Superior de Investigaciones Cientificas (Spain); Jeffrey C. Robinson, Sherry L. Baker, Jennifer B. Alameda, Lawrence Livermore National Lab. (United States); Luis Rodríguez-de Marcos, José Antonio Méndez, Juan Ignacio Larruquert, Consejo Superior de Investigaciones Científicas (Spain); Eric M. Gullikson, Lawrence Berkeley National Lab. (United States)

The 25-80 nm wavelength region is part of the operational range of extreme ultraviolet (EUV) synchrotron, free-electron laser and tabletop laser sources, which often require multilayer-coated reflective optics. Mg/SiC possesses a unique combination of favorable reflective properties in the 25-80 nm wavelength range: high reflectance, near-zero film stress, good spectral selectivity and thermal stability up to 350? C. However, Mg/SiC suffers from Mg-related atmospheric corrosion, an insidious and unpredictable problem which completely degrades reflectance and has prevented Mg/SiC from being used in scientific experiments and applications that require long lifetime stability. In recent work, we elucidated the origins and mechanisms of corrosion propagation within Mg/SiC multilayers and demonstrated efficient and simple-to-implement Al-Mg corrosion barriers for Mg/SiC multilayers. We also demonstrated Mg/SiC multilayers with corrosion barriers which achieve high reflectance in up to three narrow bands simultaneously. In this presentation, we focus on the physics of spontaneous intermixing and amorphization of the Al and Mg layers inside the Al-Mg corrosion barriers. We also discuss the long-term reflective properties of a variety of Mg/SiC multilayer concepts, with and without corrosion barriers.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.

9511-13, Session 4

X-ray filter degradation by high-energy laser plasma target debris and shrapnel

James E. Andrew, AWE plc (United Kingdom)

Laser interactions with solids in a vacuum are used as x-ray sources for a variety of applications. For high laser energy [kilo-joule to mega-joule], high irradiance applications significant ejecta plumes from the metal or dielectric targets used can cause degradation or physical destruction of thin solid x-ray filters used in plasma and other diagnostic instruments. A range of metal and dielectric filters are used at several meters from the X ray source for temporally resolved plasma temperature measurements in the range 50 – 6000 eV. These items exhibit both gradual degradation and catastrophic failure in operation. We also describe the effects of titanium and stainless steel targets on polyimide filters located close [cms] to the x-ray source. Near Infra Red and X-ray transmission spectroscopy has been used to evaluate the effects on these filters. Visible band microscopy and macroscopic photography have been utilised to map the debris and shrapnel plumes from the targets so that future experiments can be designed to minimise the plume effects on these diagnostics and the focussing optics used in the laser facilities employed for such experiments. Failure to account for these effects can cause damage to the expensive large aperture laser focussing optics, degrade x-ray filters thus increasing their replacement rate and impact experimental data interpretation.

9511-14, Session 5

Outrunning radiation damage with X-ray FEL pulses *(Invited Paper)*

Henry N. Chapman, Deutsches Elektronen-Synchrotron (Germany)

X-ray free-electron lasers have opened up the possibility of structure determination of protein crystals at room temperature, free of radiation damage. The femtosecond-duration pulses of these sources enable diffraction signals to be collected from samples at doses of 1000 MGy or higher. The sample is vaporised by the intense pulse, but not before the scattering that gives rise to the diffraction pattern takes place. Tens of thousands of patterns are collected from individual crystals that flow across the beam and the patterns are indexed and aggregated into a set of structure factors. Here, we review the interaction of intense femtosecond X-ray pulses with materials and discuss the implications for structure determination. We identify various dose regimes and conclude that the strongest achievable signals for a given sample are attained at the highest possible dose rates, from highest possible pulse intensities.

9511-15, Session 5

The role of dose rate effects in fluorescence chemical dosimetry of aqueous solutions

Martin Precek, Petr Kubelik, Libor Juha, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Ulrich Schmidhammer, Lab. de Chimie Physique (France); Jun Ma, Pierre Jeunesse, Alexandre Demarque, Jean-Philippe Larbre, Mehran Mostafavi, Univ. Paris-Sud 11 (France)

Recent developments in the utilization of high-power femtosecond lasers for generation of X-ray and particle radiation sources as well as the on-going deployment of the first multi-keV X-ray free-electron laser facilities (such as are the LCLS, SACLA and the European XFEL) have opened an opportunity for application of these ultrashort pulsed radiation sources to study radiation chemistry with truly femtosecond temporal resolution that has so far not been accessible to experimental observation.

In the study of radiolytic processes in condensed liquids on femtosecond time-scales a serious challenge is the effect of the group velocity mismatch between the pulses of ionizing radiation and the probing light. A feasible solution is to use very thin renewable windowless targets based on liquid jets of 10 ?to 100 micrometers in diameter. On the other hand, determination of the delivered final radiation doses might be complicated in these liquid-jet systems, especially if these doses are small. Several suitable fluorescence dosimeters based on hydroxyl-radical scavenging aromatic carboxylic acids were developed in the past for use in aqueous solutions and are particularly useful for determination of doses down to 0.1 Gy. A system based on fast on-line detection of fluorescence from their fluorescent radiolytic products would be capable of measuring the dose delivered by each radiation pulse.

An important issue in the development of such a fluorescence-based dosimetry system for use in ultra-fast pulse radiolysis is to identify any potential dose rate effects resulting from the vastly increased dose rates (over 15 orders of magnitude) compared to standard radiation sources that have been used in the past to calibrate their response (e.g., cobalt-60 radionuclide sources or X-ray tubes). Experiments were performed

revealing observable differences in the effect of dose rate on fluorescence yields of fluorescent dosimeter systems based on aqueous solutions (buffered) of trimesic acid (pH = 2), coumarin-3-carboxylic acid (pH = 7) and terephthalic acid (pH = 10.5) at the picosecond pulse radiolysis facility ELYSE of the Laboratoire de Chimie Physique at Université Paris-Sud in France.

9511-16, Session 5

Electronic damage effects at high intensity free-electron laser radiation *(Invited Paper)*

Lorenzo Galli, Ctr. for Free-Electron Laser Science (Germany)

X-ray free-electron lasers (XFELs) provide extremely bright X-ray pulses of femtosecond duration, that promise to revolutionize structural biology, as they can be used to collect diffraction data from submicrometer-sized crystals while outrunning radiation damage. The high fluence of the XFEL pulses induces severe electronic radiation damage to the sample, and especially the heavy atoms are strongly ionized by the X-ray radiation. Electronic damage can hinder conventional anomalous phasing approaches, but the specific bleaching effect on the heavy atoms could be used as a new approach to phasing.

Experimental data showed an effective reduction of the scattering power of a heavy atom inside a chemically modified protein, and of the sulfurs in a native protein. From the analysis of these experimental data, quantitative methods have been developed to retrieve information about the effective ionization of the damaged atomic species. I compare experimental results to predictions from molecular dynamics and plasma physics codes, and discuss how to overcome or, on the other hand, to take advantage of electronic damage effects at hard x-ray energies.

9511-17, Session 6

Thermal and nonthermal melting of silicon exposed to femtosecond pulses of X-ray irradiation *(Invited Paper)*

Nikita A. Medvedev, Zheng Li, Ctr. for Free-Electron Laser Science (Germany); Beata Ziaja, Ctr. for Free-Electron Laser Science (Germany) and Institute of Nuclear Physics (Poland)

Silicon under irradiation with intense femtosecond laser pulses can undergo a phase transition via two different channels: thermal and nonthermal. First one occurs if electron-phonon coupling heats the lattice enough to trigger melting, while the second one results from the modification of the interatomic potential energy surface by excitation of electrons from the valence to the conduction band. We extended our model from [1,2] to include both channels on the same footing. Tight-binding molecular dynamics (TBMD) is used to model atomic dynamics, where the potential energy surface depends on the state of electronic system. Simultaneously, electronic state is traced with the Boltzmann equation for low-energy electrons (the valence and the bottom of the conduction band), and Monte Carlo model for photoabsorbtion, high-energy electrons, and deep shell holes [1,2].

Our results show that electron-phonon coupling triggers phase transition into a low-density liquid phase for deposited doses > 0.65 eV/atom. For deposited doses of over 0.9 eV/atom, silicon undergoes a phase transition into high-density liquid phase triggered via interplay of thermal heating and nonthermal change of the atomic potential.

These thresholds are much lower than those predicted with the Born-Oppenheimer approximation (2.1 eV/atom, corresponding to 9% of electron excitation from the valence to the conduction band), and indicate a significant contribution of thermal electron-phonon coupling to the relaxation of the laser-excited silicon.

[1] N. Medvedev, H.O. Jeschke, B. Ziaja, New Journal of Physics 15, 015016 (2014)

[2] N. Medvedev, H.O. Jeschke, B. Ziaja, Physical Review B 88, 224304

9511-18, Session 6

FEL excited plasmas

Beata Ziaja-Motyka, Ctr. for Free-Electron Laser Science (Germany) and Deutsches Elektronen-Synchrotron (Germany)

In my talk I will give an overview on the recent results of our theoretical investigation how the unique properties of X-ray free-electron laser (FEL) radiation can be employed to create and investigate dense plasmas. I will discuss two topics that are related to various irradiation regimes that can be achieved, depending on the FEL pulse fluence and its wavelength: (i) modeling of nanoplasmas created from finite systems, and (ii) atomic processes within laser-created plasmas and warm-dense-matter.

Conference 9512: Advances in X-ray Free-Electron Lasers Instrumentation

Monday - Thursday 13–16 April 2015

Part of Proceedings of SPIE Vol. 9512 Advances in X-ray Free-Electron Lasers Instrumentation III

9512-2, Session 1

Linear polarizing undulator and optical alignment system for a THz-FEL test facility

Bin Qin, Kaifeng Liu, Xu Liu, Xiang Lei, Yangbing Wang, Ping Tan, Yongqian Xiong, Huazhong Univ. of Science and Technology (China); Wei Wei, National Synchrotron Radiation Laboratory (China); Yuanji Pei, Univ. of Science and Technology of China (China)

A Free Electron Laser oscillator with radiation wavelength 50-100 um is under commissioning in Huazhong University of Science and Technology (HUST). Physical design of a linear polarizing undulator has been performed in HUST, with variable gap for K=1.0-1.25. The undulator was manufactured by Kyma s.r.l., by using a pure permanent magnet scheme. In December 2014, this undulator was installed in HUST and acceptance test showed main tolerances including rms phase error, field integrals corresponding variable gaps are well controlled. Design considerations related to physical and engineering issues and magnetic field performance are described. Integral field measurement system and optical alignment system are introduced as well.

9512-3, Session 1

Segmented undulator operation at the SPARC-FEL test facility

Franco Ciocci, ENEA (Italy); Maria Pia Anania, INFN (Italy); Marcello Artioli, ENEA (Italy); Marco Bellaveglia, INFN (Italy); Mariano Carpanese, ENEA (Italy); Enrica Chiadroni, INFN (Italy); Alessandro Cianchi, INFN.Roma Tor Vergata and Università di Roma Tor Vergata (Italy); Giuseppe Dattoli, ENEA (Italy); Domenico Di Giovenale, INFN (Italy); Emanuele Di Palma, ENEA (Italy); Giampiero Di Pirro, Massimo Ferrario, INFN (Italy); Andrea Mostacci, Università La Sapienza di Roma (Italy); Alberto Petralia, ENEA (Italy); Vittoria Petrillo, INFN-Milano and Università di Milano (Italy); Riccardo Pompili, INFN (Italy); Elio Sabia, Ivan Spassovsky, Vincenzo Surrenti, ENEA (Italy); Cristina Vaccarezza, Fabio Villa, INFN (Italy)

A short period undulator (1.4 cm) designed by the SPARC group and realized by KYMA Srl was installed on the undulator line at the SPARC-FEL test facility at the Frascati Labs. The undulator, operating in a delta like mode, has been used as radiator in a segmented configuration. The first stage being provided by the five undulators of the SPARC FEL source “old” chain, with period 2.8 cm.

The KYMA undulator has a quatrefoil structure, a high magnetic field homogeneity and focuses both in vertical and radial directions.

The two sections, namely the bunching and radiating parts, are arranged in such a way that the second is adjusted on a harmonic of the first. Laser action occurring in the second part, is due to the bunching acquired in the first.

Simulations of the temporal and spectral profiles in different electron beam operating conditions are reported, as well as the evolution of the longitudinal phase space. The agreement with the experimental results is discussed.

The importance of this experiment is at least threefold:

1) It proves that the segmented undulator can successfully be operated

2) It proves that the laser emission in the second undulator is entirely due to the bunching mechanism, being no second harmonic signal present in the first segment

3) Encourages various improvements of the configuration itself, as e. g. the use of a further undulator with variable magnetic field configuration in order to obtain a laser field with adjustable polarization.

This paper is presented on behalf the SPARC-FEL group.

9512-4, Session 1

Cryogenic undulator *(Invited Paper)*

Marie-Emmanuelle Couprie, Fabien Briquez, Geetanjali Sharma, Chamssedine Benabderrahmane, Fabrice Marteau, Olivier Marcouillé, Philippe Berteaud, Tarik El Ajjouri, José Vétéran, Lilian Chapuis, Mathieu Valléau, Synchrotron SOLEIL (France)

No Abstract Available

9512-5, Session 1

Construction of CHESS Compact Undulator magnets at Kyma

Alexander B. Temnykh, Aaron Lyndaker, Cornell Univ. (United States); Mirko Kokole, T. Milharcic, J. Pockar, Kyma Tehnologija d.o.o. (Slovenia); Raffaella Geometrante, Kyma s.r.l. (Italy)

In 2014 KYMA S.r.l.has built two CHESS Compact Undulator (CCU) magnets that are at present installed and successfully operate at the Cornell Electron Storage Ring. This type of undulators was developed at CHESS for x-ray beam-lines upgrade, but it can be used at other facilities as well. CCU magnets are compact, in-vacuum compatible and cost efficient. The two manufactured CCUs are linearly polarized undulators with 28.4 mm period and 6.5 mm gap, made with NdFeB permanent magnets. They are adjustable phase devices with a fixed gap. Variation of magnetic field is achieved by phasing (shifting) top and bottom magnetic array.

Transitioning from the laboratory to industrial environment for a novel design required additional evaluation, design adjustment and extensive testing. Particular attention was given to the soldering technique used for fastening of the magnetic blocks to holders. This technique had thus far never been used before for undulator magnet construction by industry. The evaluation included tests of different types of soldering paste, measurements of strength of solder and determining the deformations of the soldered magnet and holder under simulated loading forces.

This paper focuses on critical features of the CCU design, results of the soldering technique testing and the data regarding permanent magnets magnetization change due to soldering. In addition it deals with optimization-assisted assembly and the performance of the assembled devices and assesses some of the results of the CCU magnets operation at CESR are presented as well.

9512-6, Session 1

Status of the PAL-XFEL undulator program *(Invited Paper)*

Dong-Eon Kim, Ki-Hyeon Park, Heung-Sik Kang, In-Soo Ko, Moo Hyun Cho, Pohang Univ. of Science and

Technology (Korea, Republic of) and Pohang Accelerator Lab. (Korea, Republic of); Joachim Pflueger, European XFEL GmbH (Germany)

Pohang Accelerator Laboratory (PAL) is developing a 0.1 nm SASE based FEL based on 10 GeV S-band linear accelerator named PAL-XFEL. At the first stage, PAL-XFEL needs two undulator lines for photon source. The hard X-ray undulator line requires 18 units of 5 m long hybrid-type conventional planar undulator and soft X-ray line requires 6 units of 5 m long hybrid type planar undulator with additional few EPUs for final polarization control. PAL is developing undulator magnetic structure based on EU-XFEL concepts. The key parameters are min pole gap of 8.3 mm, with period length 26 mm (HXU), 35 mm (SXU), and 5.0 m magnetic length. . In this report, the prototyping, and the development of pole tuning procedure to optimize the optical phase error will be reported. Also the impact of the background field error will be analyzed. In PAL-XFEL undulator magnetiic, structure the vertical background field is amplified by 2.5 times and 0.2 G background field error results in 4 degree phase error. Also the impact of the girder bending on the optical phase error is discussed. For HXU, 7 um bending (sagging) of the girder is expected which gives additional 2.0 degree phase error for operating gap range. For SXU the deformation reaches up to 10 um and the resulting phase error produces additional 3 degrees phase jitter. In this report, the detailed ideal calculation and measurement results will be presented.

9512-7, Session 1

Advances in undulator design for free electron lasers *(Invited Paper)*

Soren Prestemon, Lawrence Berkeley National Laboratory (United States)

First X-ray FEL facilities are now operational, providing exceptionally bright and short X-ray pulses for the science community. In addition, a number of FEL facilities are currently in construction. As the community gains experience in the design, construction, and operation of such facilities, advances in design and technology can be applied to yield more tailored beams for applications, including for example high-repetition pulses or pulse trains, multiple FEL lines operating in parallel, two-color experiments, or ultra-short (sub-femto-second) pulses.

Primary elements of an FEL are the electron source, the linac, and the undulators. Here we review the state of the art in undulator design, highlight advances in undulator technology, and discuss their potential impact for future facilities serving science or industrial applications. In particular we distinguish between technologies focused on providing linear or variable polarizing radiation, soft or hard X-rays, or high-power beams.

9512-71, Session 1

Recovering lost ancient literature: X-ray phase contrast tomography reveals the secrets of Herculaneum papyri *(Invited Paper)*

Vito Mocella, Istituto per la Microelettronica e Microsistemi (Italy)

We present the first experimental demonstration of a non-destructive technique that reveal the text of a carbonized and thus extremely fragile Herculaneum papyrus. Buried by the famous eruption of Vesuvius in 79 AD, the Herculaneum papyri represent a unique treasure for humanity. Overcoming the difficulties of the other techniques we prove that x-ray phase contrast tomography technique can detect the text within scrolls, thanks to the coherence and high energy properties of a synchrotron source. This new imaging technique represents a turning point for the study of literature and ancient philosophy, disclosing texts that were believed to be completely lost.

9512-8, Session 2

Characterization of partially coherent ultrashort XUV pulses

Charles Bourassin-Bouchet, Marie-Emmanuelle Couprie, Synchrotron SOLEIL (France)

Modern ultrafast metrology relies on the postulate that the pulse to be measured is fully coherent, i.e. that it can be completely described by its spectrum and spectral phase. However, synthesizing fully coherent pulses is not always possible in practice, especially in the domain of emerging ultrashort X-ray sources where temporal metrology is strongly needed. As an example, the lack of longitudinal coherence, that is shot-to-shot fluctuations, of Free-Electron Lasers (FEL) has prevented so far their full amplitude and phase temporal characterization. To sort out this issue, we have adapted Frequency-Resolved Optical Gating (FROG), the first and one of the most widespread techniques for pulse characterization, to enable the measurement of partially coherent XUV pulses even down to the attosecond timescale. To do so, we take our inspiration from other branches of physics where partial coherence is routinely dealt with, such as quantum optics and coherent diffractive imaging (CDI). The experimental protocole, borrowed from attosecond metrology, implies the measurement of photoelectron spectra obtained through XUV-laser photoionization. The partially coherent XUV pulse is then recovered by processing the spectra with an algorithm adapted from those used in CDI. Finally, the mathematical formalism used in quantum optics is utilized to perform an in-depth analysis of the retrieved pulse mixture. When applied to FELs relying on self-amplified spontaneous emission, the technique gives access to the full statistics of the emitted pulses. With seeded-FELs, the pulse shape becomes stable from shot-to-shot, but an XUV-laser time jitter remains. In that case, the technique enables the joint measurement of the FEL pulse shape (in amplitude and phase) and of the laser/FEL jitter envelope.

9512-9, Session 2

Design and characterization of the ePix10k: a high dynamic range integrating pixel ASIC for LCLS detectors

Pietro Caragiulo, Angelo Dragone, Bojan Markovic, Ryan Herbst, Kurtis Nishimura, Benjamin A. Reese, Sven C. Herrmann, Philip A. Hart, Gabriel Blaj, Julie Segal, Astrid Tomada, Jasmine Hasi, Gabriella A. Carini, Christopher J. Kenney, Gunther Haller, SLAC National Accelerator Lab. (United States)

ePix10k is a 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. The ASIC is optimized for high dynamic range application requiring high spatial resolution and fast frame rates. ePix ASICs are based on a common platform composed of a random access analog matrix of pixel with global shutter, fast parallel column readout, and dedicated sigma-delta analog to digital converters per column. The ePix10k variant has 100umx100um pixels arranged in a 176x192 matrix, a resolution of 140e- r.m.s. and a signal range of 3.5pC (10k photons at 8keV). In its final version it will be able to sustain a frame rate of 2kHz. A first prototype has been fabricated and characterized. Performance in terms of noise, linearity, uniformity and cross-talk will be discussed at the meeting.

9512-10, Session 2

Measure of the transverse coherence of a self amplified spontaneous emission of a free electron laser with the heterodyne speckles method

Marco Alberto Carlo Potenza, Univ. degli Studi di Milano (Italy)

We present the measure of the transverse coherence of the radiation from a free electron laser obtained with the recently introduced heterodyne speckle method. The technique needs a very essential setup, composed only by a water suspension of commercial colloidal particles and a CCD camera. The modulus of the complex coherence factor is retrieved from the Fourier analysis of the interference pattern generated by the stochastic superposition of the almost spherical waves scattered by the particles and the transmitted beam (heterodyne speckles). We present the results obtained at SPARC (LNF, Frascati - Italy) with the FEL source in SASE regime in the optical region (400nm). The coherence length turns out to be comparable with the beam size, slight variations of the coherence properties being only observed after the 5th undulator section. We show that this approach offers a number of advantages. It does not require any engineered, ad-hoc device and it is easily transposable to a wide range of wavelengths. Moreover, it provides a two-dimensional map of the transverse coherence without any a-priori assumption about its functional form and with no use of reconstruction algorithms. Finally, it is capable of one-shot coherence characterization and it is thus suitable for time-resolved measures and live diagnostics on photon beams.

9512-11, Session 2

Comparing various techniques for characterization of focused FEL beams: wavefront sensors, knife-edge scanning, scintillators, ptychography, and desorption/ablation imprints

Jaromír Chalupsky, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

An unflagging development of novel X-ray laser sources (eg., free-electron lasers, seeded FELs, plasma based lasers, etc.) has stimulated a continuous growth in the X-ray scientific community and in new types of scientific endeavours. The new generation of X-ray free-electron lasers has opened unique avenues for exploring matter under exotic and extreme conditions, previously unattainable with standard lasing schemes. Developments in X-ray lasing are naturally followed by new beam characterization techniques representing an integral part of any interaction experiment. Extensive spatial characterization of focused laser beams is indispensable, nevertheless difficult to be conducted directly due to very small focal spot sizes (typically ~ 1 ?m and less) and excessive radiation intensities. This places very high requirements on transverse spatial resolution, radiation resistance, and linear response of possible diagnostic tools.

Methods exist allowing remote focus characterization performed in an indirect or semi-direct manner. Numerical back-propagation approaches are very often used to reconstruct the electrical field distribution at the focus from the data obtained out of the high intensity region. Direct methods can be used to characterize intensity distributions at the focal point and its surroundings without a necessity of numerical approaches. In this paper, an overview of current techniques, enabling a rigorous focused X-ray laser beam characterization, will be given. Furthermore, recent progress in methods of ablation and desorption imprints and their potential applications in full spatial beam characterization will be discussed.

9512-12, Session 3

The new design of the THz streak camera at PSI *(Invited Paper)*

Ishkhan Gorgisyan, Paul Scherrer Institut (Switzerland) and Ecole Polytechnique Fédérale de Lausanne (Switzerland); Pavle Juranic, Rasmus Ischebeck, Andrey Stepanov, Volker Schlott, Claude Pradervand, Luc Patthey, Milan Radovic, Rafael Abela, Paul Scherrer Institut (Switzerland); Christoph P. Hauri, Paul Scherrer Institut (Switzerland) and Ecole Polytechnique Fédérale de Lausanne (Switzerland); Balazs Monoszlai, Paul Scherrer Institut (Switzerland) and Univ. of Pécs (Hungary); Rosen Ivanov, Peter Peier, Deutsches Elektronen-Synchrotron (Germany); Jia Liu, European XFEL GmbH (Germany); Tadashi Togashi, Japan Synchrotron Radiation Research Institute (Japan); Shigeki Owada, RIKEN (Japan); Kanade Ogawa, RIKEN (Japan); T. Katayama, Makina Yabashi, RIKEN (Japan); Leonid Rivkin, Paul Scherrer Institut (Switzerland) and Ecole Polytechnique Fédérale de Lausanne (Switzerland)

A new terahertz streak camera is being developed for SwissFEL, the upcoming free electron laser at PSI, which aims at providing users with X-ray pulses with length down to 2 femtoseconds. By using clustered xenon pulses in the chamber high resolution measurements with hard X-Ray photons can be performed.

I will present here the first measurements obtained with a prototype setup, the pulse arrival time and length monitor (PALM). The experiments were carried out at SACLA with photon energies up to 10 keV.

These results point the way towards improvements, which will be incorporated in the new design. We will utilize a twin interaction region to measure streaked and un-streaked photoelectron spectra. This will allow us to compensate for the shot-to-shot jitter of the spectral width, improving the resolution of the photon pulse length measurement. The effect of the Gouy phase shift on the resolution will be discussed. The ways of increasing the dynamic range of the detector for measuring the pulses with large arrival time jitter will be proposed.

9512-13, Session 3

6D electron beam diagnostics at SPARC_LAB *(Invited Paper)*

Alessandro Cianchi, Univ. degli Studi di Roma “Tor Vergata” (Italy) and Istituto Nazionale di Fisica Nucleare (Italy); Maria Pia Anania, Istituto Nazionale di Fisica Nucleare (Italy); Alberto Bacci, Istituto Nazionale di Fisica Nucleare - Sezione di Milano (Italy); Marco Bellaveglia, Michele Castellano, Enrica Chiadroni, Domenico Di Giovenale, Giampiero Di Pirro, Massimo Ferrario, Istituto Nazionale di Fisica Nucleare (Italy); Luca Innocenti, Univ. degli Studi di Roma “Tor Vergata” (Italy); Andrea Mostacci, Univ. degli Studi di Roma La Sapienza (Italy); Riccardo Pompili, Istituto Nazionale di Fisica Nucleare (Italy); Andrea Renato Rossi, Istituto Nazionale di Fisica Nucleare - Sezione di Milano (Italy); Vladimir Shpakov, INFN- LNF (Italy); Cristina Vaccarezza, Fabio Villa, Istituto Nazionale di Fisica Nucleare (Italy)

To create very short electron bunches or comb-like beams, able to drive a SASE-FEL or to produce THz radiation, is needed advanced phase space manipulation. The characterization of the 6D phase space is of paramount importance in order to verify that the beam parameters fulfill the expectation. At SPARC_LAB we have integrated several longitudinal and transverse beam diagnostics for single bunch or for a train of comb-like bunches at THz repetition rate. Longitudinal diagnostic is based on RF deflecting cavity, on Electro Optical Sampling, and in the analysis of Coherent Diffraction and Transition radiation. Quadrupole scan technique is used to measure the transverse emittance in single bunch mode or in conjunction respectively with a dipole, to separate beams of different energy, and RF deflector, to discriminates bunches with different time of arrival.

In this talk we report about our setup and measurements.

9512-14, Session 3

Diagnostic for a high-repetition rate electron photo-gun and first measurements *(Invited Paper)*

Daniele Filippetto, Fernando Sannibale, Lawrence R. Doolittle, Gang Huang, Houjun Qian, Lawrence Berkeley National Lab. (United States)

The APEX electron source at LBNL combines the high-repetition-rate with the high beam brightness typical of photo-guns, delivering low emittance electron pulses at MHz frequency. Proving the high beam quality of the beam is an essential step for the success of the experiment, opening the doors of the high average power to brightness-hungry applications as X-Ray FELs, MHz ultrafast electron diffraction etc. . As first step, a complete characterization of the beam parameters is foreseen at the Gun beam energy of 750 keV. Diagnostics for low and high current measurements have been installed and tested, and measurements of cathode lifetime and thermal emittance in a RF environment with mA current performed. The recent installation of a double slit system, a deflecting cavity and a high precision spectrometer, allow the exploration of the full 6D phase space.

Here we discuss the present layout of the machine and future upgrades, showing the latest results at low and high repetition rate, together with the tools and techniques used.

9512-16, Session 3

Longitudinal diagnostics results and future challenges for FERMI

Eugenio Ferrari, Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and Univ. degli Studi di Trieste (Italy); Marco Veronese, Enrico M. Allaria, Paolo Sigalotti, Paolo Cinquegrana, Luca Giannessi, Giuseppe Penco, Fabio Rossi, Mauro Predonzani, Mario Ferianis, Elettra-Sincrotrone Trieste S.C.p.A. (Italy)

The seeded FEL FERMI has completed the commissioning of both the FEL lines, and it is now providing the User Community with a coherent and tunable UV radiation (from 100 nm to 4 nm) in a number of different configurations. These also include original FEL-pump – FEL-probe schemes with twin-seeded FEL pulses. Among the key systems for the operation of FERMI, there is the femtosecond optical timing system and dedicated longitudinal diagnostics, specifically developed for FERMI. In this paper, after a short review of the FERMI optical timing system and of its routinely achieved performances, we focus on the results obtained from the suite of longitudinal diagnostics (Bunch Arrival Monitor, Electro Optical sampling station and RF deflectors) all operating in single shot and with 10s fs resolution which demonstrate the FERMI achieved performances. The results from these longitudinal diagnostics are compared between each other on shot-to-shot basis, in order to find correlations.

9512-18, Session 4

Temporal property of XFEL for X-ray nonlinear optics

Kenji Tamasaku, RIKEN (Japan)

The success of XFEL at LCLS and SACLA opens up a new frontier of nonlinear optics, namely, X-ray nonlinear optics. A part of basic nonlinear processes, such as sum-frequency generation, second harmonic generation, two-photon absorption, and saturable absorption, is reported so far. To promote applications of these nonlinear and to explore more complex nonlinear processes, it is important to understand and control the temporal property of XFEL radiation. For example, the pulse duration determines the peak intensity, affecting the efficiency of nonlinear process. The spiky temporal structure of SASE may enhance multi-photon process. Thus, understanding and measurement of the pulse duration and the statistical property are indispensable to analysis of experimental data of nonlinear phenomena.

Recently, it becomes possible to use two-color XFEL recently, which will enable more sophisticated nonlinear process. In such experiment, one may use strong pump and weak probe beams, and to control the relative delay. It is also important to measure the pulse energies of the pump and the probe pulses shot by shot. We will discuss what kind of temporal property of XFEL we need to understand and control based on our recent X-ray nonlinear optics experiments.

9512-19, Session 4

Optically induced Fe magnetization reversal in Fe/MnAs/GaAs(001)

Carlo Spezzani, Laboratoire de Physique des Solides (France)

The possibility to achieve the optical control of the local mangetization of given supporting media is of large interest to several communities because of its potential for applications in the development of future sensor and data storage technologies. The manipulation of the magnetic order can be driven or assisted by means of optical illumination with ultrashort laser pulses, the underlying mechanism being strongly depends on the material properties.

I will present and discuss the results of a time-resolved resonant scattering study exploring the magnetic and structural properties of the Fe/MnAs/GaAs(001) system.

We used a 100 fs optical laser pulse to trigger local temperature variations across the magneto-structural phase transition that takes place in the MnAs thin film in the 10 - 40 C range, and 100 fs soft x-ray free-electron laser pulses from the FERMI@Elettra FEL_1 light source to probe the induced magnetic and structural dynamics. The experiment provides direct evidence that a single optical laser pulse can reverse the Fe overlayer magnetization locally. The interpretation of the experimental data is supported by model calculations and it reveals that the magnetization reversal dynamics can be driven only by the self-organized coexistence of the two phases in the MnAs template that, in the present case, is occurring only during the slow regain of the system of its thermal equilibrium.

9512-20, Session 4

Current status of SACLA and applications to high energy density science

Yuichi Inubushi, Kensuke Tono, Tadashi Togashi, Tetsuo Katayama, Japan Synchrotron Radiation Research Institute (Japan); Shigeki Owada, Makina Yabashi, RIKEN (Japan)

Since the user operation started in 2012, X-ray Free Electron Laser (XFEL), SACLA [1] has produced a number of interesting results in scientific fields raging in ultrafast material science, chemistry, biology, x-ray nonlinear optics and high energy density science. In this presentation, we will report status and perspectives of SACLA, and overview of experimental results.

Characterization of every XFEL pulse is important issue for XFEL experiments. In order to achieve non-destructive diagnostics on single-shot spectra and arrival timing jitters during user experiments, we developed and installed a new system using a transmission grating as a XFEL beam splitter.

In order to accommodate user's requirements of increased beam times, we have developed new hard x-ray beamline, BL2, which is designed for routine experiments in biology, such as a crystallography and a coherent diffraction imaging. We achieved fist lasing of BL2 in Oct. 2014, and we are proceeding fine tuning for the user operation.

We will also introduce noteworthy results produced in SACLA, for example, x-ray nonlinear optics [2]. Furthermore, we will report recent results related with x-ray amplification.

[1] T. Ishikawa, et al., Nature Photonics 6, 540 (2012).

[2] K. Tamasaku, et al., Nature Photonics 8, 313 (2014).

9512-21, Session 4

The hard X-ray instrument for matter in extreme conditions studies at LCLS

Hae Ja Lee, SLAC National Accelerator Lab. (United States)

The ability to directly examine dynamics of structural deformation and phase transition in materials under extreme conditions has been a long-standing scientific challenge. The area of matter in extreme conditions refers to states under high pressure up to hundreds of GPa and under high temperature up to hundreds of thousands of Kelvin, and a region between solids and plasmas. The matter in this region has been studied through dynamic shock compression and warm dense matter research and there has been significant progress made over many decades. However, experiments are still needed that can access directly to identify atomic structure in new high pressure phases and obtain information on thermodynamic properties during both the loading process and during transformations.

The Matter in Extreme Conditions (MEC) instrument is designed to overcome the unique experimental challenges that the study of matter in extreme conditions bring. It combines a suite of diagnostics and high power and high energy optical lasers, which are standard fare in this research field, with the unmatched LCLS X-ray beam, to create an instrument that will be at the forefront of, and have a major impact on MEC science, in particular in the field of high pressure, warm dense matter, high energy density, and ultra-high intensity laser-matter interaction studies. The LCLS beam allows for unique investigation in all these extreme states using diagnostic methods such as X-ray Thomson Scattering, X-ray emission spectroscopy, X-ray diffraction, X-ray absorption spectroscopy, X-ray phase-contrast imaging, and pumping specific absorption lines to study (dense) plasma kinetics. Augmented with optical diagnostics, such as Velocity Interferometry for Any Reflector (VISAR) and Fourier Domain Interferometry (FDI), the instrument provides information of surface velocity, shock conditions and pressure that is reached. The MEC instrument equips two relatively high power and high energy optical laser systems to produce extreme conditions. The long pulse beam at 527 nm from the frequency-doubled Nd-YAG MEC laser system is operated in a power-limited mode (~1.5 GW) within a flat-top or temporally-shaped 2-200 ns pulse to produce high pressure phases through shock compression. The short pulse beam at 800nm from Ti:Sapphire laser system delivers 1.5 J with a repetition rate of 5 Hz. The beam is compressed in vacuum to 50 fs and sent to a target chamber with about 1 J on target. Here, we will present the details of the MEC instrument and related experiments.

9512-22, Session 4

Covariance mapping of multiply-ionized atoms and molecules exposed to strong X-radiation fields

Raimund A. Feifel, M. Mucke, V. Zhaunerchyk, Uppsala Univ. (Sweden); Leszek J. Frasinski, Imperial College (United Kingdom); Richard Squibb, Uppsala Univ. (Sweden); Mirko Siano, Imperial College (United Kingdom); John H. D. Eland, Univ. of Oxford (United Kingdom); M. Kaminska, The Institute of Physics (Poland); J. Salen, P. van der Meulen, P. Linusson, R. D. Thomas, Mats Larsson, Stockholm Univ. (Sweden); Timur Osipov, Li Fang, Brendan Murphy, Nora Berrah, Western Michigan Univ. (United States); Lutz Foucar, Max-Planck-Arbeitsgruppen für strukturelle Molekularbiologie (Germany); J. Ullrich, Max-Planck-Institut für Kernphysik (Germany); Kosaku Motomura, S. Mondal, Kiyoshi Ueda, Tohoku Univ. (Japan); James M. Glownia, James P. Cryan, Ryan N. Coffee, Christoph Bostedt, John Bozek, Sebastian Schorb, Marc Messerschmidt, Brian K. McFarland, Markus Koch, Jakob Grilj, Emily Sistrunk, M. Gühr, SLAC National Accelerator Lab. (United States); Hiromitsu Takahashi, S. Wada, Hiroshima Univ. (Japan); M. N. Piancastelli, Uppsala Univ. (Sweden); Robert Richter, Kevin C. Prince, Elettra-Sincrotrone Trieste S.C.p.A. (Italy)

When exposed to ultra-intense X-radiation, as available at the Linac Coherent Light Source (LCLS) Free Electron Laser (FEL) at Stanford, CA, USA [1], the innermost electronic shells are easily emptied creating transient hollow atoms [2] or molecules (see, e.g., Refs. [3] and refs. therein). Depending on the pulse duration of the FEL, other exotic multiply-ionized electronic states [4] can be observed as well (see, e.g., Refs. [2,3]). Investigating the ionization dynamics of atoms and molecules under such conditions is of fundamental interest and is expected to have an impact on achieving atomic resolution in flash diffraction imaging of non-crystallized complex biological samples. To probe the electronic structure and dynamics of atoms and molecules exposed to ultrafast X-ray pulses in an efficient way, we demonstrate the capacity of a new technique based on a magnetic bottle (see, e.g., Ref. [5] and refs. therein) in combination with a statistical analysis method called "covariance mapping" [6], which we developed further by also taking the intensity fluctuations of the FEL into account. A complete picture of ionization processes competing in hollow atom formation and decay is visualised with unprecedented ease and the maps reveal new sequences of photoionization and Auger events as exemplified by our proof-of-principle investigation on multiply ionized Ne atoms [7]. The technique is particularly well suited to the high counting rate inherent in FEL experiments.

References:

[1] P. Emma et al., Nature Photonics 4, 641 (2010).

[2] L. Young et al., Nature 466, 56 (2010).

[3] N. Berrah et al., PNAS 108, 16912 (2011) and P. Salén et al., Phys. Rev. Lett. 108, 153003 (2012).

[4] N. Rohringer and R. Santra, Phys. Rev. A 76, 033416 (2007).

[5] J.H.D. Eland et al., Phys. Rev. Lett. 90, 053003 (2003).

[6] L.J. Frasinski et al., Science 246, 1029 (1989).

[7] L.J. Frasinksi et al., Phys. Rev. Lett. 111, 073002 (2013).

Acknowledgements:

This work has been financially supported by the Swedish Research Council, the Göran Gustafsson Foundation (UU/KTH), and the Knut and Alice Wallenberg Foundation, Sweden. MK thanks the Swedish Institute for financial support. LJF and RJS thank the EPSRC, UK (Grants No. EP/F021232/1, EP/F034601/1 and EP/I032517/1). KCP and RR acknowledge the MIUR, Italy (Grants No. FIRB-RBAP045JF2 and No. FIRB-RBAP06AWK3). KU and KM are grateful to MEXT for funding the X-FEL Utilization Research Project and the X-FEL Priority Strategy Program. SM is grateful to JSPS for financial support. NB, TO, LF, and BFM acknowledge financial support by the U.S. Department of Energy of Science, Basic Energy Science, Chemical, Geosciences, and Biological Divisions. MNP wishes to thank the French ANR (Agence Nationale de la Recherche) for partial support during her stay at the LCLS. Portions of this research were carried out at the LCLS at the SLAC National Accelerator Laboratory. LCLS is an Office of Science User Facility operated for the U.S. Department of Energy Office of Science by Stanford University.

9512-23, Session 5

Instrumentation challenges for the European XFEL *(Invited Paper)*

Thomas Tschentscher, European XFEL GmbH (Germany)

The European X-Ray Free-Electron Laser (European XFEL) is currently under construction in the Hamburg metropole area, Germany. First electrons have been generated in the laser-driven injector and commissioning of the accelerator with beam will commence in summer

2015. First FEL beam is planned for early 2017 and early user experiments can be performed during 2017. The current installation of the x-ray systems includes the very long FEL undulators, the very long x-ray beam transports including x-ray diagnostics, and the science instruments with its several sub-systems. Many of these components have very challenging performance requirements leading to tight requirements for the design and installation. Amongst these temperature stability and vibration tolerances are tightest. Another aspect is the European XFEL specific requirement to match the high repetition rate of up to 4.5 MHz inside the pulse trains produced at a rate of 10 Hz. For x-ray optics, diagnostics and detectors, but also for the optical pump lasers and the sample delivery systems, the extreme requirement imposed by the high repetition rate has led to special conceptual and mechanical solutions. In the presentation a selection of these solutions and their status of implementation will be presented.

9512-24, Session 5

FLASH: the first soft x-ray FEL operating two undulator beamlines simultaneously *(Invited Paper)*

Katja Honkavaara, Deutsches Elektronen-Synchrotron (Germany)

Since 2005, FLASH, the free-electron laser user facility at DESY (Hamburg, Germany), delivers high brilliance XUV and soft X-ray FEL radiation for photon experiments. It is recently being upgraded with a second undulator beamline, FLASH2. The two beamlines are operated simultaneously sharing the same RF-pulse. FLASH2 commissioning takes place parallel to FLASH1 user operation. The first lasing of FLASH2 was achieved in August 2014. We report our first experience operating two FEL beamlines simultaneously.

9512-25, Session 5

Present status of SACLA *(Invited Paper)*

Tetsuya Ishikawa, RIKEN (Japan)

SACLA is the world second X-ray free-electron laser in operation, and the first Compact X-ray free-electron laser. It has been operating for users for three years, and providing the users with X-rays from 4 keV to 15 keV. Recently, 2nd FEL line was completed and opened for users. In this talk, the present status of SACLA and future plans will be given.

9512-26, Session 5

Status of PAL-XFEL *(Invited Paper)*

In Soo Ko, Pohang Univ. of Science and Technology (Korea, Republic of)

No Abstract Available

9512-27, Session 5

Status of Shanghai FEL *(Invited Paper)*

Dong Wang, Shanghai Institute of Applied Physics (China)

No Abstract Available

9512-28, Session 6

Status of SwissFEL, the X-ray free electron laser at PSI *(Invited Paper)*

Marco Pedrozzi, Paul Scherrer Institut (Switzerland)

The Paul Scherrer Institute (PSI) is the largest research center for natural and engineering sciences within Switzerland. The institute builds and operates large accelerator based research facilities such the Swiss synchrotron Ligth Source (SLS), the neutron spallation source (SINQ), the muon source and the center for proton therapy.

The X-ray free-electron laser SwissFEL is the next major research facility presently under construction at PSI. The baseline design consists of a 5.8 GeV normal conducting linear accelerator and two FEL lines covering the wavelength range from 0.1-0.7 nm and 0.7-7 nm, respectively. SwissFEL features a linear accelerator in C-band technology, a novel design of variable gap in-vacuum undulators for the hard X-ray FEL and Apple II undulators with full polarization control for the soft X-ray FEL. The two FELs are operated independently and simultaneously with 100 Hz pulse rate each. The construction activities started in spring 2013 with the groundbreaking, while the beginning of the machine installation is foreseen two years later in spring 2015. We foresee a staged assembly and commissioning with a first phase aiming for a commissioning of the hard X-ray FEL by the end of 2016. The soft X-ray FEL is planned in a second phase starting 2018. In this presentation we will give an overview of the status of the project and of the related R&D activities.

9512-29, Session 6

Operation of FERMI FELs for users

Michele Svandrlik, Elettra-Sincrotrone Trieste S.C.p.A. (Italy)

The FERMI seeded free electron laser facility, located at the Elettra laboratory in Trieste (Italy), has been operated for user experiments in the past years using the first FEL line, FEL-1, covering the VUV – EVU spectral range (100 – 20 nm). After the conclusion of the commissioning for the soft-X ray FEL line, FEL-2, the facility is now ready to provide the scientific community with intense FEL pulses (>10 uJ) characterized by a high degree of coherence and spectral stability in the whole range from 100 nm down to 4 nm.

We report about the recent achievement of FERMI FELs and our experience with operations for user requiring specific FEL configurations.

9512-30, Session 6

Seeded FEL with two energy level electron beam distribution at SPARC_LAB

Fabio Villa, David Alesini, Maria Pia Anania, Marco Bellaveglia, Michele Castellano, Enrica Chiadroni, Domenico Di Giovenale, Giampiero Di Pirro, Massimo Ferrario, Alessandro Gallo, Giancarlo Gatti, Riccardo Pompili, Stefano Romeo, Vladimir Shpakov, Cristina Vaccarezza, Istituto Nazionale di Fisica Nucleare (Italy); Mariano Carpanese, Franco Ciocci, Giuseppe Dattoli, Emanuele Di Palma, Luca Giannessi, Alberto Petralia, Elio Sabia, Ivan P. Spassovsky, Marcello Artioli, ENEA (Italy); Alessandro Cianchi, Francesco Filippi, Anna Giribono, Istituto Nazionale di Fisica Nucleare (Italy); Julietta V. Rau, Istituto di Struttura della Materia (Italy); Alberto Bacci, Andrea Renato Rossi, Istituto Nazionale di Fisica Nucleare (Italy); Najmeh Sada Mirian, Istituto Nazionale di Fisica Nucleare (Italy) and Univ. degli Studi di Milano (Italy); Vittoria Petrillo, Univ. degli Studi di Milano (Italy) and Istituto Nazionale di Fisica Nucleare (Italy); Andrea Mostacci, Univ. degli Studi di Roma La Sapienza (Italy); Luca Innocenti, Univ. degli Studi di Roma "Tor Vergata" (Italy)

The generation of free-electron laser (FEL) radiation with two or more simultaneous colors opens new scenarios in applications and in the study of the underlying physics [1].

At SPARC_LAB [2] we studied [3] and characterized [4,5] the operation with two bunches at different energies, allowing two color FEL emission. The effect of the electron beam has been explored by controlling the transport with an ad hoc developed control system, allowing the beam transport in different configurations. We measured the effect frequency and intensity stabilization of seeding on both frequencies compared to Self-Amplified Spontaneous Emission (SASE) of FEL radiation

[1] C. M. Guenther et al., Nat. Photonics 2011, 5, 99.

[2] M. Ferrario et al., Nucl. Instr. Meth. Phys. Res. B 2013, 309, 183

[3] F. Ciocci et al., Phys. Rev. Lett. 2013, 111, 264801

[4] V. Petrillo et al., Phys. Rev. Lett. 2013, 111, 114802.

[5] C. Ronsivalle et al., New J. Phys. 16, 033018, 2014.

9512-31, Session 7

A single-shot, high-repetition rate scheme for electro-optic detection of short pulses *(Invited Paper)*

Eléonore Roussel, Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and Univ. des Sciences et Technologies de Lille (France) and Ctr. d'Etudes et de Recherches Lasers et Applications (France); Clément Evain, Univ. des Sciences et Technologies de Lille (France) and Ctr. d'Etudes et de Recherches Lasers et Applications (France); Marc Le Parquier, Ctr. d'Etudes et de Recherches Lasers et Applications (France); Christophe Szwaj, Univ. des Sciences et Technologies de Lille (France) and Ctr. d'Etudes et de Recherches Lasers et Applications (France); Laurent Manceron, Jean-Blaise Brubach, Marie-Agnès Tordeux, Jean-Paul Ricaud, Lodovico Cassinari, Marie Labat, Marie-Emmanuelle Couprie, Pascale Roy, Synchrotron SOLEIL (France); Serge Bielawski, Univ. des Sciences et Technologies de Lille (France) and Ctr. d'Etudes et de Recherches Lasers et Applications (France)

The electro-optic detection technique offers the possibility to measure directly, in a non-destructive manner, the shape and the length of individual relativistic electron bunches with a sub-picosecond resolution. In the future upgrade towards high-repetition rate FELs, single-shot recordings at high-acquisition rate in the MHz range will be required and the present classical single-shot techniques, as the spectral encoding, are limited by the camera speed. Using a novel opto-electronic strategy, based on the photonic time-stretch, we demonstrate high-repetition rate (up to 88 MHz) single shot recordings of THz pulses emitted at SOLEIL with a resolution in the ps range. However the time-stretch technique is not specific to THz pulses and can be potentially adapted to other wavelengths and situations, provided it is possible to imprint the ultrafast signal on chirped laser pulses.

9512-32, Session 7

The SPARC_LAB femtosecond synchronization for electron and photon pulsed beams *(Invited Paper)*

Marco Bellaveglia, Alessandro Gallo, Istituto Nazionale di Fisica Nucleare (Italy); Luca Piersanti, Istituto Nazionale di Fisica Nucleare (Italy) and Univ. degli Studi di Roma La Sapienza (Italy); Riccardo Pompili, Giancarlo Gatti, Maria Pia Anania, Massimo Petrarca, Fabio Villa, Enrica Chiadroni, Istituto Nazionale di Fisica Nucleare (Italy); Angelo Bagioni, INFN - LNF (Italy); Andrea Mostacci, INFN - ROMA1 (Italy)

The SPARC_LAB complex hosts a 150MeV electron photo-injector equipped with an undulator for FEL production (SPARC) together with a high power TW laser (FLAME). Recently the synchronization system reached the performance of <100fs RMS relative jitter between lasers, electron beam and RF accelerating fields. This match the requirements for next future experiments: (i) the production of x-rays by means of Thomson scattering (first collisions achieved in 2014) and (ii) the particle driven PWFA experiment by means of multiple electron bunches. We report about the measurements taken during the machine operation using BAMs (Bunch Arrival Monitors) and EOS (Electro-Optical Sampling) system. A new R&D activity concerning the LWFA using the external injection of electron bunches in a plasma generated by the FLAME laser pulse is under design. The upgrade of the synchronization system is under way to guarantee the <30fs RMS jitter required specification. It foresees the transition from electrical to optical architecture that mainly affects the reference signal distribution and the time of arrival detection performances. The new system architecture is presented together with the related experimental data.

9512-37, Session 7

Optical diagnostics for femtosecond electron pulses *(Invited Paper)*

Rasmus Ischebeck, Paul Scherrer Institut (Switzerland)

Today's X-Ray and Terahertz sources make use of compressed electron bunches to generate radiation for a wide range of users. We are designing instrumentation based on optical techniques, which will be used for an initial setup of the accelerator, as well as for continuous monitoring of the compression process. I will present here an overview of these systems and show how they will be used for SwissFEL.

9512-72, Session 7

Tracking the XUV-induced ultrafast electron dynamics in biomolecules *(Invited Paper)*

Francesca Calegari, Politecnico di Milano (Italy)

Electron transfer within a single molecule is the fundamental step of many biological processes and chemical reactions. Theoretical studies have pointed out that very efficient charge dynamics along the molecular backbone can be driven by purely electronic effects, which can evolve on a temporal scale ranging from few femtoseconds down to tens of attoseconds. Here, we report the application of XUV (17-35 eV) attosecond pulses to prompt ionization of the amino acid phenylalanine and the subsequent detection of ultrafast dynamics on a sub–4.5-femtosecond temporal scale, which is shorter than the vibrational response of the molecule [1]. This ultrafast dynamics can only be associated with a purely electronic process, thus constituting the first experimental measurement of charge migration in a biomolecule. [1] F. Calegari et al, Science 346, 336-339 (2014).

9512-34, Session 8

Investigation of the ultrafast light-induced dynamics in clusters and droplets with short wavelength free-electron laser *(Invited Paper)*

Yevheniy Ovcharenko, Thomas Möller, Technische Univ. Berlin (Germany)

With the advent of short-wavelength free-electron laser the interaction of high intensity, short-wavelength, short-pulse radiation with matter has become a very active field of research [1-4] and a very exciting topic in atomic and molecular physics. A deep knowledge of the physics in such small systems further helps to develop an understanding of ultra-fast light induced dynamics in more complex systems. An ideal sample for that can

be rare gas clusters as well as He nanodroplets, since they are a form of matter intermediate between atoms and bulk solids. Furthermore, they are finite systems with the density of bulk solids or liquids allowing the investigation of inner- and interatomic phenomena [2,5-9]. Accelerator based free electron lasers with pulse length in the 10 - 100 femtosecond regime have already provided a wealth of new results [6,8-11]. Recent studies give evidence that a complicated electron dynamics including interatomic Coulombic decay as well as electron scattering takes place on a timescale of a few fs or even less [12,13]. Initial experiments have shown that nmsized gas phase particles can also be imaged by single shot scattering [14-17].

[1] W. Ackermann et al., Nat. Photonics 1, 336 (2007).

[2] H. Wabnitz et al., Nature (London) 420, 482 (2002).

[3] T. Shintake et al., Nat. Photonics 2, 555 (2008).

[4] L. Young et al., Nature, 466, 56 (2010).

[5] T. Ditmire, T. Donnelly, A. M. Rubenchik, R. W. Falcone, and M. D. Perry, Phys. Rev. A 53, 3379 (1996).

[6] C. Bostedt, et al., Phys. Rev. Lett. 100, 133401 (2008).

[7] U. Saalmann, C. Siedschlag, and J. M. Rost, J. Phys. B 39, R39 (2006).

[8] T. Fennel et al., Rev. Mod. Phys. 82, 1793 (2010).

[9] B. Ziaja, H. Wabnitz, F. Wang, E. Weckert, and T. Moller, Phys. Rev. Lett. 102 (2009).

[10] K. Nagaya et al., J. Phys. B 46, 164023 (2013).

[11] C. Bostedt et al., New J. Phys. 12 (2010).

[12]Y. Ovcharenko,et al., Phys. Rev. Lett. 112, 073401 (2014).

[13] A. LaForge et al., Sci. Rep. 4, 3621 (2014).

[14] C. Bostedt et al., J. Phys. B 43, 194011 (2010).

[15] D. Rupp, et al., New J. Phys. 14 (2012).

[16] C. Bostedt, et al., Phys. Rev. Lett. 108, 093401 (2012).

[17] T. Gorkhover, et al., Phys. Rev. Lett. 108 (2012).

9512-35, Session 8

DiProI, the coherent diffraction imaging end-station at FERMI@Elettra FEL user facility: present status and future research opportunities

Flavio Capotondi, Emanuele Pedersoli, F. Casolari, Michele Manfredda, Maya Kiskinova, Lorenzo Raimondi, Marco Zangrando, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Enrico M. Allaria, Istituto Nazionale di Ottica (Italy); Filippo Bencivenga, Claudio Masciovecchio, Miltcho B. Danailov, D. Fausti, Luca Giannessi, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Sasa Bajt, Miriam Barthelmess, Holger Fleckenstein, Richard A. Kirian, Deutsches Elektronen-Synchrotron (Germany); Chun Hong Yoon, Joachim Schulz, European XFEL GmbH (Germany); Henry N. Chapman, Ctr. for Free-Electron Laser Science (Germany); Carsten Nils Gutt, Heidelberg School of Medicine (Germany); Lutz Müller, Gerhard Grübel, Deutsches Elektronen-Synchrotron (Germany); B. Pfau, Univ. Pierre et Marie Curie (France); C. von Korff Schmising, Stefan Eisebitt, Technische Univ. Berlin (Germany); Boris Vodungbo, Lab. d'Optique Appliquée (France); J. Luning, Univ. Pierre et Marie Curie (France); Janos Hajdu, Uppsala Univ. (Sweden)

The multipurpose measurement station for Coherent Diffraction Imaging, operating at the DiProI beamline of the FERMI@Elettra XUV/soft X-ray free electron laser, is designed to meet the users' requirements for performing a wide range of static and dynamic studies, and has been open to the users since 2012. The flexible design permits to fully exploit the state of the art performance of the ultrashort, highly coherent, tunable and multi-polarizable pulses of seeded FERMI FEL source. This presentation will overview the different class of experiments already performed, which include single-shot coherent diffraction imaging, time-resolved magnetic holography, two-color FEL pump-probe diffraction and interferometric phenomena observed in FEL-induced transient IR reflectance and transmittance. The emphasis will be on demonstrating the new research opportunities for studies of transient states of matter with high temporal resolution opened thanks to the implemented almost jitter-free pump-probe schemes that allow for time-resolved experiments using multi-color twin FEL pulses or IR/FEL configurations. The shorter wavelengths, down to 4 nm in the first lasing harmonic, that will soon be provided by FERMI-FEL-2, will expand the instrument capabilities to CDI experiments with free-standing samples, injected in aerosol to the FEL interaction region as well dynamic studies reaching the L2,3-adsorption edges of magnetic transition metals in the third harmonic. Implementation of grazing geometry and 3D set-ups is under consideration and development, which will allow new class of "exotic" experiments.

9512-36, Session 8

Beam diagnostics based on atomic physics methods at the low-density matter beamline of FERMI

Paola Finetti, Carlo Callegari, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Marcello Coreno, Consiglio Nazionale delle Ricerche (Italy); Riccardo Cucini, Miltcho B. Danailov, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Raimund A. Feifel, Univ. of Gothenburg (Sweden); Michele Di Fraia, Luca Giannessi, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Antti Kivimali, Istituto Officina dei Materiali (Italy); Tommaso Mazza, Michael Meyer, European XFEL GmbH (Germany); Oksana Plekan, Kevin C. Prince, Robert Richter, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Richard Squibb, Univ. of Gothenburg (Sweden); Stefano Stranges, Univ. degli Studi di Roma La Sapienza (Italy); Kiyoshi Ueda, Tohoku Univ. (Japan); Marco Zangrando, Elettra-Sincrotrone Trieste S.C.p.A. (Italy)

The development of femtosecond free electron laser (FEL) sources emitting in the vacuum ultraviolet (VUV) and X-ray spectral region, is paving the way to the study of electron dynamics and non-linear spectroscopy involving core electrons which are markers of the emitting atom. The study of the interaction of radiation with matter via high field, time-resolved photon excitation greatly benefits from the features of a seeded VUV/X-ray FEL source such as FERMI [1]. These include high and stable energy per pulse, tunable energy with a highly reproducible central wavelength and narrow wavelength spread. FERMI FEL-1 delivers pulses in the range ?=100 nm-20nm with an energy per pulse of 20 ?J to 100 ?J and ??/? of the order of 1x10-3 FWHM. This paper presents some simple atomic physics experiments, based on ion and electron spectroscopy, that prove to be valuable photon beam diagnostics for experiments aiming at time resolution. Along with more routine tasks, such as pulse energy determination, atomic physics was already used as diagnostics at FERMI to measure the variable polarization state of the FERMI FEL-1 source [2]. The experiments presented in this paper were carried out on the low density matter (LDM) beamline. The experimental methods we present rely on the aforementioned properties of FERMI. The fully tunable energy and narrow wavelength bandwidth in fact, allow to pump a shot to shot stable population in any desired atomic resonant state. Sharp, long-lived states (e.g. from He or Ne) provide a quick, wide-range and accurate way to measure the temporal delay between the pumping FEL and a probe laser ionizing the long-lived state. The seeded FEL scheme of FERMI allows two color experiments by overlap of the FEL pulse with light from the same 780 nm (and higher harmonics) Ti:sapphire laser that originates the FEL seed pulse. Such a pump and probe system is nearly time jitter free (measured ?tjit<10 fs) [3]. Under these favorable conditions, FERMI pulse duration measurements can be made by means of cross-correlation methods. One of these consists in measuring the intensity of

sidebands in photoemission, i.e. the satellite peaks due to simultaneous absorption of one FEL photon and one or more infrared photons, as a function of the time delay between the two laser pulses. In this paper we show that by making use of angle integrated photoemission data from a magnetic bottle [4] sidebands from He can be used to measure the FERMI pulse duration in a wide photon energy range. The effect of data post-processing by sorting pulses according their spectral quality is also discussed.

[1] E. Allaria et al., Nature Photonics, 6, 699 (2012).

[2] E. Allaria et al., Phys. Rev. X (2014). P. Finetti et al., Proc. SPIE Vol. 9210 92100K-1 (2014). T. Mazza et al., Nat. Commun. 5:3648 doi: 10.1038/ncomms4648 (2014).

[3] P. Cinquegrana et al., Phys. Rev. ST Accel. Beams 17, 040702 (2014). M. B. Danailov et al., Optics Express 22, 12871 (2014).

[4] J.H.D. Eland et al., PRL 90, 053003 (2003).

9512-38, Session 8

Grating-based pulse compressor for applications to FEL sources

Luca Poletto, Fabio Frassetto, Paolo Miotti, CNR-IFN UoS Padova (Italy); David Gauthier, Univ. of Nova Gorica (Slovenia) and Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Benoit Mahieu, Univ. of Nova Gorica (Slovenia) and Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and Commissariat à l'Énergie Atomique (France); Marta Fajardo, Instituto de Plasmas e Fusão Nuclear (Portugal); Marco Zangrando, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Philippe Zeitoun, Ecole Nationale Supérieure de Techniques Avancées (France); Giovanni De Ninno, Univ. of Nova Gorica (Slovenia) and Elettra-Sincrotrone Trieste S.C.p.A. (Italy)

We present the optical layout of a reflective grating compressor specifically designed for extreme-ultraviolet FEL sources, having its main application in FEL chirped pulse amplification.

The layout is based on the use of a couple of plane gratings used at grazing incidence and illuminated by divergent light. Two possible grating configurations are discussed, the on-plane and off-plane geometry.?The group delay dispersion (GDD) introduced by the compressor is analytically analyzed and quantified for both the proposed configurations. Moreover, a suitable linear approximation of the GDD in the typical spectral bandwidth of FEL emission is presented. The spatial chirp at the output, that cannot be avoided due to the two passages on the gratings, is also analytically analyzed. The advantages and drawbacks of both the geometries are discussed.

The deviation from the ideal case, in which the instrument is illuminated by a collimated beam, is considered in the real case of a diverging beam. The effect of the angular divergence is quantified and the application of the proper GDD is performed by finely "de-tuning" the grating alignment, i.e., by operating the two gratings slightly out from the parallel geometry. This solution allows the use of the compressor without any pre-collimating optics, giving higher throughput and simplifying the optical and mechanical design, as well as the instrumental operations. Finally, it is shown how the compressor can be designed in order to be inserted in the optical path without any deviation of the photon beam with respect to its nominal path.

To corroborate the analysis of the instrumental throughput, measurements of the grating efficiency in both geometries in the spectral interval 25–40 nm are presented.

Finally, a test case applied to the FERMI FEL is discussed.

9512-39, Session 8

Atomic photoionization dynamics in combined XUV and NIR radiation fields

Michael Meyer, Tommaso Mazza, European XFEL GmbH (Germany); Markus Ilchen, European XFEL GmbH (Germany) and SLAC National Accelerator Lab. (United States); Carlo Callegari, Paola Finetti, Oksana Plekan, Kevin C. Prince, Marcello Coreno, Robert Richter, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Patrick O'Keeffe, Lorenzo Avaldi, Paola Bolognesi, Istituto di Struttura della Materia (Italy); Kiyoshi Ueda, Tohoku Univ. (Japan); John T. Costello, Dublin City Univ. (Ireland); Elena V. Gryzlova, Alexei N. Grum-Grzhimailo, Lomonosov Moscow State Univ. (Russian Federation); Andrey K. Kazansky, Donostia International Physics Ctr. (Spain); Nikolay M. Kabachnik, European XFEL GmbH (Germany)

New opportunities for investigations of the photoionization dynamics are opened up by the new soft X-ray free electron laser (FEL) facilities. While direct time-resolved observation of electron processes requires application of sub-femtosecond pulses, detailed information on the dynamics is accessible on the femtosecond time scale through modification of the X-ray induced ionization by a superimposed strong optical dressing field (>1012 W/cm2). Recent experimental results obtained at the extreme ultraviolet FEL FERMI (Trieste, Italy) will be presented and compared to the corresponding theoretical description of the processes.

In photoionization experiments, the combined XUV and optical fields give rise to the formation of so-called sidebands in the energy-resolved electron spectrum. The variation of the intensity of these sidebands, when changing the relative orientation of the linear or circular polarization of one of the photons, is known as linear or circular dichroism in the photoionization. The study of these dichoic phenomena together with the measurement of the angular distribution of the photoelectrons (PAD) provides unique information on the photoionization process, in particular on the distribution of angular momenta for the outgoing electrons. By taking advantage of the particular characteristics of FERMI, especially the availability of circularly polarized XUV radiation, we have explored these dichroic effects in atomic two-color photoionization processes [1]. The comparison of the experimental data with the results of theoretical models describing the two-color circular dichroism enables us to analyze in detail the multi-photon ionization dynamics and to determine the degree of circular polarization of the FEL beam as well as the sign of the helicity, i.e. parameters, which are generally difficult to extract by other means. Possibilities of future applications, including resonant phenomena, will be outlined and discussed.

[1] T. Mazza et al . Nat.Comm. 5, 3648 (2014).

9512-40, Session 8

FEL-based transient grating spectroscopy

Riccardo Cucini, Filippo Bencivenga, Elettra-Sincrotrone Trieste S.C.p.A. (Italy)

No Abstract Available

9512-41, Session 9

Applications of the transverse gradient undulators on high-gain FELs in China

Bo Liu, Tong Zhang, Haixiao Deng, Chao Feng, Wei Zhang, Dong Wang, Zhentang Zhao, Shanghai Institute of Applied Physics (China)

Transverse gradient undulator (TGU) introduces correlation between undulator strength and position, and can dramatically reduce the

sensitivity to energy spread. In a so-called phase-merging enhanced harmonic-generation (PEHG) scheme, it is also possible utilizing TGU to manipulate the phase space of the electron beam, hence increase the bunching efficiency at high harmonics. With TGU, greater FEL power gain, better transverse mode and purer spectral characteristics are expected for the all-optical EUV-FEL project funded by National Natural Science Foundation of China (NSFC). Demonstration of the PEHG scheme is also planned at the Shanghai Deep-Ultraviolet Free-Electron Laser (SDUV-FEL) test facility. Recent progress on these applications of TGU will be presented.

9512-42, Session 9

Measurement of the seed laser to electron bunch time jitter at the FERMI free electron laser

Paolo Sigalotti, Enrico M. Allaria, Paolo Cinquegrana, Miltcho B. Danailov, Alexander A. Demidovich, Eugenio Ferrari, Gabor Kurdi, Ivaylo P. Nikolov, Fabio Rossi, Marco Veronese, Elettra-Sincrotrone Trieste S.C.p.A. (Italy)

FERMI is a seeded FEL, that relies on several laser systems to generate tunable femtosecond pulses in the Extreme UV range (from 100 nm to 4 nm). On the machine side, reducing as much as possible the timing jitter between the electron bunch and the seed laser pulses is essential to achieve reliable FEL operation. On the users side it is equally important to guarantee a low jitter between the FEL and the pump-probe laser because it is essential to investigate ultrafast phenomena on the femtosecond timescale.

The aim of this work is to present the improvements recently introduced to the seed laser synchronization scheme, a complete characterization of the time jitter between Seed Laser and the electron bunch, some results on the timing stability in Pump Probe experiments using FEL and seed laser and to discuss foreseen future developments.

In this paper, after a short review of the FERMI laser sources' synchronization layout, we present the improved performance of the Seed Laser timing, both on the locking of the ultrafast oscillator to the timing reference, and the stabilization of the time of flight across the Ti:Sa amplifier. An estimation of the time jitter introduced by the conversion to the UV and the beam transport to the undulator is also presented.

The relative time jitter between the electron bunch and Seed Laser pulses is measured, identifying the main sources and their contribution. .

The time stability achieved for Pump Probe experiments is also presented, with some examples that show how FEL tuning could affect such stability.

9512-44, Session 9

Using a transverse gradient undulator to improve the FEL performance in a laser plasma accelerator

Zhirong Huang, SLAC National Accelerator Lab. (United States)

Laser-plasma accelerators can produce a few GeV electron beams over a distance of a few cm. Such a beam typically has relatively low emittance, high peak current but a rather large energy spread and jitter. The large energy spread hinders the potential applications for coherent free-electron laser (FEL) radiation generation. We discuss a method to compensate the effects of beam energy spread by introducing a transverse variation of the undulator magnetic field. Such a transverse gradient undulator (TGU) together with a properly dispersed beam can greatly reduce the effects of electron energy spread and jitter on FEL performance. In this paper, we review the TGU concept, theory and discuss technical implementations. Using particle-in-cell simulations of a GeV laser-plasma accelerator and the FEL simulation code GENESIS that is modified to accommodate TGU, we show a soft x-ray FEL operating in the ``water window'' wavelengths can reach saturation with a undulator length of about 10 m.

9512-45, Session 9

Experimental characterization of the FERMI laser heater and its impact on the FEL operations

Eugenio Ferrari, Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and Univ. degli Studi di Trieste (Italy); Enrico M. Allaria, Luca Giannessi, Giovanni De Ninno, Giuseppe Penco, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Simone Spampinati, Univ. of Liverpool (United Kingdom); Simone Di Mitri, William M. Fawley, Alexander A. Demidovich, Miltcho B. Danailov, Silvano Bassanese, Laura Badano, Mauro Trovò, Marco Veronese, Bruno Diviacco, Carlo Spezzani, Davide Castronovo, Giulio Gaio, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Lars Froehlich, Deutsches Elektronen-Synchrotron (Germany)

High brightness electron beams are required for high gain FELs. In order to mitigate or suppress the microbunching instabilities that build up in different parts of the accelerator a laser heater is installed in the low energy part of the machine. The device increases the energy spread of the electron beam in a controlled way and mitigates, via Landau damping, the microbunching instability growth. Microbunching suppression is essential for FEL operations for both SASE and seeded based machines. In the case of HGHG like FERMI FEL-1 the FEL process is extremely sensitive to the amount of energy spread at the undulator entrance and the shape of the energy distribution. In this work we describe the Laser Heater operations at FERMI and we characterize the dependence of the FEL output as a function of the laser heater intensity in the case of FERMI FEL-1.

9512-46, Session 9

Circular polarization control in X-ray FELs by reverse undulator tapering

Evgeny A. Schneidmiller, Mikhail V. Yurkov, Deutsches Elektronen-Synchrotron (Germany)

Baseline design of a typical X-ray FEL undulator assumes a planar configuration which results in a linear polarization of the FEL radiation. However, many experiments at X-ray FEL user facilities would profit from using a circularly polarized radiation.

As a cheap upgrade one can consider an installation of a short helical (or cross-planar) afterburner, but then one should have an efficient method to suppress powerful linearly polarized background from the main undulator. In this paper we propose a new method for such a suppression: an application of the reverse taper in the main undulator.

We discover that in a certain range of the taper strength, the density modulation (bunching) at saturation is practically the same as in the case of non-tapered undulator while the power of linearly polarized radiation is suppressed by orders of magnitude. Then strongly modulated electron beam radiates at full power in the afterburner.

Considering SASE3 undulator of the European XFEL as a practical example, we demonstrate that soft X-ray radiation pulses with peak power in excess of 100 GW and an ultimately high degree of circular polarization can be produced. The proposed method is rather universal, i.e. it can be used at SASE FELs and seeded (self-seeded) FELs, with any wavelength of interest, in a wide range of electron beam parameters, and with any repetition rate. It can be used at different X-ray FEL facilities, in particular at LCLS after installation of the helical afterburner in the near future.

9512-47, Session 9

The universal method for optimization of undulator tapering in FEL amplifiers

Mikhail V. Yurkov, Evgeny A. Schneidmiller, Deutsches Elektronen-Synchrotron (Germany)

Technique of undulator tapering in the post-saturation regime is used at the existing x-ray FELs for increasing the radiation power. There are also discussions on the future of high peak and average power FELs for scientific and industrial applications. In this paper we present derivation of simple and universal formulae to determine the tapering function to maximize the FEL output. Analysis is based on consideration on the radiation power from microbunched beam. Application of similarity techniques allowed us to derive universal law of the undulator tapering. The results may have impact to those who are involved in designing the FEL machine.

9512-48, Session 10

Gamma-ray production from resonant betatron oscillations of accelerated electrons in a plasma wake *(Invited Paper)*

Silvia Cipiccia, Mohammad R. Islam, Bernhard Ersfeld, Gregor H. Welsh, Enrico Brunetti, Gregory Vieux, Xue Yang, S. Mark Wiggins, Peter A. Grant, David Reboredo-Gil, David W. Grant, Dino A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

The laser-plasma wakefield accelerator is a novel ultra-compact particle accelerator. A very intense laser pulse (>10^18 Wcm-2) is focused into plasma to excite a plasma wave. If the laser pulse duration is shorter than the plasma wavelength the process is highly non-linear and the plasma density structures resembles a bubble following the laser pulse. Background electrons injected into the bubble experience a longitudinal accelerating force in excess of 1 GV/cm. Moreover, the electrons enter the bubble with a non-zero transverse momentum, accelerated and wiggle in the transverse plane at the betatron frequency, emitting synchrotron radiation into an approximately 1/gamma cone, where gamma is the Lorentz factor. The presence of the laser field inside the bubble dramatically changes the electron dynamics and the electron motion can become resonant with the laser field. This occurs when the laser frequency, as seen by the electrons, equals the betatron frequency, and leads to effective energy exchange between electrons and laser. The process is described by a damped driven harmonic oscillator equation of motion where the damping term is proportional to 1/gamma. As a result of the resonance the synchrotron emission is strongly enhanced leading to direct laser acceleration and an increase of the critical energy to the hard x-ray (> 100 keV) and high peak brilliance ~10^23 photons/(s mrad mm2 0.1% BW).

9512-49, Session 10

Generation of femtosecond to sub-femtosecond x-ray pules in free-electron lasers *(Invited Paper)*

Yuantao Ding, SLAC National Accelerator Lab. (United States)

Generation of high power, femtosecond to sub-femtosecond x-ray pulses is attracting much attention within the x-ray free-electron laser (FEL) user community. At the existing FEL facilities, such as the Linac Coherent Light Source at SLAC, several methods have been developed to produce such short x-rays. Low-charge operation mode and emittance-spoiling scheme have been successfully used for user experiments, with pulse duration below 10 fs. A nonlinear compression mode has been recently developed and the pulse duration could be about 200 as. This is based on the existing LCLS hardware and some initial measurements have been done. A fully coherent short pulse mode based on selfseeding mode will also be discussed. We report the studies for the different short pulse schemes and discuss the operational challenges.

9512-50, Session 10

Crossed-planar undulators technique for free-electron laser polarization switching

Haixiao Deng, Shanghai Institute of Applied Physics (China)

In this talk, I would like to give a general introduction of polarization switching for modern free-electron lasers, mainly focus on the crossed-planar undualtors technique. The princinple of crossed-planar undulators, theoretical investigations, experimental demonstrations at visiable light region (SDUV-FEL) and EUV spectral region (FERMI, do I need to include this? or there may be another talk on FERMI experiment), and future plans at Shanghai x-ray free-electron laser facility will be reported.

9512-51, Session 10

longitudinal space charge assisted echo seeding of a free electron laser

Kirsten Hacker, Deutsches Elektronen-Synchrotron (Germany)

Seed lasers are employed to improve the temporal coherence of free-electron laser (FEL) light. The sinusoidal energy modulation of an electron bunch from a seed laser can be bunched into a sawtooth pattern in longitudinal phase space as in high gain harmonic generation (HGHG) seeding or it can be first folded over prior to a second modulation and bunching as in echo-enabled harmonic generation (EEHG) seeding. If the bunching in either of these schemes is done through a magnetic chicane, coherent synchrotron radiation (CSR) will distort the microbunches. If it is instead done through velocity bunching in a drift, longitudinal space charge (LSC) forces will dominate the process. Through careful selection of chicane and drift parameters, new bunching methods can be used to improve the properties of seeded microbunches for applications ranging from higher-efficiency FEL radiation to attosecond duration FEL pulses. These LSC-assisted HGHG and EEHG concepts and tolerances are presented using several 1-D and 3-D simulation codes with conditions at the soft x-ray FEL in Hamburg, FLASH.

9512-52, Session 10

Dual color x rays from Thomson or Compton sources

Vittoria Petrillo, Univ. degli Studi di Milano (Italy)

The possibility of producing two-color x or gamma radiation by Thomson/Compton backscattering between a high intensity laser pulse and a two-energy level electron beam is analyzed. The electron beam is constituted by a couple of beamlets separated in time and/or energy obtained by a photoinjector with comb laser techniques and linac velocity bunching. The parameters of the Thomson source at SPARC_LAB have been simulated, proposing a set of realistic experiments.

9512-53, Session 11

Super-radiant high-field THz sources operating at quasi-cw rep rates

Michael Gensch, Sergey Kovalev, Bertram Green, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

At the super-conducting radiofrequency electron accelerator ELBE

in Dresden a world-wide unique THz facility is currently under commissioning. The facility aims at delivering fourier-limited ultra-short THz pulses, with pulse energies of up to 100 ?J corresponding to transient electric field in the GV/m regime or transient magnetic fields in the few T regime. These pulses are generated at adjustable repetition rates between few Hz and 500 kHz from two different super-radiant THz sources providing for quasi-single cycle as well as tunable multicycle fields. In this paper the design of the facility is presented, first results from the commissioning are discussed and an outlook into future challenges and opportunities is given.

9512-54, Session 11

Experiment preparation towards a demonstration of laser plasma-based free electron laser amplification

Alexandre Loulergue, Marie Labat, Synchrotron SOLEIL (France); Clément Evain, PhLAM/CERCLA (France); Nicolas Hubert, Fabien Briquez, Fabrice Marteau, Chamseddine Benabderrahmane, Phillipe Berteaud, Charles Bourassin-Bouchet, Francois Bouvet, Lodovico Cassinari, Lilian Chapuis, Moussa El ajjouri, Christian Herbeaux, Martin Khojoyan, Alain Lestrade, Olivier Marcouillé, Jean-Louis Marlats, François Polack, Keihan Tavakoli, Mathieu Valleau, Daniel Zerbib, Wei Yang, Synchrotron SOLEIL (France); Xavier Davoine, CEA/DAM/DIF, Arpajon, (France); Igor Andriyash, Guillaume Lambert, Victor Malka, Cédric Thaury, LOA (France); Serge Bielawski, PhLAM/CERCLA (France); Christophe Szwaj, LOA (France); David Dennetiere, Nicolas Leclercq, Jean-Pierre Duval, Patrick Rommeluere, Paul Morin Morin, Marie-Emmanuelle Couprie, Synchrotron SOLEIL (France)

One direction towards compact Free Electron Laser is to replace the conventional linac by a laser plasma driven beam, provided proper electron beam manipulation to handle the value of the energy spread and of the divergence. Applying seeding techniques enables also to reduce the required undulator length. The rapidly developing LWFA are already able to generate synchrotron radiation. With an electron divergence of typically 1 mrad and an energy spread of the order of 1 %, an adequate beam manipulation through the transport to the undulator is needed for FEL amplification. A test experiment for the demonstration of FEL amplification with a LWFA is under preparation in the frame of the COXINEL ERC contract. Electron beam transport follows different steps with strong focusing with variable strength permanent magnet quadrupoles, demixing chicane with conventional dipoles, a second set of quadrupoles for further focusing in the undulator. Progress on the equipment preparation and expected performance is described.

9512-55, Session 11

A free-electron laser design for four-wave mixing experiments with soft x-ray pulses

Gabriel Marcus, SLAC National Accelerator Lab. (United States); Gregory Penn, Alexander A. Zholents, Lawrence Berkeley National Lab. (United States)

The design of a single-pass free-electron laser beamline for the production of soft x-ray pulses suitable for four-wave mixing experiments is presented. The scheme relies on multiple applications of a selective amplification process where a chirped electron beam and a tapered undulator are used to isolate the gain region to only a small fraction of the electron beam. This process is analyzed in detail while numerical particle simulations are used to demonstrate the more impressive features of this scheme.

9512-56, Session 11

Applying longitudinal space charge amplifier to linac-based tunable terahertz sources

Sergei Seletskiy, Boris V. Podobedov, Xi Yang, Brookhaven National Lab. (United States); Yuzhen Shen, The United States Patent and Trademark Office (United States)

A linac-based tunable coherent terahertz (THz) source was recently developed and demonstrated at BNL Source Development Laboratory. This source generates tunable, narrow-band few-cycle and multicycle coherent THz radiation by intercepting the electron bunch modulated in density with an aluminum mirror.Although a higher charge per bunch is desirable for strong THz radiation, it fundamentally is limited by the space charge effects at low energy, which also set the upper limit to the modulation frequency of the electron beam. In this presentation we discuss how a Longitudinal Space Charge Amplifier (LSCA) can be applied to overcome these limitations. We consider a single stage LSCA, which starts with a coherently seeded electron beam and includes the acceleration section followed by a bunch compressor. We show that such LSCA can significantly increase both the charge and the modulation frequency available to the linac-based tunable few-cycle and multicycle THz sources.

9512-57, Session 11

An XUV source using a femtosecond enhancement cavity for photoemission spectroscopy

David J. Jones, The Univ. of British Columbia (Canada)

No Abstract Available

9512-58, Session 11

Optical klystron SASE at FERMI

Giuseppe Penco, Elettra-Sincrotrone Trieste S.C.p.A. (Italy)

The optical klystron enhancement to a self-amplified spontaneous emission (SASE) free electron laser (FEL) has been deeply studied in theory and in simulations. In this FEL scheme, a relativistic electron beam passes through two undulators, separated by a dispersive section. The latter converts the electron-beam energy modulation produced in the first undulator in density modulation, thus enhancing the free-electron laser gain.

We report the first experiment that has been carried out at the FERMI facility in Trieste, of enhancement to a SASE by using the optical klystron scheme. Intense XUV photons have been produced with an intensity several oder of magnitude larger than in pure SASE mode. The impact of the uncorrelated energy spread of the electron beam on the optical klystron SASE performance has been also investigated.

9512-1, Session PS

Pulsed wire measurement for insertion devices

Alex D'Audney, Colorado State Univ. (United States)

The performance of a Free Electron Laser (FELs) depends in part on the integrity of the magnetic field in the undulator. The magnetic field on the axis of the undulator is transverse and sinusoidally varying due to the periodic sequence of dipoles. The ideal trajectory of a relativistic electron bunch, inserted along the axis, is sinusoidal in the plane of oscillation.

Phase errors are produced when the path of the electron is not the ideal sinusoidal trajectory, due to imperfections in the magnetic field. The result of such phase errors is a reduction of laser gain impacting overall FEL performance.

A pulsed-wire method can be used to determine the profile of the magnetic field. This is achieved by sending a square current pulse through the wire, which will induce an interaction with the magnetic field. Measurement of the displacement in the wire over time using a motion detector yields the first or second integrals of the magnetic field. Dispersion in the wire can be corrected using algorithms resulting in higher accuracy. Once the fields are known, magnetic shims are placed where any corrections are needed.

This high precision pulsed-wire method will be used to characterize an undulator which has 50 periods of 25 mm each. The undulator has a K value of 1 and a betatron wavelength of 300 nm for an electron beam of 6 MeV.

9512-67, Session PS

Laser arrival measurement tools for SwissFEL

Marta Csatari Divall, Albert Romann, Patrick Mutter, Stephan G. Hunziker, Paul Scherrer Institut (Switzerland); Christoph P. Hauri, Paul Scherrer Institut (Switzerland) and Ecole Polytechnique Fédérale de Lausanne (Switzerland)

SwissFEL is aiming to produce X-ray pulses down to the attosecond scale. This requires the compression of the several picosecond long electron bunches produced by a photo-injector to sub-fs level. To achieve this, 40fs accurate injection of the electron bunches into the main linear accelerator is necessary. Therefore high timing accuracy is required from the drive laser of the electron gun. Furthermore fs scan capability is foreseen for the experimental stations of the FEL. The ultra-short pulse pump-probe lasers therefore need to exhibit outstanding, below 10fs short term jitter relative to the X-rays. Timing tools for both the electron gun laser and for the experiments are developed. The former is based on electro-optical modulation of the optical reference at 1550nm by a signal produced from the gun laser at 260nm, a concept similar to beam arrival monitors in the linear accelerator, with an expected resolution below 20fs. The latter will use spectrally resolved cross-correlation technique to determine relative jitter between the optical reference and the laser used at the experiments at 800nm, with fs resolution. These systems will be complemented by electron and X-ray timing tools. In this paper we present the general concept for the laser arrival time measurement and correction, with first results obtained on the existing laser systems (Nd:YLF and Ti:Saph). Shot to shot, short term jitter and long term timing drift measurements are presented, with discussion on the sources of the noise. Plans for the feedback stabilization and the resolution and limitation of the systems is also covered.

9512-68, Session PS

Construction status of CXI beamline at PAL-XFEL

Jaehyun Park, Ki Hyun Nam, Sangsoo Kim, Bongsoo Kim, In Soo Ko, Moo Hyun Cho, Pohang Accelerator Lab. (Korea, Republic of)

Pohang Accelerator Laboratory X-ray Free Electron Laser (PAL-XFEL) is a research facility currently under construction. It will provide ultra-bright (assuming 1 X 1012 photon/pulse at 12.4 keV) and ultra-short (10-60 femtosecond) X-ray pulses. The CXI (Coherent X-ray Imaging) end-station, which will be constructed for hard X-ray beamline at the PAL-XFEL, is designed to deliver brilliant hard x-rays (2-20 keV) and to measure diffraction signals with forward scattering geometry, mainly. Not only will it offer imaging studies of biological, chemical and physical samples by the “diffract-before-destroy” technique, but will also be helpful in high field hard x-ray physics and material science. The scientific programs are currently aimed at serial femtosecond crystallography (SFX) for macromolecular systems and coherent diffraction imaging for bio specimens and nano structures etc. We have developed prototype liquid phase sample injector to deliver protein crystals in fully hydrated condition under stable operation. Its compact design enables multiport injection without nozzle change for various samples at a time. For the sample delivery with the fixed target, a high speed scanning system for the full repetition rate will be applied to the dedicated chamber. High resolution microscope system is also considered to conduct experiments more systematically. In this poster, we describe the details of the beamline layout, X-ray focusing optics (Kirkpatrick-Baez mirror and Beryllium CRLs), liquid jet sample injector, laser-based alignment tool and other components that will be installed at the CXI beamline. Our poster will provide a better understanding of the CXI beamline instruments at PAL-XFEL.

9512-69, Session PS

Towards a novel THz-based monitor for sub-picosecond electron bunches working at MHz repetition rates and low bunch charges

Sergey Kovalev, Bertram Green, Michael Gensch, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

The control and measurement of electron bunch properties at the femtosecond (fs) level has become an important field in modern accelerator physics, in particular since these became crucial parameters for the operation of 4th Generation X-ray Light-sources. In order to operate modern-day photon factories such as LCLS and the future European X-FEL reliably, a number of novel approaches have been developed that allow the noninvasive measurement of electron bunch form and arrival time. Some of those are based on the electro-optic detection of the coulomb field of the electron bunches in the electron beamline; some detect the super-radiant THz pulses from the electron bunch. However, none of these concepts allows for pulse-to-pulse detection on a quasi-CW accelerator operating at the MHz repetition rates planned for the next generation of X-ray free electron lasers. In this contribution we present first results from a new monitor concept, based on the single-shot electro-optic detection of super-radiant THz pulses, that has the potential to operate at MHz repetition rates. We describe a concept for a non-invasive monitor for the arrival time and shape of sub-picosecond electron bunches, based on the single-shot detection of super-radiant THz pulses. Initial measurements using this approach at the quasi-CW linear electron accelerator ELBE are presented.

9512-70, Session PS

High-efficiency bispectral laser for EUV

Alexsandr S Grishkanich, Aleksandr Zhevlakov, National Research Univ ITMO (Russian Federation); Ruben Seisyan, Ioffe Physical Technical Institute RAS (Russian Federation); Viktor Bespalov, Valentin Elizarov, Sergey Kascheev, National Research Univ ITMO (Russian Federation)

No Abstract Available

9512-59, Session 12

Operational experiences of the free-electron laser FLASH *(Invited Paper)*

Siegfried Schreiber, Deutsches Elektronen-Synchrotron (Germany)

FLASH, the free-electron laser user facility at DESY (Hamburg, Germany), delivers since 2005 high brilliance XUV and soft X-ray FEL radiation for photon experiments. FLASH is based on a superconducting electron accelerator able to deliver several thousand pulses per second. The burst

mode of operation is especially demanding for the electron injector: a warm RF-gun with a high duty cycle is in operation to produce the bursts of electron bunches with small emittance required to drive the SASE process. We report the status of the FLASH facility, and discuss operational experiences in view of reliability, stability in electron and photon beam performance

9512-60, Session 12

The new IR and THz FEL facility at the Fritz Haber Institute in Berlin *(Invited Paper)*

Wieland Schöllkopf, Sandy Gewinner, Heinz Junkes, Alexander Paarmann, Gert von Helden, Fritz-Haber-Institut der Max-Planck-Gesellschaft (Germany); Hans P. Bluem, Alan M. M. Todd, Advanced Energy Systems, Inc. (United States)

A mid-infrared (MIR) oscillator FEL has been commissioned at the Fritz-Haber-Institut. The electron accelerator consists of a thermionic gridded gun, a subharmonic buncher and two S-band standing-wave copper structures [1,2]. It provides a final electron energy adjustable from 15 to 50 MeV, low longitudinal (<50 keV-ps) and transverse emittance (<20 ϖ mm-mrad), at more than 200 pC bunch charge with a micro-pulse repetition rate of 1 GHz and a macro-pulse length of up to 15 ?s. The electrons are steered in either of two FEL's; a MIR FEL (fully operational) and a THz FEL (to be installed in the future). From the MIR FEL pulsed radiation with up to 100 mJ macro-pulse energy at about 0.5% FWHM bandwidth is routinely produced in the wavelength range from 4 to 48 ?m. We will review the design of the MIR FEL and its performance as determined by IR power, bandwidth, and micro-pulse length measurements.

Regular user operation started in Nov. 2013 with 6 user stations. We will give an overview of the new FHI FEL facility and first user results [3]. The latter include, for instance, vibrational spectroscopy of bio-molecules (peptides and small proteins) which are either conformer selected in the gas-phase by ion mobility spectrometry or embedded in superfluid helium nano-droplets at 0.4 K. Further user experiments include vibrational spectroscopy of mass-selected metal-oxide clusters and protonated water clusters in the gas phase. In another user project, ultrafast dynamics in solid-state systems is investigated. In these experiments the FEL pulses serve as pump pulses and are combined with various probes, such as visible reflectivity or sample magnetization, to study fundamental interactions among low-energy excitations. Common to all these experiments is the method of "action spectroscopy". Instead of detecting absorption of the FEL radiation, one detects some resulting action such as, e.g., molecular or cluster fragmentation, ionization, demagnetization, etc. Action spectroscopy often allows for observation of IR spectra with good signal-to-noise ratio even for weakly absorbing samples like, e.g., molecules in the gas-phase.

Furthermore, we will present the status of ongoing work to implement sub-ps time synchronization of the MIR FEL micro-pulses with ultra-short pulses from a commercial, near-IR femtosecond laser. To this end it is planned to operate the MIR FEL in a reduced micro-pulse repetition rate of 55.5 MHz identical to the pulse rate of the femtosecond laser.

[1] W. Schöllkopf et al., MOOB01, Proc. 34th Int. Free Electron Laser Conference 2012.

[2] W. Schöllkopf et al., WEPSO62, Proc. 35th Int. Free Electron Laser Conference 2013.

[3] W. Schöllkopf et al., WEB04, Proc. 36th Int. Free Electron Laser Conference 2014.

9512-61, Session 12

Operational experience at ELBE

Peter Michel, Ulf Lehnert, Wolfgang Seidel, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

The ELBE center for high power radiation sources is the largest user facility in the Helmholtz Center Dresden-Rossendorf. The facility is based on a 36 MeV superconducting RF Linac which can be operated up to 1.6 mA in cw mode. The electron beam is used to generate secondary radiation, such as infrared light (Free Electron Lasers), coherent THz radiation, MeV-Bremsstrahlung, fast neutrons and positrons for a wide range of basic research like semiconductor physics, nuclear astrophysics and radio biological investigations. Two high power laser systems (500 TW TiSa laser, 2 PW diode pumped laser) are under construction for laser acceleration experiments and X-ray generation by Thomson scattering. The FELs are in operation since 2004 (mid-IR FEL, 2-22μm) and 2006 (far-IF FEL, 20-300μm). In the contribution the fundamental features of the ELBE IR FEL's, the FEL instrumentation and advanced beam diagnostics for both electron and photon beam are shown. The operational experiences which were collected during ten years of user operation including operational statistics will be described.

9512-62, Session 12

Tests of photocathodes for high repetition rate x-ray FELs at the APEX facility at LBNL

Fernando Sannibale, Daniele Filippetto, Houjun Qian, Christos Papadopoulos, Lawrence Berkeley National Lab. (United States); Ruixuan Huang, Univ. of Science and Technology of China (China); Max Zolotorev, John W. Staples, Lawrence Berkeley National Lab. (United States)

After the formidable results of X-ray 4th generation light sources based on free electron lasers around the world, a new revolutionary step is undergoing to extend the FEL performance from the present few hundred Hz to MHz-class repetition rates. In such facilities, temporally equi-spaced pulses will allow for a wide range of previously non-accessible experiments. The Advanced Photoinjector EXperiment (APEX) at the Lawrence Berkeley National Laboratory (LBNL), is devoted to test the capability of a novel scheme electron source, the VHF gun, to generate the required electron beam brightness at MHz repetition rates. In linac-based FELs, the ultimate performance in terms of brightness is defined at the injector, and in particular, cathodes play a major role in the game. Part of the APEX program consists in testing high quantum efficiency photocathodes capable to operate at the conditions required by such challenging machines. Results and status of these tests at LBNL are presented.

9512-63, Session 12

Optimization of high average power FEL beam for EUV lithography source

Akira Endo, Institute of Physics of the ASCR, v.v.i./HiLase Center (Czech Republic)

Extreme Ultraviolet Lithography (EUVL) is entering into high volume manufacturing (HVM) stage, with high average power EUV source from laser produced plasma at 13.5nm. Semiconductor industry road map indicates a scaling of the source technology to 1kW average power by high repetition rate FEL.

Recently demonstrated SASE FEL pulse is typically 0.1mJ, 100fs, 1mm diameter, and has higher beam fluence than the resist ablation threshold, and high spatial coherence which results in speckle patterns on resist, and random longitudinal mode beat which leads to high peak power micro spikes.

A grazing incidence total reflection bended metal mirror is installed after the undulator to expand the beam area to reduce the beam fluence lower than the ablation threshold of resist. External-seeding configuration is employed to reduce the longitudinal mode beat, and beam homogenizer based on total reflection is used for spatial mode mixing. The pulse repetition rate is assumed more than 3MHz to cancel the speckle patter formation by averaging illumination.

This paper discusses on the lowest risk approach to construct a prototype based on superconducting linac and normal conducting undulator, to

demonstrate a high average power 13.5nm FEL equipped with optimized optical components, to study FEL application in EUV lithography .

9512-64, Session 12

FERMI magnet power supplies: design strategies and five years of operational experience

Roberto Visintini, Elettra-Sincrotrone Trieste S.C.p.A. (Italy)

FERMI is the FEL-based light source in operations for external users since December 2012 at the Elettra Research Center in Trieste, Italy. FERMI@ Elettra is the name of the project for the construction and commissioning of this new source. The design strategies adopted in the project had to consider the extremely close presence and the routine operation for users of the synchrotron–based source Elettra. This was one of the major constraints for the construction of FERMI.

There are more than 350 magnets and coils distributed along the linear accelerator, the two chains of undulators and the electron beam dump. Almost all these magnetic elements require a dedicated DC power supply. Magnets, power supplies, and the connecting cables constitute a system, strongly interconnected with the remote control system, the machine and personnel safety system, and the infrastructure. All this has to fulfill the requirements from the particle physics specialists. We adopted a “systemic” approach in the design of new magnets and the re-use of the old ones, as well as the choice and the design of the associated power supplies. The minimization of the number of types of different power supplies and the cross section of magnet cables, were some of the criteria adopted in the design of the magnets, while the smooth interfacing with the control system was one of the criteria in the design of power supplies.

FERMI construction was completed in 3 years and the first lasing occurred on December 13, 2010. The commissioning of the systems started early 2010 and almost all magnet power supplies are in operation since then. During these 5 years, we introduced few minor upgrades and patches while the adopted solutions proved their soundness in terms of performance and reliability, causing very little downtime to the FERMI operations.

9512-65, Session 12

Operational experience on the generation and control of high brightness electron bunch trains at SPARC-LAB

Andrea Mostacci, Univ. degli Studi di Roma La Sapienza (Italy); David Alesini, Maria Pia Anania, Alberto Bacci, Marco Bellaveglia, Michele Castellano, Enrica Chiadroni, Istituto Nazionale di Fisica Nucleare (Italy); Alessandro Cianchi, Univ. degli Studi di Roma “Tor Vergata” (Italy); Domenico Di Giovenale, Giampiero Di Pirro, Massimo Ferrario, Istituto Nazionale di Fisica Nucleare (Italy); Francesco Filippi, Univ. degli Studi di Roma La Sapienza (Italy); Alessandro Gallo, Giancarlo Gatti, Istituto Nazionale di Fisica Nucleare (Italy); Anna Giribono, Univ. degli Studi di Roma La Sapienza (Italy); Riccardo Pompili, Stefano Romeo, Andrea Renato Rossi, Cristina Vaccarezza, Fabio Villa, Istituto Nazionale di Fisica Nucleare (Italy)

Sub-picosecond, high-brightness electron bunch trains are routinely produced at SPARC-LAB via the velocity bunching technique. Such bunch trains can be used to drive multi-color Free Electron Lasers (FELs) and plasma wake field accelerators. In this paper we present recent results at SPARC-LAB on the generation of such beams, highlighting the key points of our scheme. We will discuss also the on-going machine upgrades to allow driving FELs with plasma accelerated beams or with short electron pulses at an increased energy.

9512-66, Session 12

Design and initial characterisation of X-ray beam diagnostic imagers for the European XFEL

Andreas Koch, Wolfgang Freund, Jan Grünert, Marc Planas, Thomas Roth, Liubov Samoylova, Viktor Lyamayev, European XFEL GmbH (Germany)

The European X-Ray Free-Electron-Laser facility requires diagnostics of its x-ray photon beam. Imaging stations will be employed for characterisations of beam properties like position, profile, and pointing, before and after different types of mirrors, slits and monochromators. In combination with monochromators or dispersive devices, imagers can also deliver spectral information. The imagers will usually absorb the beam (invasive devices), however, for some applications they will be partially transmissive to allow beam pointing monitoring together with a second imaging unit further downstream. For the first commissioning 25 diagnostic imagers are planned at various positions in the photon beam tunnels. Further similar devices are under development for monitoring the beam properties at the experimental stations.

This contribution will describe the design of several imaging stations, their expected performance and first characterisations, especially in terms of signal-to-noise properties, spatial resolution and radiation hardness. The challenge in the design is to deal with a wide range of beam properties: photon energies from 0.26 – 36 keV, beam sizes from several 100 mm to several mm, pulse durations of 10 fs and pulse energies up to 10 mJ which may destroy materials by single pulses.

The main components of these imaging stations are: scintillators for conversion of x-rays to visible light, mirrors – both in vacuum - specialised optics and CCD / CMOS cameras for image recording, and the associated control electronics. In terms of radiation hardness the scintillator is the most critical component, followed by the mirror with its specific coatings. A simplified theory for radiation damage under short x-ray FEL pulses will be presented and the choice of materials will be motivated.

Conference 9513: High-Power, High-Energy, and High-Intensity Laser Technology

Tuesday - Wednesday 14–15 April 2015

Part of Proceedings of SPIE Vol. 9513 High-Power, High-Energy, and High-Intensity Laser Technology II

9513-1, Session 1

DiPOLE100: A 100 J, 10 Hz DPSSL using cryogenic gas cooled Yb:YAG multi slab amplifier technology *(Invited Paper)*

Paul D. Mason, Saumyabrata Banerjee, Klaus G. Ertel, Jonathan Phillips, Thomas J. Butcher, Jodie M. Smith, Mariastefania De Vido, Stephanie Tomlinson, Oleg V. Chekhlov, Waseem Shaikh, Cristina Hernandez-Gomez, Justin Greenhalgh, John L. Collier, STFC Rutherford Appleton Lab. (United Kingdom)

There is increasing demand for efficient pulsed lasers operating at high energy and high repetition rate for a range of applications including, pump sources for high-intensity PW-class amplifiers and direct sources for studying new material processing techniques or exploring high energy density physics phenomena. To meet this demand, the DiPOLE project within the Central Laser Facility (CLF) is developing an efficient high pulse energy diode-pumped solid-state laser (DPSSL) architecture based on cryogenic gas cooled, multi-slab ceramic Yb:YAG amplifier technology, capable of amplifying ns pulses to kJ pulse energies. Recently, a scaled-down prototype amplifier has met its design specification delivering 10 J pulses at 1030 nm and 10 Hz repetition rate with an optical-to-optical conversion efficiency of 21%. Furthermore, long term shot-to-shot energy stability of 0.5% rms at 7 J output was demonstrated during extended operation over 48 hours, corresponding to almost 2 million shots. Following on from this success a larger scale laser, DiPOLE100, is under development at the CLF that will confirm the scalability of the cryo-cooled amplifier concept. The current laser system is being built for the HiLASE project in the Czech Republic and will deliver 100 J temporally-shaped ns pulses at 10 Hz with a fully integrated control system. A second system is also under development for the High Energy Density (HED) Beamline on the European XFEL project, jointly funded by the UK STFC and EPSRC. In this paper we will provide initial performance results from DiPOLE100, with particular emphasis on the active temporal and spatially-shaped front end, intermediate 10 J cryogenic amplifier and the main 100 J cryogenic power amplifier, and a progress update on delivery of the complete system to HiLASE scheduled for the second quarter of 2015.

9513-2, Session 1

High-energy picosecond hybrid fiber/crystal laser for thin films solar cells micromachining

Jean-Bernard Lecourt, Multitel A.S.B.L. (Belgium); Simon Boivinet, Multitel ASBL (Belgium); Anthony Bertrand, Didier Lekime, Yves Hernandez, Multitel A.S.B.L. (Belgium)

We report on a hybrid fiber/crystal ultra-short pulsed laser delivering high pulse energy and high peak power in the picosecond regime. The laser is composed of a mode-lock fiber oscillator, a fiber pulse picker and subsequent fiber amplifiers. The last stage of the laser is a single pass Nd:YVO4 solid-state amplifier.

The fiber oscillator is a mode-locked Fabry-Perot cavity for which the mirrors are a 1064 nm FBG (reflectivity = 80%, spectral bandwidth = 0.5 nm) and a high contrast SESAM (modulation depth = 54%, relaxation time = 10 ps). The oscillator delivers stable pulse train at a repetition rate of 45 MHz. The pulse duration is 5 ps and the average output power is 3 mW. The optical pulses are then stretched by a chirped FBG to 25 ps. A first fiber amplifier increases the average power to about 100 mW. An acousto-optic modulator based pulse-picker is used for decreasing the repetition rate down to 50 kHz. This latter also induces an overall 33 dB reduction of the average laser signal. Then, a second fiber amplifier is added in order to increase the average output power to about 10 mW which is required for an efficient operation in the crystal amplifier. The Nd:YVO4 amplifier is pumped with 808 nm multimode laser diodes delivering 60 Watts of average output power. The output power is 5,27 Watts corresponding to 105 µJ pulse energy and 4,21 MW peak power.

The achieved laser benefits from the advantages of fiber technology that can efficiently lead to environmentally stable ultra-short sources in a very compact way; and solid-state technology with Nd:YVO4 high gain crystal amplification that permits to increase the pulse energy beyond the 100 µJ level (i.e. peak power higher than 4 MW) where optical fibers cannot operate properly because of the induced optical nonlinearities. We believe that this combination of both technologies is a very promising approach for making efficient, compact and low cost lasers compatible with industrial requirements. This laser will be integrated in an ablation system dedicated to the processing of thin film solar cells in the frame of the EU project LASHARE-FPCS.

9513-3, Session 1

Amplification of picosecond pulses to 100 W by an Yb:YAG thin disk with CVBG compressor

Martin Smrz, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Michal Chyla, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Ondrej Novák, Taisuke Miura, Akira Endo, Tomás Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

We report on a progress in development of 100-kHz high average power picosecond disk lasers with high output beam quality at the Hilase centre. Although thin disk lasers are promising technology to provide such an output, thermal management is one of the key issues at high power operation. Industrial applications also require acompact and robust system for long-term stable operation. We adopted zero-phonon line (ZPL) pumping, which is an effective solution to reduce thermal load in gain media, and compression of high-power pulses by a chirped-volume Bragg grating (CVBG) with diffraction efficiency reaching almost 90%. By means of such a 100kHz Yb:YAG CPA regenerative amplifier pumped at 969-nm, millijoule-level picosecond pulses in almost diffraction limited Gaussian beam (M2 = 1.2) have been generated.

The amplifier was seeded by an Yb-doped fiber oscillator providing a 50-MHz train of pulses supporting bandwidth limit bellow 100-fs. Although the spectrum was clipped during pulse stretching and following amplification process, the bandwidth of the amplified pulses still supported pulse compression bellow 1-ps. We employed a pulse stretcher and compressor based on a highly dispersive chirped volume Bragg grating. It allows designing of an easy-to-align robust device (8x8x20-mm compressor dimensions) in comparison with a conventional gratings-based pulse stretcher and compressor for ultrashort pulses. Using CVBG supports stretching and compression of a Fourier transform limited sub-picosecond pulse with high net efficiency exceeding 88%. We managed to recompress amplified pulses to 1.8-ps. To our knowledge, pulse compression of 100-W of average power by a CVBG with 88% diffraction efficiency is the highest power value at this moment. Despite high thermal load of the grating we have not observed any distortions of beam profile.

A standing wave cavity of the amplifier comprises of a single laser head in position of a turning mirror with a 7% Yb doped 220-um thick YAG disk, several spherical mirrors, and a BBO Pockels cell. The cavity was designed so that a fundamental mode beam was obtained with a pump spot size of 2.7-mm. The amplifier operated with 20% optical efficiency but latest experiments show that it can be increased up to 30% in a short time. A fiber-coupled diode pump source can deliver 0.5-kW of CW radiation at 969-nm. The narrow bandwidth, which is required for the efficient

pumping at 969-nm, was guaranteed by VBG stabilization of the diodes. Since the fiber coupling of a pump source allowed its easy substitution by a 940-nm pump, we also carefully studied advantages of the ZPL pumping.

In summary, we built a millijoule-level Yb:YAG ZPL-pumped regenerative amplifier operating at 100-kHz. A compact CVBG compressor was used in that setup and successful compression of the output beam back to 1.8-ps was demonstrated. By the time of the conference we will also demonstrate design and first results of a multi-hundred-watt upgrade of this amplifier.

This work benefitted from the support of the Czech Republic's Ministry of Education, Youth and Sports to the HiLASE (CZ.1.05/2.1.00/01.0027), DPSSLasers (CZ.1.07/2.3.00/20.0143), and Postdok (CZ.1.07/2.3.00/30.0057) projects co-financed from the European Regional Development Fund.

9513-4, Session 1

High average power picosecond and nanosecond laser operating at 1342nm wavelength

Aleksej M. Rodin, Ctr. for Physical Sciences and Technology (Lithuania); Mikhail Grishin, Andrejus Michailovas, Ctr. for Physical Sciences and Technology (Lithuania) and EKSPLA UAB (Lithuania)

We demonstrate results of design and optimization of high average power picosecond and nanosecond laser operating at 1342 nm wavelength. Comprised of mode-locked master oscillator, regenerative amplifier and output pulse control module this laser is suitable for variety of applications ranging from selective processing of thermo-sensitive materials such as scribing of thin film CIGS to photodynamic therapy. Passively mode-locked by means of semiconductor saturable absorber (SESAM) and pumped with 808 nm wavelength Nd:YVO4 master oscillator emits ~10 ps pulses at repetition rate of 55 MHz with average output power of ~140 mW. The four-pass confocal delay line with image relay forms a longest part of the oscillator cavity in order to suppress thermo-mechanical misalignment. Optimization of the intracavity pulse fluence ensures significant lifetime improvement for the SESAM. This oscillator was used as the seeder for regenerative amplifier based on composite diffusion-bonded Nd:YVO4 rod pumped with 880 nm wavelength. Without seeding the regenerative amplifier transforms to electro-optically cavity-dumped Q-switched laser producing ns pulses at high repetition rates with nearly difraction limited beam quality. When operating at 300 kHz the laser delivers ns or ps pulses with average power of up to 10 W at 1342 nm allowing efficient conversion to 671 nm and 447 nm harmonics.

9513-5, Session 1

Design and experiment research of a helium gas cooled Yb:YAG laser

Xin-ying Jiang, China Academy of Engineering Physics (China)

Inertia fusion energy(IFE) is recognizwed as a clean energy. IFE put forward new and higher technology requirements of solid state laser drivers. The thermal effect is a key technology problem which must be solved. In this paper, a helium gas cooled laser head was designed, the thickness of laser medium was 5mm,and the highest vel velocity of gas flow was 115m/s. The flow velocity and surface heat transfer coefficient were simulated by FLUENT. The results shown that the gas flow near the laser medium and in the expansion section was laminar flow and the distribution along the medium was uniform. The result also shown that the heat transfer efficient can reach the request of the temperature deficit of the inner and the outflow lower than 2K.The thermal wavefront aberration of laser medium which was pumped by 20kW diode laser was measured. The laser medium was Yb:YAG ceramic which was 5mm in thickness and 35mm in diameter. The experimental results shown that the increment of aberration from the 10Hz pumping was 0.04?(?=1030nm).

9513-6, Session 2

Full ASE characterisation of high-power laser-systems with various laser materials: a comparative study *(Invited Paper)*

Sebastian Keppler, Jörg Körner, Alexander Sävert, Marco Hornung, Hartmut Liebetrau, Joachim Hein, Malte C. Kaluza, Friedrich-Schiller-Univ. Jena (Germany)

The temporal intensity contrast (TIC) is one of the most crucial parameters of relativistic laser-plasma experiments. Intense prepulses as well as a continuous pedestal of energy generated by amplified spontaneous emission (ASE) can alter the target properties significantly leading to a significantly modified laser-plasma interaction or even the complete suppression of an intended acceleration mechanism.

For this reason the ASE of the POLARIS [1] system, operational at the Helmholtz-Institute Jena and the University Jena, was characterized with a dynamic range of 18 orders of magnitude as well as in a temporal range from -10ms≤t≤10ms [2]. Due to the non-saturated operation of the different amplifiers of the fully diode-pumped POLARIS, the ASE contributions of each amplifier could be measured separately. From this measurement it was determined that the main part of the ASE originates from the first regenerative amplifier. With a newly developed double CPA –frontend including a non-linear temporal cleaning via XPW [3] it was possible to decrease the TIC to a relative level of 2?10^(-13).

Furthermore, we have developed a theoretical model based on the material properties of the gain medium which describes the total ASE level of high-power laser system [4]. Comparative ASE measurements performed at the POLARIS (Yb:glass, P_0=100 TW) and the JETI200 (Ti:Sa, P_0=200 TW), are in a very good agreement with this model. Subsequently, we will compare different laser materials suitable for high-power performance in terms of the achievable ASE contrast which is important for the design and modelling of high-power laser-systems with respect to specific applications.

Finally, since cryogenic cooling is a promising possibility for increasing the efficiency we present the ASE scaling for different temperatures of operation from 80K≤T≤340K for Ti:Sa, Yb:glass and Yb:CaF2.

References:

[1] Hornung M., et al. „The all-diode pumped laser system Polaris – an experimentalist's tool generating ultra-high contrast pulses with high energy", High Power Laser Sci. Eng. 2 e20 (2014).

[2] Keppler S., et al. „Full characterization of the amplified spontaneous emission from a diode-pumped high-power laser system", Opt. Express 22, 11228-11235 (2014).

[3] Liebetrau H., et al. „Ultra-high contrast frontend for high peak power fs-lasers at 1030nm", Opt. Express 22, 24776-24786 (2014).

[4] Keppler S., et al. in preparation

9513-7, Session 2

Alignment method of a four-grating compressor for the petawatt-class PEARL-X laser system

Ivan V. Yakovlev, Institute of Applied Physics (Russian Federation)

Successful operation of high-power laser systems based on chirped pulse amplification and optical parametric chirped pulse amplification (?????) is impossible without perfect fitting of dispersion characteristics of stretchers and compressors. Improvement of methods for their alignment allows advancing to regions of shorter pulses and higher laser radiation power.

Beams with a diameter of tens of centimeters are used in high-power laser systems and accuracy of angular alignment of compressor gratings is demanded to be units of arc seconds. Improperly aligned gratings lead to increased duration, worse intensity contrast and pulse front tilting.

We present an original method of aligning a four-grating compressor of optical pulses developed for the multipetawatt laser OPCPA complex PEARL-X under construction at IAP RAS. The alignment method was successfully used in the compressor of the petawatt laser system FEMTA created earlier at RFNC-VNIIEF jointly with IAP RAS.

The considered alignment method is based on a specially designed optical scheme as well as on an original diffraction grating unit with a glass adjusting cube with pairwise parallel opposite polished faces.

At the preliminary stage the working planes and the direction of compressor grating grooves were aligned parallel to the vertical axes of their rotation. Then using a CW diode laser beam matched with the signal path the position of the first grating and the direction of the input radiation beam incident on it were aligned.

A focusing system with a CCD camera was placed in the beam mirror-reflected by the first grating. The complementary mirror moved by a translator was fixed strictly parallel to the surface of the first grating in a certain calculated position of the beam reflected by the second grating. As a result, two images of far field of two beams: incident on the first grating and reflected from the second grating were observed on the CCD. Given equal densities of grating grooves and parallel vertical axes of rotation, matching of the reference points unambiguously implied parallel planes and grooves of the first and second gratings. The third and fourth gratings were aligned analogously.

All optical elements of the compressor, including auxiliary optics, were remote controlled by a computer. Geared stepper motors ensured accuracy of rotations and movements of units of arc seconds and micrometers. Note that digital image processing may enhance alignment accuracy by more than an order of magnitude and provide subsecond measurement accuracy.

Final alignment of the compressor was performed using broadband radiation. The residual angular dispersion was controlled by an imaging spectrograph. The duration of the output pulses was measured by a single-shot autocorrelator. The duration was minimized by parallel shifting of the gratings by means of translators.

9513-8, Session 2

Current status of the PEnELOPE-project

Markus Loeser, Daniel Albach, Fabian Röser, Mahias Siebold, Harald Nehring, Gunter Harzendorf, Igor Tysbin, Ulrich Schramm, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

We present an overview of the current status of the PEnELOPE project (Petawatt, Energy-Efficient Laser for Optical Plasma Experiments) at the Helmholtz-Zentrum Dresden - Rossendorf. The system comprises five diode-pumped laser amplifier stages each utilizing Yb3+:CaF2 as gain medium. The first 3 amplifier stages use an active mirror approach, while amplification to the 10 J and 150 J level employs a transverse He-gas flow between multiple laser slabs.

With increasing energy, pump powers range from several Watts for the first amplifiers to 80 kW for the 10 J stage and a total pump power of 1.2 MW for the final amplifier. The pump is hereby guided co-linearly in double-pass configuration from both sides of the laser medium. A hexagonally shaped homogeneous pump profile ensures a good overlap with the circular laser beam at up to 12 passes. A fully image relayed extraction setup relying on reflective optics minimizes B-integral build-up and allows for wave front correction, as well as depolarization loss compensation for each multi-pass amplifier.

Both amplifiers are operated under vacuum condition. This ensures protection against contamination, dust particles, beam fluctuation due to turbulences as well as air break down within the focal range of the imaging telescope setup.

The stretcher-compressor setup for such a PW-class high energy laser is a challenging task, in view of laser induced damage issues and temporal pulse shape control. The stretcher yields a temporal elongation factor of 213 ps/nm in an 8 pass configuration and thus delivers up to 10 ns long pulses for the following amplifiers. Amplified pulses are recompressed in a 21 m? large vacuum chamber holding 940x420 mm? sized gratings and final adaptive optics, enabling optimum pulse conditions in the target area. Stretcher and compressor are designed for a 50 nm hard-clip bandwidth. The transfer efficiency of the compressor is estimated to be more than 80 %.

We will present experimental data for the first three laser amplifiers. First results for the stretcher system are presented. Furthermore we will focus on design and setup of the final two amplification stages.

9513-9, Session 2

Multi PW laser design for the SHENGUANG II laser facility

Xinglong Xie, Jianqiang Zhu, Qingwei Yang, Haidong Zhu, Jun Kang, Ailin Guo, Ping Zhu, Shanghai Institute of Optics and Fine Mechanics (China)

The National laboratory on High Power Laser and Physics in china is now undergoing a 5 PW project which is expected to be finished at the end of 2015 by using SHENGUANG II laser facilities. In the project, OPCPA technology is used in the design of the laser as one beam of SG-II and the 9th beam of SG II are used as the pump source for the last two OPCPA stages (OPCPA II and OPCPA III). and the final energy of uncompressed laser pulse (800nm) can achieve 260J, We are expected to obtain a compressed pulse with energy 150J and pulse width about 30fs. The presented paper introduces the details of the design and some discussions are given to the related critical problems such as SN contrast ratio as well as the beam quality control etc.

9513-10, Session 2

Timing jitter measurement and stabilization of mode-locked ytterbium fiber laser

Jakub Mesicek, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Jens Linnemann, Martin Smrz, Taisuke Miura, Akira Endo, Tomás Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Development of highly stable fiber laser oscillators for seeding of power amplifier chains has been started in the Hilase centre. Our concept is based on the all-normal-dispersion (ANDi) scheme. Mode-locking in this kind of lasers is maintained by reaching balance between self-phase modulation and dispersion in an optical fiber. Our system delivering 1.9 nJ in 1.5-ps long pulses (20-nm bandwidth) operated at 47-MHz repetition rate. However, phase noise and jitter in pulse period make it difficult to use them in future applications when synchronization with a high frequency electron source is essential. In this paper, we report on characterization and suppression of a timing jitter of the oscillator.

Long-term drift in a pulse period is a major obstacle in this laser oscillator. Because of its narrow bandwidth the widely used spectral measurement technique proposed by von der Linde is inaccurate in that case. In the first approximation we just need to measure repetition rate of the oscillator with high accuracy. A highly accurate frequency counter with rubidium time base has been adopted for this purpose. The counter is capable of measuring frequencies up to 20-GHz and detect single shot signals with 100-ps resolution. For detection of the laser output, we use a fast InGaAs photodiode with rise/fall time shorter than 25-ps, which corresponds to the bandwidth of >15-GHz. Repetition rate of our laser oscillator was measured for one hour. We evaluated obtained data and found that its repetition rate was drifted up to 3.7-MHz. This is equivalent to a timing change of 1.8-ns. This relatively large timing drift is primarily caused by thermal expansion and nonlinear refractive index change of the fiber.

We are developing a compensation mechanism of this timing drift. After suppression of the timing drift, we are going to use a fast digital lock-in amplifier operating in the frequency range up to 600MHz. Since the lock-in-amplifier can provide amplitude fluctuations and the phase fluctuations independently, we can analyze remaining timing jitter of the oscillator precisely. Also, the phase fluctuation data can be applied as a timing error signal of a feedback loop of a jitter stabilization system. Details of timing jitter measurement and a stabilization system will be presented.

This work benefitted from the support of the Czech Republic's Ministry of Education, Youth and Sports to the HiLASE (CZ.1.05/2.1.00/01.0027), DPSSLasers (CZ.1.07/2.3.00/20.0143), and Postdok (CZ.1.07/2.3.00/30.0057) projects co-financed from the European Regional Development Fund.

9513-11, Session 3

Industrial mJ-class all-fiber front end with spatially coherent top-hat beam output used as seeder for high-power laser *(Invited Paper)*

Jean-François Gleyze, Pierre Calvet, Pierre Gouriou, Florent Scol, Commissariat à l'Énergie Atomique (France); Constance Valentin, Géraud Bouwmans, Univ. des Sciences et Technologies de Lille (France); Emmanuel Hugonnot, Commissariat à l'Énergie Atomique (France)

In large scale laser facility dedicated to laser-matter interaction including inertial confinement fusion, such as LMJ or NIF, high-energy main amplifier is injected by a laser source in which the beam parameters must be controlled. For many years, the CEA has developed nano-joule pulses all-fiber front end sources, based on the telecommunications fiber optics technologies. Thanks to these technologies, we have been able to precisely control temporal shaping and phase-modulated pulse. The limitation of our LMJ system, which has been implemented since years, is the very low energy per pulse.

Nowadays, fiber lasers are able to deliver very high power beams and high energy pulses for industrial needs (laser marking, welding,...), for laser-biological tissues interactions, and much more. This new fiber laser technology has a great potential to improve stability and versatility of high-energy system front-end.

Therefore, we have currently developed new nanosecond pulses fibered amplifiers able to increase output pulse energy up to the mJ level. These amplifiers are based on flexible fiber and not on rod type. This permits us to achieve a compact design. This amplifier allows the generation of multi-kHz nanosecond pulses with accurate tailored temporal pulse profiles.

For this first industrial demonstration we decide to use LMJ nano-joule source as a seeder for a two stage amplifier. The seed pulses from LMJ source are amplified in a preamplifier to achieve ?J pulse energy. Then pulses are launched inside the energy fiber amplifier. We finally obtained a strictly single mode beam, narrow-bandwidth, multi-kHz nanosecond pulse amplification at mJ level, with more than 50 dB optical signal-to-noise ratio, 15 dB polarization extinction ratio and sub-nanosecond resolution temporal shaping.

Further large-scale laser facility requires a spatially coherent beam with a good quality and therefore single-mode fibers have to be used to deliver the beam. Nevertheless the intensity profile of theses fibers usually has a Gaussian shape. To be compatible with main amplifier section injection, the Gaussian intensity profile must then be transformed into 'top-hat' profile. To reach the goal, we have recently developed an elegant and efficient solution based on a single-mode fiber which directly delivers a spatially coherent 'top-hat' beam. Thanks to this fiber, a mJ-class top-hat all-fiber laser system has then been achieved. In the conference, we will present this system, the results and the industrial prototype which can be used as a front-end of high-power lasers or as a seeder for other types of lasers.

9513-12, Session 3

Ultrahigh contrast seed pulses for a petawatt-scale diode-pumped solid state laser

Hartmut Liebetrau, Marco Hornung, Andreas Seidel, Sebastian Keppler, Joachim Hein, Malte C. Kaluza, Friedrich-Schiller-Univ. Jena (Germany)

The knowledge and control of the temporal evolution of the pulse's intensity turned out to be a crucial parameter for successfully performing experiments with high-intensity laser pulses, as produced by the Petawatt-class, all-diode-pumped solid state laser system POLARIS [1] at the Helmholtz Institute in Jena.

By implementing a double – chirped pulse amplification (DCPA) architecture to the frontend of the POLARIS laser system and subsequent nonlinear filtering, we present a reduction of the relative intensity of the amplified spontaneous emission by more than four orders of magnitude [2].

The DCPA scheme is implemented by adding an Öffner-type stretcher, which temporally stretches the 100-fs oscillator pulses to 20 ps, enabling these pulses to be amplified to 3 mJ in a regenerative amplifier. Before the pulses can be filtered, they are recompressed to 112 fs by a grating compressor. The nonlinear filtering is achieved by using crossed-polarized wave generation (XPW) in a BaF2 holographic-cut crystal, completing the first CPA-stage. This filtering process leads to pulses with energies exceeding 100 µJ with an internal conversion efficiency of at least 12%, which then can be further amplified to the Joule-level by the nanosecond-CPA.

The nonlinear filtering process leads to a reduction in pulse duration as well as an enhanced temporal intensity contrast. The temporal intensity profile of the filtered pulses was measured using a 3rd order cross-correlator (Sequoia, Amplitude Technologies) and a photodiode. The relative intensity approaches 10-10 at around 50 ps before the main pulse, dropping below the detection limit of the correlator. The photodiode measurement yields a final relative intensity of 2?10-13, which, to the best of our knowledge, is the lowest ASE level achieved with a high-energy diode-pumped solid state laser system reported so far.

References:

[1] M. Hornung et al., Polaris - an experimentalist's tool generating ultra-high contrast pulses with high energy," High Power Laser Sci.Eng.2, e20 (2014)

[2] H. Liebetrau et al., "Ultra-high contrast frontend for high peak power fs-lasers at 1030 nm," Opt. Express 22, 24776-24786 (2014)

9513-13, Session 3

Reliable pump sources for high-energy class lasers

Martin Wölz, Agnieszka Pietrzak, JENOPTIK Diode Lab GmbH (Germany); Alex Kindsvater, Jürgen Wolf, Jens Meusel, Jenoptik Laser GmbH (Germany); Ralf Hülsewede, Jürgen Sebastian, JENOPTIK Diode Lab GmbH (Germany)

High-energy class laser systems operating at high average power are destined to serve fundamental research and commercial applications. System cost is becoming decisive, and JENOPTIK supports future developments with the new range of 500 W laser diode bars. In response to different strategies in implementing high-energy class laser systems, pump wavelengths of 808 nm, 880 nm, and 940 nm are available. The higher power output per chip increases array irradiance and reduces the size of the optical system, lowering system cost.

We explain the development path of the new range of high power diodes, and present the latest reliability testing data. At the time of submission, the 880 nm laser diode bar has been tested to 0.6 Gshots at 500 W and 300 µs pulse duration. Parallel operation in diode stacks will be discussed. At this time, 4 kW pulse power operation from eight-bar stacks emitting at 880 nm and 940 nm has been shown.

A new high-density conduction-cooled package for the semiconductor lasers is under development at JENOPTIK. Cost and reliability being the design criteria, the diode stacks are made by simultaneous soldering of submounts and insulating ceramic. The new QCW stack assembly technology permits an array irradiance of 12.5 kW/cm?. We present the current state of the development, including laboratory data from prototypes using the new 500 W laser diode in dense packaging.

9513-14, Session 3

Multifunctional lens arrays for beam shaping and pump sources

Thomas Mitra, Udo Fornahl, Manfred Jarczynski, Jens Meinschien, Lutz Aschke, LIMO Lissotschenko Mikrooptik GmbH (Germany)

High power diode lasers as pump sources as well as large aperture optics can be simplified by multifunctional lens arrays.

This paper focusses on reducing the number of components and surfaces by multifunctional optical elements and lens arrays. Pump sources are simplified by new monolithic coupling lens-arrays for laser-bars. They combine collimation and focusing functions in one single part. In combination with laser-diode-stacks the number of components for a pump source can be reduced by about three orders of magnitude. With the combination of collimation and homogenization in one lens or combination of homogenization and focusing the number of surfaces can be reduced. The unique and scalable wafer-based production technology of LIMO with today up to 350x350mm? wafer sizes allows mass-produced micro-optics as well as large aperture optics made of glass or CaF2 for instance. Methods are shown how to further increase the current production capabilities of already world leading millions of lenses per year by improved measurement strategies and new surface-descriptions.

Beam shaping by means of monolithic micro optics lens arrays is a very efficient and comfortable approach to match the beam properties of laser sources to the requirements of various applications.

9513-15, Session 3

AlGaInN laser diode bar & array technology for high power and individual addressable applications

Stephen P. Najda, Piotr Perlin, TopGaN Ltd. (Poland); Tadek Suski, Institute of High Pressure Physics (Poland); Lucja Marona, Michal Bockowski, Mike Leszczynski, Piotr Wisniewski, Robert Czernecki, Robert Kucharski, Grzegorz Targowski, TopGaN Ltd. (Poland)

The AlGaInN material system allows for laser diodes to be fabricated over a very wide range of wavelengths from u.v., ~380nm, to the visible ~530nm, by tuning the indium content of the laser GaInN quantum well, giving rise to new and novel applications for medical, industrial and scientific purposes. Ridge waveguide laser diode structures are fabricated to achieve single mode operation with high optical powers of >100mW with high reliability. We demonstrate the operation of a single chip, high power AlGaInN laser diode 'mini-array' consisting of a 3 stripe common p-contact configuration at powers up to 2.5W cw in the visible wavelength range. Low defectivity and highly uniform GaN substrates allow arrays and bars of nitride lasers to be fabricated. Laser bars with up to 20 emitters have shown optical powers up to 4W cw at ~395nm with a common contact configuration. These bars are suitable for optical pumps and novel extended cavity systems. An alternative package configuration for AlGaInN laser arrays allows for each individual laser to be individually addressable allowing complex free-space and/or fibre optic system integration within a very small form-factor.

9513-16, Session 3

AOM optimization with ultra stable high power CO2 lasers for fast laser engraving

Markus Bohrer, Dr. Bohrer Lasertec GmbH (Austria)

A new ultra stable CO2 laser in carbon fibre resonator technology with an average power of more than 600 watts has been developed especially as basis for the use with AOMs. Stability of linear polarisation and beam pointing stability are important issues as well as appropriate shaping of the incident beam. AOMs are tested close to the laser-induced damage threshold with pulses on demand close to one megahertz. Transversal and rotational optimization of the AOMs benefits from the parallel-kinematic principle of a hexapod used for this research. Recent measurements from the lab are compared with theory and the use for many applications in daily life is shown - starting from high speed engraving for dry offset printing to highly sophisticated banknote printing.

9513-17, Session 4

Large aperture adaptive optics for intense lasers *(Invited Paper)*

François Deneuville, Laurent Ropert, Paul Sauvageot, Sébastien Theis, ISP System (France)

Large aperture adaptive optics for intense lasers

ISP SYSTEM has developed a deformable mirror compatible with UHV environment, suitable for ultra short pulsed lasers with beam diameters from 22mm to 800mm. The aim of the development was to bring to the market a deformable mirror with very large aperture for intense lasers at reasonable price. The deformable mirror should have a very good resistance to electro-magnetic pulses, a very good linearity, a very low hysteresis and should avoid any print through effect in order to be able to reach a Strehl ratio higher than 0.9.

The principle of the deformable mirror is based on force application on numerous locations. μ-AME actuators are driven by stepper motors, and their patented astatic special design allows controlling the force with a very high accuracy and avoiding generation of parasite forces on the membrane, it reduces significantly the print through effect. The consequence is that the cost for components, assembly and electronics remains reasonable, even for large diameters. The assembly is performed in clean room environment and materials used in the mirror are chosen in order to be compatible with UHV environment.

A big challenge of this large aperture adaptive optics was to design and manufacture a membrane with the right stiffness and the right flatness. It must be stiff enough for manipulation and to limit the impact of gravity on flatness if the mirror is used in horizontal and vertical positions. A high stiffness facilitates also the polishing process. On contrary the mirror cannot be too stiff so that it is possible to reach a sufficient correction dynamics with a reasonable force actuator. The right substrate and thickness were defined thanks to finite elements simulations and thanks to a strong cooperation with membrane supplier.

Optical aberrations up to Zernike order 4 (excluding piston) can be corrected. Hysteresis is lower than 0.1% and linearity better than 99%. Contrary to piezo-electric actuators, the irreversibility of μ-AME actuators permits to keep the mirror shape stable even unpowered, electro-magnetic pulses generated by intense lasers have no impact on mirror shape. This avoids also some hotspots in case there is a power failure of deformable mirror. After first correction loop it is only necessary to adjust mirror shape (by applying a correction loop) to compensate the deformations that could occur due to thermal drift. The correction strategy avoids also hot spots even for corrections performed during laser shots.

The deformable mirror design allows changing easily an actuator or even the membrane if needed. Maintenance tools have been developed so that the end-user can replace himself the membrane by another spare paired membrane, in order to improve the system availability.

It is designed for circular, square or elliptical aperture from 22mm up to 600mm or more, with incidence angle from 0° to 45°. They can be equipped with passive or active cooling for high power lasers with high repetition rate.

MD-AME mirrors are compatible with all dielectric or metallic coatings that are feasible by coating suppliers for such large aperture membranes.

9513-18, Session 4

Alignment system for high-power large aperture laser systems

Roberto Ziano, Jean-Baptiste Accary, Birgit Ploetzeneder, Roberto Versaci, Bruno LeGarrec, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

We will be giving an overview on the development of the "ELI-beamline facility" [1] built within the Extreme Light Infrastructure (ELI) project based on the European ESFRI (European Strategy Forum on Research Infrastructures) process.

ELI-Beamlines will be a high-energy, repetition-rate laser pillar of the ELI (Extreme Light Infrastructure) project [2]. It will be an international facility for both academic and applied research, slated to provide user capability since the beginning of 2018. The main objective of the ELI-Beamlines Project is delivery of ultra-short high-energy pulses for the generation and applications of high-brightness X-ray sources and accelerated particles. The laser system will be delivering pulses with length ranging between 10 and 150 fs and will provide high-energy Petawatt and 10-PW peak powers. For high-field physics experiments it will be able to provide focused intensities attaining above 1022 Wcm2, while this value can be increased in a later phase without the need to upgrade the building infrastructure to go to the ultra-relativistic interaction regime in which protons are accelerated to energies comparable to their rest mass energy on the length of one wavelength of the driving laser. The alignment of the high power lasers is an essential operation to be performed before shooting. The critical part of the alignment procedure is to define the references for the alignment. The most common procedure is to insert a cross shaped mask into the beam path. The centre of the cross defines the optical axis. A semi automatic procedure is used in many facilities due to difficulties to automate this procedure. During the procedure an operator has to interact with the alignment system. The purpose of this work is to present how to use fibre coupled light source as references for a fully automated alignment system.

References

[1] Web page of ELI (http://www.eli-beams.eu).

[2] G. Mourou, G. Korn,W. Sandner, and J.L. Collier. ELI - Extreme Light Infrastructure: Science and Technology with Ultra-Intense Lasers Whitebook, 2011.

9513-20, Session 4

Thermally induced depolarization in the optical elements of the transition configuration

Aleksey V. Starobor, Oleg V. Palashov, Institute of Applied Physics (Russian Federation)

Currently, in solid-state laser systems with high average power optical elements (OE) with different shapes and different ways of the cooling design are widely used. Rod-shaped OE (length of element is much larger than its diameter) with side cooling is a classical and widely used solution. Other common example is the disk-shape OE (length is much smaller than the diameter) with an end-face cooling.

However, there are many other OE configurations, which we call "transition", which are not described in these expressions, but are used in high power lasers. For example, in disk lasers "sandwich" active elements are used in order to reduce amplified spontaneous emission. Sandwich structure consists of doped disc with undoped ends, so whole OE can't be consider as a thin, the sandwich structure is also used to reduce temperature gradients in the cryogenic Faraday isolators. For the transmission OE side cooling is relevant. Increasing the magnetic field of magnetic systems and using of new magnetooptical media in the case of Faraday isolators operate at room temperature leads to conversion of MOE to thick disks with side cooling. It is logical to call them "short rods".

In this work we investigate the behavior of thermally induced depolarization in the practically important cases of "transition configuration" of the OE, when the length of the OE is less than or comparable to its diameter, for both side and end-face cooling.

Dependence of thermally induced depolarization on the diameter of the laser beam and the ratio of the length of the optical element to its diameter is investigated experimentally and numerically. The conditions under which the thermal depolarization depends on the diameter of the beam for end-face and side cooling are determined. Numerical modeling is supported by experimental results obtained on terbium-gallium garnet crystal and magnetooptical glass MOG-04 samples.

We studied the dependence of the thermally induced depolarization on the aspect ratio of the length of optical element to its diameter for lateral cooling. It was shown that the depolarization is reduced (1-?)2 times during the transition from long rod to a short, thereby dividing the cylindrical element into several short rods can reduce depolarization (1-?)2 times without complicating heat removal system. It should be noted that such configuration is relevant today for FI built on powerful magnetic systems.

There have also been investigated the thermally induced depolarization dependence on the beam diameter in the element, the thickness of which is comparable with its diameter. It is shown that with the side cooling depolarization also depends on the diameter of the beam, decreasing by 20% while increasing the beam diameter. With the end-face cooling depolarization will be reduced by more than 10 times if the diameter of the beam is increasing from minimum to the maximum possible.

The numerical model gives a good agreement between the calculated values, experimentally measured and obtained analytically, which makes reliable using it in the calculation of more complex optical elements, such as sandwich structures.

9513-45, Session 4

High reflective diffraction grating for ultrafast pulse compression

Galina Kalinchenko, Stepan Vyhlidka, Daniel Kramer, ELI Beamlines (Czech Republic); Alexander Lerer, Southern Federal Univ. (Russian Federation); Bedrich Rus, ELI Beamlines (Czech Republic)

A diffraction grating based on all-dielectric multi-layer structure is designed for compression of ultrafast pulses with spectrum centered at 900 nm. The grating at Littrow angle with an off-plane configuration shows more than 95% efficiency over the reflective band of 100 nm for the angle of incidence 41 degrees. We suggest grating grooves and the very first layer under the grooves to be made of fused silica. Reflective mirror under corrugated layer is designed as a stock of three types of dielectric nanolayers. Tolerances for groove depth and angle of incidence are estimated, optimal duty-cycle parameter is found out. Electric field distribution inside of the grating is also numerically studied. The model is simulated by two methods: numerical Fourier Modal Method in LightTrans Virtual Lab and semi-analytical Volume Integral Equation Method. The results obtained by both methods show excellent agreement.

9513-47, Session 4

Isolation of the amplifier cavity from retro-reflected laser pulse by the target for XG-III PW beamline

Jun Zhang, Jian-Gang Zheng, Xiong-jun Zhang, Jingqin Su, Wanguo Zheng, China Academy of Engineering Physics (China)

The XG-III laser facility is constructed for intense laser-matter interaction research. One beamline of this facility delivers 300J~500J, 650fs~10ps width adjustable, pettawatt-class laser pulse to the target. In this short-pulse system, the OPA front-end seed is amplified by two-stage OPCPAs, then boosted to hundreds of joules by the four-pass flashlamp pumped Nd: glass amplifier, and then compressed back to short pulse. The laser pulse is not frequency converted before being transferred to the target. Therefore, any light reflected by the target would experience gain as it propagates back through the Nd: glass gain-medium. Because the stored energy in Nd:glass slabs are unsaturatedly extracted, as well as its long fluorescence time of Nd:glass, a reflected pulse can acquire high gain, arising a significant threat of the system damage, thus requiring isolation of the amplifier cavity from retro-reflected laser in this system.

The XG-III PW beamline will be introduced briefly. Then we will analyze the polarization evolvement, propagating and amplifying process of the retro-reflected laser pulse, and damage threat to the laser system. Finally, give emphasis to the scheme of retro-reflected laser isolating and the isolation effect. A large aperture Pockels cell (PC), placed in front of the compressor, is used to control the polarization of the main laser pulse and the retro-reflected laser pulse. The PC is activated before the main laser pulse arrives, whereas it is switched to its unenergized state before the retro-reflected laser pulse comes. The unwanted retro-reflected laser can, therefore, be diverted from the main light-path by analyzer. Because the bandwidth of the main laser pulse will narrow dramatically while passing through large aperture thin film polarizers, the compressing gratings and Brewster angle placed Nd: glass slabs are used as PC's polarizer and the analyzer respectively, offering a 103 isolating ratio.

9513-48, Session 4

A new method of optical transmittance and birefringence uniformity measurement with coherent heterodyne detection

Jie Miao, Shanghai Institute of Optics and Fine Mechanics (China); Dongxian Chen, Pengqian Yang, Shanghai Institute of Optics and Fine Mechanics (China); Yaling Yang, Shanghai Institute of Optics and Fine Mechanics Club (China); Jie Zhang, Baoqiang Zhu, Dean Liu, Jianqiang Zhu, Shanghai Institute of Optics and Fine Mechanics (China)

The uniformity measurement, such as transmittance, reflectance and birefringence, is one of the essential specifications for those large optics of high power laser facilities. Commercial multifunction instruments for those small pieces, or specialized for one parameter for large optics, are already available. Direct measuring way is mostly adopted in such instruments. Therefore, limited by ability of photoelectrical elements, both high reproducibility for large-size and precision with wide dynamic range, make such testing a real challenge to take.

In this paper, a new method of optical transmittance and birefringence uniformity measurement with coherent heterodyne detection is proposed. Coherent heterodyne detection and optical balanced demodulation technique are employed. With the help of 2x4 optical balanced detection, transmittance and birefringence of the sample can be simultaneously obtained with this system. With a laser source at 1053nm, some tests are operated both by conventional direct detection and the testing system. The results show that this system can realize simultaneously transmittance and birefringence measurement, and advantage in its wide dynamic range.

Experimental results are analyzed and compared with conventional direct detection, and verify a promising method for higher precision during further practical applications, such as large optics and quick measurement request for uniformity.

9513-22, Session 5

Yb:Lu2SiO5 crystal : characterization of the laser emission along the three dielectric axes

Guido Toci, Istituto Nazionale di Ottica (Italy); Angela Pirri, Istituto di Fisica Applicata Nello Carrara (Italy); Alena Beitlerová, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Yasuhiro Shoji, Akira Yoshikawa, Tohoku Univ. (Japan); Jiri Hybler, Institute of Physics, Academy of Sciences (Czech Republic); Martin Nikl, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Matteo Vannini, Istituto Nazionale di Ottica (Italy)

The generation and the amplification of ultrashort laser pulses for the achievement of extreme intensity levels, as needed for high energy plasma research, for laser particle acceleration, and in perspective for the realization of the laser driven inertial confinement fusion, require laser media that can be directly pumped by diode lasers, with a high conversion efficiency of the pump power (or energy), and featuring a broad emission band.

Yb doped laser materials usually fulfill the first two requirements, but have a relatively narrow emission bandwidth that can limit their use in these applications.

In this sense, Yb-doped orthosilicates represent an interesting exception, because they features fluorescence bands and tuning ranges that are significantly broader than the majority of Yb doped materials.

This work is devoted to the characterization of the laser properties of the Yb:doped Lu2SiO5 (Lutetium orthosilicate, LSO), with emission in the range 1000-1100 nm. Lasing action from this material was demonstrated for the first time by Jacquemet et al (App.Phys B 80, 171-176 (2005). LSO is a biaxial crystal, with different absorption and emission spectra with polarization along its three optical axes (X, Y and Z), but until now laser action has been mainly reported in literature and characterized along only one of the crystallographic axes (the one conventionally labelled X).

LSO single crystal with 5% Yb doping was grown by the Czochralski method using an iridium crucible with a diameter of 100 mm, heated by induction at a frequency of 8 kHz, in a Ar gas flow. An undoped LSO single crystal was used as a seed. Pulling rate was 1 mm/hour and rotation rate was 10 rpm.

We have characterized the laser emission properties of Yb:LSO along all the three optical axis, evidencing differences that can be exploited in the design of ultrafast laser sources. The material was tested in a longitudinally pumped laser cavity using a fiber coupled laser diode with emission at 968 nm as a pump source, with a maximum pump power of 19 W. Emission with polarization along the desired optical axis was obtained by properly orienting the sample and using an intracavity fused silica plate placed at the Brewster angle. Tuning was obtained with an intracavity prism with faces set at the Brewster angle, which also acted as a polarization selector.

The laser emission efficiency was found similar along all the three optical axes, with slope efficiencies exceeding 85% in most cases.

Regarding the tuning range, for the most favourable optical axis we obtained a continuously tunable emission between 993 and 1088 nm (i.e. 95 nm) peaked at 1040 nm. The tuning curve along the three axes spanned similar ranges but with relevant differences in shape .

In a multistage pulse amplifier these differences in the gain spectral shape could be exploited to optimize the amplification process, by properly tailoring the length and orientation of the various amplification stages.

9513-23, Session 5

Tb:CaF2: new promising medium for multikilowatt-class high power Faraday isolators

Dmitry S. Zheleznov, Aleksey V. Starobor, Oleg V. Palashov, Institute of Applied Physics (Russian Federation)

Intense development of laser technique and average power enhancement of CW and pulse-periodic radiation demand reduction of thermal effects appearing in different optical elements due to laser radiation absorption. One of the devices subject to significant thermal self-action is Faraday isolator (FI) because of strong absorption (~10-3cm-1) of its magneto-optical elements (MOE). Absorption-induced inhomogeneous over cross-section temperature distribution leads to inhomogeneous distribution of the angle of rotation of polarization plane caused by temperature dependence of Verdet constant, to appearance in addition to the Faraday rotation of linear birefringence (photoelastic effect), and to distortions of the wave front of optical radiation passing through FI (thermal lens).

The depolarization caused by radiation absorption in optical elements referred to as "hot" or "thermally induced" depolarization greatly depends on the power of optical radiation and may exceed significantly the "cold' one arising due to magnetic field inhomogeneity and MOE imperfection.

Verdet constant of paramagnetic materials increases on cooling. Besides, other thermo-optical characteristics of the medium also improve with decreasing temperature. This feature was used for creation of a cryogenic FI (CFI) – a device where both MOE and the FI magnetic system are

cooled down to the temperature of boiling liquid nitrogen. Application in CFI of traditional media is not always fully justified, as parameters of a magneto-optical medium change on cooling. Consequently, with cooling to nitrogen temperatures traditional FI media (e.g., TGG crystals) may be inferior to novel ones than have not been used in CFI before.

Over the recent decade with appearance of the technologies of production new magnetooptical media the problem of development of the Faraday isolators for high average power and high pulse energy radiation seems to have new approaches for solution. In details, it is reported the research results for the new kind of magnetooptical media – calcium fluoride doped with terbium (10% at.). Great advantages of this medium as compared to the traditional one – terbium gallium garnet – is a high transparency up to 1600 nm wavelengths (makes the medium suitable for Faraday isolators for “eye-safe” range erbium lasers) and dn/dT<0 (makes the medium suitable for additional adaptive compensating of the thermally induced effects)

The medium seems to have rather good magnetooptical characteristics (Verdet constant ~ 0.24 deg/kOe?cm, but 4.5-fold increase with the liquid nitrogen cooling) and outstanding thermooptical parameter (adsorption ~10-5 cm-1), which gives the opportunity to estimate the isolation ratio of the Faraday isolator base on the investigated be as high as 30 dB at the record radiation power ~ 30kW. It should be noted, that the magnetic system, which is needed in this case, is already designed and assembled.

9513-24, Session 5

Calcium fluoride, a low n2 material for high aperture windows in high-power laser systems

Gordon von der Goenna, Thomas Toepfer, Hellma Materials GmbH (Germany)

Window material requirements for target chambers in CPA systems are defined by low dispersion, low n2 and excellent homogeneity refractive index and stress distribution.

Calcium Fluoride from Hellma Materials, available in diameters up to 440mm can be material of choice for these applications.

We report stress birefringence and refractive index homogeneity measurements of large CaF2 blanks.

The influence of large angle grain boundaries on the optical performance is discussed.

9513-25, Session 5

Graded Yb:YAG ceramic structures: design, fabrication and characterization of the laser performances

Guido Toci, Antonio Lapucci, Marco Ciofini, Istituto Nazionale di Ottica (Italy); Laura Esposito, Consiglio Nazionale delle Ricerche (Italy); Jan Hosta?a, Consiglio Nazionale delle Ricerche (Italy) and Institute of Chemical Technology (Czech Republic); Andreana Piancastelli, CNR - ISTEC National Research Council, Institute of Science and Technology for Ceramics (Italy); Leonida A. Gizzi, Luca Labate, Paolo Ferrara, Istituto Nazionale di Ottica (Italy); Angela Pirri, Istituto di Fisica Applicata Nello Carrara (Italy); Matteo Vannini, Istituto Nazionale di Ottica (Italy)

Ceramic-based materials have shown to be a competitive alternative to single crystals for solid state lasers especially in case of high power applications. The ceramic process is highly flexible in terms of feasible geometries and shapes, as well as dopant distribution control. This approach allows the implementation of technical solutions which are unfeasible or very difficult to implement with the current crystal growth and fabrication technologies.

One of the key aspects for producing high power laser sources and amplifiers based on ceramic active media is the management of the thermal effects (TEs) and thermo-mechanical effects (TMEs) (e.g. thermal lens, stress-induced depolarization, surface deformations) deriving from the laser pumping process, which degrade the performance of the laser source and can eventually lead to a catastrophic failure of the laser active element.

In this frame, we have investigated the issues related to the design, the production process and the characterization of the laser emission properties of YAG ceramic elements doped with Yb, with complex shapes and structured doping, for the mitigation of the TEs and TMEs in specific laser pumping and cooling geometries.

Regarding the fabrication, we have explored the possibilities offered by the tape casting technique used in combination with thermal compression of ceramic tapes. With this technique it is possible to assemble several tapes with a different composition, press them at a moderate temperature and after the proper thermal treatments obtain graded structures with a changing composition in one direction.

To exploit the potentialities of this process, planar structures of Yb:YAG with longitudinal distribution of Yb concentration were designed and optimized by means of simulations based on Finite Elements Analysis, for the evaluation of their thermal and thermo-mechanical behavior under various pumping and cooling configurations. The simulations show that by this approach an effective reduction of the internal thermo-mechanical stress can be obtained with respect to homogeneous structures operating in the same configuration.

The microstructure of the fabricated elements and the Yb diffusion profile across the doped/undoped interfaces have been characterized by FEG SEM and ESEM equipped with EDS.

The laser performance has been characterized under high intensity power pumping in a longitudinally diode pumped laser cavity. The laser efficiency under high thermal load conditions has been compared to that obtained from samples with uniform doping, under the same test conditions. The thermal lens effect in the various structures was characterized both in terms of imparted wavefront deformation on a probe beam (measured with a Shack-Harmann wavefront sensor) and in terms of its overall impact on the laser beam quality. Moreover, we have extensively characterized depolarization effects in the structures with uniform and graded doping under lasing and non-lasing condition, in order to size the role of different stress distributions in the differently doped structures.

9513-26, Session 5

Investigation of Yb3+-doped alumino-silicate glasses for high energy class diode-pumped solid state lasers

Jörg Körner, Joachim Hein, Mirko Tiegel, Stefan Kuhn, Joachim Buldt, Fangxin Yue, Reinhard Seifert, Andreas Herrmann, Christian Ruessel, Malte C. Kaluza, Friedrich-Schiller-Univ. Jena (Germany)

The direct generation of high peak power laser pulses using a diode pumped solid state laser is a very challenging task. Since many materials doped with Yb3+-ions offer a relatively long excited state lifetime, a low quantum defect of about 10% and an absorption band well-adapted to 9xx nm high power InGaAS laser diodes, such materials are favorable for this application. Though there are several suitable active materials for the generation and the amplification of these laser pulses up to the mJ level, most host materials are barely scalable to diameters sufficient to amplify chirped femtosecond pulses to the 100 J level and above. So far there are only few broadband host materials available in a sufficient size of several centimeters in diameter. One is Yb:CaF2 which offers a rather high thermal conductivity as it is a crystalline material. Other solutions are glasses, which in general have a very smooth spectrum for absorption and emission due to inhomogeneous broadening. While Yb:CaF2 is the material of choice for lasers aiming on high peak and high average power, glasses are favorable for ultra-high peak power lasers with low repetition rate.

The POLARIS laser system, as a facility dedicated to generate Petawatt-level laser pulses within a standard CPA-scheme, is using Yb3+ doped

fluoride-phosphate glass (Yb:FP-glass) as the active medium. Though this glass has favorable attributes such as a long excited state lifetime, the thermo-mechanical properties and the producibility have proven to be a major problem for long term operation. To find a suitable replacement for Yb:FP-glass, new laser materials based on alumino-silicate glasses were developed and characterized within the ALASKA project.

We present a detailed investigation of different compositions of alumino-silicate glasses. To generate detailed datasets for the emission and absorption cross sections the spectral properties of the materials were recorded at room temperature and in the low temperature range. It was found that the newly developed materials offer significantly higher emission cross sections at 1030 nm than Yb:CaF2 and Yb:FP-glass, resulting in a lower saturation fluence for laser extraction and therefore have a potential for higher laser extraction efficiency.

Quenching of the fluorescence lifetime on early samples was analyzed and attributed to the hydroxide (OH) concentration of the glasses. Due to special measures in the glass manufacturing, OH concentrations were lowered up to two orders of magnitude. This resulted in a significant enhancement of the lifetime and the quantum efficiency for samples doped with more than 6x10^20 ions per cm?.

First laser experiments within a tunable CW laser setup allowed for a broad tuning range of about 60 nm, which was superior to Yb:CaF2 and Yb:FP-glass in the same setup. Further measurements were carried out to compare the laser induced damage threshold (LIDT) for different coating techniques on doped substrates. Here a 1 on 1 procedure was applied.

9513-27, Session 5

A new-old laser crystal Nd:Y:CaF2 for IFE driver

Jian-Gang Zheng, China Academy of Engineering Physics (China); Liang-Bi Su, Shanghai Institute of Ceramics (China); Xin-ying Jiang, Zhenguo Wang, Xiongwei Yan, Jun Zhang, China Academy of Engineering Physics (China)

Because of the large emission and absorption section, large aperture, Nd:Glass is widely used in the Inertial Confinement Fusion (ICF) laser driver. But, owing to the low thermal conductivity this kind of laser driver can not be operated repeatedly (typically one shot in several hours). Especially in the laser drivers for Inertial Fusion Energy (IFE) and high-energy high brightness ray source, this material can not meet the requirements of repetition rate (typically 10Hz-20Hz). The Nd:CaF2 may be used in repetition rate fusion laser because of the high thermal conductivity and large size, meeting the requirements of high-energy and repetition rate. But the conventional Nd:CaF2 crystal exhibits concentration quenching, it can not be directly used in the laser system.

In our work, we co-doped the Y-ion and Nd-ion in CaF2 to adjust the crystal lattice structure and laser properties of material, and then we measured the emission and absorption spectrum, the gain properties of the Nd:Y:CaF2, and compared the results with that of the Nd:Glass. The results show that, the bandwidth near 1053nm exhibits 20nm, which is similar to Nd:Glass, and gain of amplifier for 0.65at.%Nd:10at.%Y:CaF2 reached 1.4 times, which is equivalent to the 0.7at% doped Nd:Glass under the same pumping condition, the slope efficiency exhibits about 40%. At the same time we measured the emission cross-section and life time of this material, the emission cross-section is about 5?1020cm-2?and the lifetime of upper energy level is about 350us, the lifetime is similar to Nd:Glass and the cross-section is slightly larger than Nd:Glass. Moreover the large size CaF2 can be achieved. So we think that this material maybe a potential gain material for IFE laser driver.

The uniformity of Nd:Y:CaF2 is not very perfect, it should be improved to be used in high-energy laser system in the future. Fortunately, the larger aperture uniform Yb:CaF2 has been achieved by Hellma Materials. We believe that, the uniform Nd:Y:CaF2 can also be achieved in the future.

9513-28, Session 6

Multi-mJ, kHz picosecond deep UV source based on a frequency-quadrupled cryogenic Yb:YAG laser *(Invited Paper)*

Kyung-Han Hong, Chun-Lin L. Chang, Peter Krogen, Houkun Liang, Gregory J. Stein, Jeffrey Moses, Chien-Jen Lai, Massachusetts Institute of Technology (United States); Franz X. Kärtner, Massachusetts Institute of Technology (United States) and Ctr. for Free-Electron Laser Science (Germany) and Univ. Hamburg (Germany)

High-power deep ultraviolet (DUV, <300 nm) lasers have various scientific, industrial, military and medical applications, such as spectroscopy, photolithography, precise micromachining, security inspection, and ophthalmology. DUV pulses can bring benefits in terms of high spatial resolution due to a short wavelength and minimal thermal effects due to a high-absorption cold processing if its pulse duration is shorter than ~10 ps. For practical applications and commercialization, the development of both high peak and average power picosecond DUV lasers based on a diode-pumped solid-state (DPSS) laser is crucial. Recently the generation of powerful DUV pulses with a peak power of >MW level and a repetition rate at kHz level has been demonstrated [1], where the pulse duration is longer than 500 ps and the energy per pulse is ~0.54 mJ.

In this paper, we report on the development of a multi-mJ, ~4.2 ps, ~257.5 nm DUV laser at 1 kHz based on frequency quadrupling of 31.5 mJ, 8.4 ps, ~1030 nm near-infrared (NIR) laser pulses, generated from a diode-pumped, ultrafast cryogenic Yb:YAG chirped-pulse amplification (CPA) laser system [2]. The DPSS cryogenic Yb:YAG laser is composed of a Ti:sapphire seed oscillator, a Yb:KYW regenerative amplifier, two cryogenic Yb:YAG multipass amplifiers, a chirped volume Bragg grating stretcher, and a dielectric grating compressor. The maximum energy from the compressor is higher than 50 mJ with a compression efficiency of 80%. The NIR pulse has an excellent beam profile and an M-square value as low as 1.3.

We have used a two-stage second harmonic generation scheme at LBO (NIR-to-green) and BBO crystals (green-to-DUV), respectively, to achieve the fourth-harmonic generation (FHG). The temperature-controlled noncritically phase-matched LBO crystal allows a NIR-to-green conversion efficiency of 41.1%. The input energy of NIR pulses is limited to 31.5 mJ due to the self-focusing at the LBO crystal, but the further energy can be produced with a larger aperture crystal. We have tested 1.5-mm-long and 0.5-mm-long BBO crystals for DUV generation from the green pulses. The peak power of the produced DUV laser pulses is as high as 652 MW with 2.74 mJ of energy from the 0.5-mm-long BBO crystal. The NIR-to-DUV conversion efficiency of 9.4% in the FHG is obtained. We will discuss the systematic optimization of the FHG experiment. The beam profiles at near-field and far-field are found to be very good and the M-square value is measured as ~2.6. We have also achieved a focused intensity of ~10^14 W/cm^2 and easily generated air breakdown. To our best knowledge, this is the most intense DUV generation from a DPSS laser source at kHz repetition rates.

[1] L. Deyra et al., Appl. Phys. B 111, 573-576 (2013).

[2] K.-H. Hong et al., Opt. Lett. 39, 3145-3148 (2014).

9513-29, Session 6

Picosesond pulses in deep ultraviolet produced by a 100-kHz solid-state thin disk laser

Hana Turcicova, Ondrej Novák, Martin Smrz, Taisuke Miura, Akira Endo, Tomás Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

We report on the generation of 100 kHz mJ-level deep ultraviolet pulses based on frequency-quadrupled (257.5 nm) and frequency-quintupled (206 nm) beam of an Yb:YAG thin disk laser. The seed pulses of this high average power laser system at fundamental wavelength of 1030 nm

stems from a fiber oscillator. Pulses are stretched from 5 ps to 200 ps by a chirped volume Bragg grating. The amplification is performed in a regenerative amplifier where the thin disk serves as an active mirror. The diode pumping at 969 nm improves the conversion efficiency and stability of the system. Average output power of 100 W level and 2 picosecond pulsewidth were achieved after a chirped volume Bragg grating compressor. The design of the fourth and fifth harmonics generation was optimized by numerical calculations with respect to conversion efficiency, pulse delays, and beam sizes. To generate the fourth harmonic the fundamental laser beam is first frequency-doubled in an LBO crystal, then again frequency-doubled in BBO or CLBO crystals. To generate the fifth harmonic, a part of the fundamental beam is not converted and is overlaped with the fourth harmonic in another CLBO crystal. We suggested measures to prolong the crystal lifetime. The characteristics of both deep ultraviolet beams will be presented, i.e. the pulse energy, the output power, the optical efficiency, and the data characterizing the optical quality of the beams. Moreover, the fifth harmonic output dependence on the delay between the fourth harmonic and the fundamental beams will be compared with the theoretical predictions.

9513-30, Session 6

Large-aperture and noncritically phase-matched fourth harmonic generation experiments

Fang Wang, Fuquan Li, Wei Wang, Bin Feng, Wei Han, China Academy of Engineering Physics (China)

Large aperture and non-critically phase-matched (NCPM) fourth harmonic generation (FHG) has been experimentally demonstrated. The fundamental frequency light with wavelength of 1053nm in a 1ns flat-top pulse was output from beam S4 of SG-III prototype facility, and the beam size was restricted to be 140mm?140mm. A 170mm?170mm?7mm conventional grown DKDP crystal with 65% deuteration was prepared to reach NCPM near room temperature, and mounted in a temperature-controlled chamber consist of two fused silica windows and a constant temperature shell. The temperature homogeneity of the whole crystal aperture was controlled to be 0.1? by the double water circulation design of the chamber and operation at a low vacuum environment. FHG experiments were first carried out in the collimated beam, the NCPM temperature was found to be 29.7? with a FWHM temperature bandwidth of 2.3? when the input 2? intensity was 0.5GW/cm2, the maximum 4? energy of 114J was generated corresponding to 2?-to-4? conversion efficiency of 77% with 2? drive intensity up to 0.8GW/cm2. To verify the super-wide angular acceptance characteristic of NCPM technique, FHG experiments in the convergent beam with F number of 21.4 were also conducted, the best matching temperature was corrected to be 29.5? to compensate the degradation on the edge of near-field due to the limited flattop of efficiency-angular curve, the 2?-to-4? efficiency curve showed to be in consist with the collimated beam as the input 2? irradiance increases, and the peak of 79% was achieved when 2? intensity up to 1GW/cm2. Thus, the high efficiency and angular insensitivity of NCPM FHG has been proved by large aperture experiments.

9513-19, Session PS

Experimental benchmarking of the code for Yb:YAG multislab gas-cooled laser system operating at cryogenic temperatures

Magdalena Sawicka-Chyla, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Ondrej Slezak, Institute of Physics ASCR (Czech Republic); Martin Divoky, Antonio Lucianetti, Tomás Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Ultra-high-intensity laser matter interaction applications such as particle acceleration or the inertial confinement fusion will benefit from or require laser sources capable of delivering energies at a kJ level with multi Hz repetition rate and good wall plug efficiency. One of the suitable architectures for these sources is based on diode pumped cryogenically cooled multi-slab architecture [1, 2].

In Europe, there are currently two systems utilizing this cryogenically cooled multi-slab architecture that are or soon will be operated. Both will serve as prototypes for kJ class lasers. One of them is located in the Institute of Physics AS CR, and the other system is in the Rutherford Appleton Laboratory, STFC , UK. Both are 10 J/10 Hz cryogenically cooled multi-slab laser systems. The laser head of each system consists of four, 5 mm thick slabs separated by 2 mm gaps. Each slab is composed of 35 mm diameter Yb:YAG active material which is surrounded by 10 mm thick absorptive cladding made of an index matched material: Cr:YAG. The doping concentration of Yb ions in the active material varies along the laser head. Slabs are cooled by forced He flow to 150 K. The slabs are pumped from both sides by homogenized diode arrays which in total deliver up to 40 kW of pump power in 1 ms pulses with a central wavelength of 940 nm, bandwidth 6 nm and pump spot 20mm x 20 mm. The amplifier is built in a multi-pass configuration allowing up to 8 passes.

In order to design and optimize parameters of the laser head, amplified spontaneous emission, stored energy, heat distribution and amplification in the high energy class multi-slab laser system is calculated by a 3-D MATLAB code [3, 4]. The model is fully spatially and spectrally resolved. It utilizes Monte Carlo ray tracing method to follow pump radiation and spontaneously emitted rays through the active element. Detailed description of the code was given in [3, 4].

In this work, we present the benchmarking of the home-made MATLAB model with the experimental data obtained for the systems described above. Details of the experimental results with comprehensive study of the performed simulations will be presented.

The laser head has been modelled to predict gain in the slabs and the amplification of the seed beam for the temperatures of operation ranging from 100 K to 180 K. Output energy for different pump pulse durations have been calculated. It was determined that the maximum output energy obtained after 6 passes for the amplifier operating at the temperature of 125K and repetition rate 1 Hz was 9 J for the seed energy of 30 mJ. For higher temperature of 150 K the output energy was 8 J. The corresponding maximum single pass gain in the amplifier head was 8 for 125 K and 4 for 150 K. Results of the simulations are in a very good agreement with the measured data presented in [5].

1. A. Bayramian, S. Aceves, T. Anklam, K. Baker, E. Bliss, C. Boley, A. Bullington, J. Caird, D. Chen, R. Deri, M. Dunne, A. Erlandson, D. Flowers, M. Henesian, J. Latkowski, K. Manes, W. Molander, E. Moses, S. Powers, S. Rana, S. Rodriguez, R. Sawicki, K. Schaffers, L. Seppala, M. Spaeth, S. Sutton, and S. Telford, "A Compact Line Replaceable Unit Laser Driver for Laser Inertial Fusion Energy," 2012 Conference on Lasers and Electro-Optics (Cleo) (2012).

2. P. Mason, K. Ertel, S. Banerjee, P. Phillips, C. Hernandez-Gomez, J. Collier, J. Hein, L. Silva, G. Korn, L. Gizzi, and C. Edwards, "Optimised Design for a 1 kJ Diode Pumped Solid State Laser System," Diode-Pumped High Energy and High Power Lasers Eli: Ultrarelativistic Laser-Matter Interactions and Petawatt Photonics and Hiper: the European Pathway To Laser Energy 8080 (2011).

3. M. Sawicka, M. Divoky, J. Novak, A. Lucianetti, B. Rus, and T. Mocek, "Modeling of amplified spontaneous emission, heat deposition, and energy extraction in cryogenically cooled multislab Yb3+:YAG laser amplifier for the HiLASE Project," Journal of the Optical Society of America B-Optical Physics 29, 1270-1276 (2012).

4. M. Sawicka, M. Divoky, A. Lucianetti, and T. Mocek, "Effect of amplified spontaneous emission and parasitic oscillations on the performance of cryogenically-cooled slab amplifiers," Laser and Particle Beams 31, 553-560 (2013).

5. S. Banerjee, K. Ertel, P. Mason, J. Phillips, J. Greenhalgh, and J. Collier, "DiPOLE: A Multi-Slab Cryogenic Diode Pumped Yb:YAG Amplifier," Proc. SPIE 8780, 878006-878006-878007 (2013).

9513-31, Session PS

Thermal distortion real-time detection and correction of a high-power Laser beam-splitter mirror based on double Shack-Hartmann wavefront sensors

Yu Ning, Quan Sun, Hongyan Wang, Wuming Wu, Shaojun Du, Xiaojun Xu, National Univ. of Defense Technology (China)

With the incessant increase of the power of a laser system, thermal distortion will appear unavoidably in the optical train, especially of a large aperture optics system. The thermal distortion seriously depresses the quality of the output laser beam. In order to get a better focusing spot or transmit the high-power laser to a further distance, many researches turn to the adaptive optics (AO) for help. AO has been proved to compensate wavefront distortions efficiently in various laser systems.

In a high-power laser system, a beam splitter refers to the mirror which locates at the cross point of the path of high-power beam and the weak light section. It acts as a crucial element in the optical train of the system, because the transmission beam which passes through it carries important information of the distorted wavefront to the sensor of the AO system. Unfortunately, even the most advanced film technology cannot prevent the high-power laser from entering into the body of the mirror. Because of the thermo-optic effect and elasto-optic effect, a beam splitter deforms under intense laser radiation. This deformation adds extra phase on the incident waves and deliveries inaccurate information to the wavefront sensor. According to this error massage, the AO system controls the corrector to add a redundant conjugate wavefront onto the output laser. Consequently, the output laser focuses at finite distance and gets divergent when arrives at the target.

To settle the above problem, this paper presents a new method for real-time correction of the thermal distortion of beam splitter, based on algorithm of the data fusion of two Shack-Hartmann wavefront sensors (SH-WFS). Different from the traditional AO system, which contains a wavefront sensor, a corrector and a servo controller, two extra Shack-Hartmann wavefront detectors are adopted in our AO system, to detect the transmitted and reflected aberrations of beam splitter mirror. And these aberrations are real-timely delivered to the wavefront sensor. Based on coordinate conversion and data fusion algorithm, it makes the wavefront sensor of AO can "see" the aberrations of splitter mirror by itself. Thus, the servo system controls the corrector to compensate these aberrations correctly.

In this paper, the theoretical model of data fusion algorithm is carried out. And the factors, such as the incidence angle of light, wavelength difference and mismatch of spatial resolution, which possibly influence the fusion efficiency of algorithm, are discussed in detail. A closed-loop AO system, which consists of a typical AO system and two extra Shack-Hartmann wavefront detectors, is set up to validate the data fusion algorithm. Experimental results show that, the distortion of a CaF_2 beam splitter can be real-time corrected when the AO closed-loop control is on. The beam quality factor of output laser decreases from 4 to 1.7 times of diffraction limit. Besides, the experimental results fit well with the conclusion of theoretical analysis.

9513-32, Session PS

Wavelength-tunable Erbium-doped fiber laser using silicon-on-insulator (SOI) based microring with narrow laser linewidth

Ling-Gang Yang, Chi-Wai Chow, National Chiao Tung Univ. (Taiwan); Chien-Hung Yeh, Feng Chia Univ. (Taiwan); Hon Tsang, The Chinese Univ. of Hong Kong (Hong Kong, China)

Wavelength-tunable and stable fiber laser is important light source for many applications, such as optical-sensing, material processing, spectroscopy, medicine and optical communications. In these fiber lasers, tunable band-pass filter, Fabry-Perot etalon or fiber-Bragg-grating (FBG) have been widely used inside the fiber ring cavity to generate the lasing wavelengths. For the gain-media, erbium-doped fiber amplifier (EDFA) or semiconductor-optical-amplifier (SOA) are usually used inside the fiber ring cavity. Recently, using silicon-on-insulator (SOI) based photonic devices in optical networks are attractive since they are complementary-metal–oxide–semiconductor (CMOS) compatible, compact in size and have low-power consumption. The SOI based micro-ring is a promising candidate to act as a wavelength filter offering a high extinct-ratio.

In this work, we propose and demonstrate a wavelength-tunable and narrow-linewidth erbium-doped fiber (EDF) laser using SOI based micro-ring. We first discuss the wavelength selection and wavelength-tunable operation of the proposed fiber laser. The proposed fiber laser is constructed of a C-band EDFA module, two polarization controllers (PCs), a 1 x 2 and 90:10 fiber optical coupler (CP) and a SOI based micro-ring with uniform period grating couplers. Then, we discuss the fabrication of the SOI based micro-ring. It is fabricated on a SOI wafer with a 0.22 um thick top silicon layer and a 2 um thick burial-oxide (BOX) layer. The length of micro-ring straight coupling region and the circumference are 6 um and 232 um respectively. The gap between the ring and the straight waveguide structures is 200 nm in the coupling region. The total length of straight waveguide structure is less than 1 cm. In order to enhance the coupling efficiency between the SOI based micro-ring and the EDF, a pair of uniform period grating couplers are used. The uniform period grating coupler has the length and width of 14 um and 9 um respectively, and its period and etch depth are 580 nm and 70 nm, respectively. They are fabricated by using deep-ultra-violet (DUV) 193 nm lithography and reactive-ion etching (RIE) technique. Due to the different birefringent losses in the proposed laser, different lasing wavelengths can be generated. In the experiment, thirteen lasing wavelengths can be tuned in the wavelengths range from 1532 nm to 1567.2 nm with a tuning step of 2 nm. The wavelength range and the tuning step are determined by the EDF gain-bandwidth and the free spectral range (FSR) of the SOI based micro-ring respectively. The optical single-to-noise ratio (OSNR) of each lasing wavelength is > 42 dB. By using a double-ring configuration, a narrow laser linewidth of 50 kHz can be achieved. The output power variations of these tunable wavelengths are ± 1.5 dB over the 35.2 nm wavelength range. Moreover, a short-term stability test is performed, and the wavelength variation and power fluctuation are about 0.02 nm and 0.8 dB respectively, over 30 minutes observing time without any temperature control and feedback circuit.

9513-33, Session PS

Active mode control of solid state laser using an intra-cavity beam shaper

Wenguang Liu, Qiong Zhou, Baozhu Yan, Zongfu Jiang, National Univ. of Defense Technology (China)

In high power solid state lasers, Thermal induced aberrations always give rise to the multimodes oscillating in the resonator. The beam quality will deteriorate with the increase of output power or running time. In this paper, To preserving the mode contents of a diode side-pumped Nd:YAG rod laser, an intra-cavity beam shaper is introduced to actively control the low order aberrations in the resonator. The beam shaper consists of two x-oriented cylindrical lens and two y-oriented cylindrical lens. By adjustment of the distance and tilt angle of the cylindrical lens, defocus, astigmatism and spherical aberrations can be compensated. An optimization control algorithm is presented, in which the error signal is obtained from the M2 factor of the laser, and control signal is generated by the control algorithm to maintain the M2 factor by actively adjustment of the optical layout parametr of the intra cavity beam shaper. The effectiveness and performance of active mode control with the intra-cavity beam shaper are verified by experiments. It shows that the M2 factor is well maintained below 1.7 even the output power increased 10 times.

9513-34, Session PS

Temperature dependent absorption measurement of various transition metal doped laser materials

Lucie Horackova, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Jan Sulc, Helena Jelínková, Czech Technical Univ. in Prague (Czech Republic); Venkatesan Jambunathan, Antonio Lucianetti, Tomás Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

In recent years, there has been a vast development of high energy class lasers of the order of 100 J to kJ level which has potential applications in the field of science and technology. Many such systems use the gain media cooled at cryogenic temperatures which will help in enhancing the spectroscopic and thermo-optics properties. Nevertheless, parasitic effects like amplified spontaneous emission enhance and affect the overall efficiency. The best way to suppress this effect is to use cladding element attached to the gain material. Based on these facts, this work was focused on the systematic investigation of temperature dependent absorption of several materials doped with transition metals, which can be used as cladding, as laser gain material, or as passive Q-switching element. The Ti:sapphire, Cr:YAG, V:YAG, and Co:MALO samples were measured in temperature range from 80 to 330 K by step of 50 K. Using Lamberts law we estimated the absorption coefficient of these materials. The results show that the absorption of ?-polarization at 490 nm is not affected by the temperature change. Moreover, the maximum of Cr:YAG absorption at 1064 nm was observed at 180 K. The V:YAG absorption at 1064 nm does not show any change with temperature, but at 1340 nm it increases by nearly 70 % with temperature decrease from 330 to 80 K. The absorption of Co:MALO increased by 20 % with the given decrease of temperature. The absorption spectra of these materials at room and low temperatures were published in the past; however, as far as we are aware, this is the first report of the absorption temperature dependence of Cr:YAG, V:YAG, Co:MALO and ?-polarization of Ti:Sapphire.

9513-35, Session PS

Influence of boundary condition and pumped scheme on thermal effect in spaceborne laser

Peibei Meng, Fanjiang Yan, Xu Li, Yongchao Zheng, Beijing Institute of Space Mechanics and Electricity (China)

The crystal's thermal effect in laser diode (LD)-side-pumped spaceborne solid-state laser with different thermal boundary condition and pump structure has been studied. In theory, based on the operating environment characters of space-based laser such as microgravity, significant platform resources (primarily power and volume) and high requirement of reliability and lifetime, heat radiation and heat conduction have been conventional cooling means and a transversely LD with Gaussian beam distribution pulse pump laser thermal model has been set up. The finite difference method has been used to solve the isotropic thermal conductive Poisson equation. The pump power distribution, the temperature distribution and the thermal focal length have been obtained. The influence factors on thermal distribution and thermal effect has been analyzed numerically, including thermal boundary condition (such as actively cooling and passively cooling), pumped manner (such as three-side annular pump structure, five-side annular pump structure and hemihedral pump structure) and pump parameters (such as pump waist diameter, pump divergence angle, distance from pump waist to crystal, absorption coefficient, pump power and pump repetition frequency). Compared with the passively cooling, the actively cooling would reduce the central temperature in crystal evidently and not significantly affect the temperature gradient namely thermal lens effect. Increasing the pump directions of annular pump structure and utilizing the cross hemihedral pump structure could increase the uniformity of gain distribution and temperature distribution. Both the thermal effect and the gain would be enhanced with the decreasing of pump waist diameter, pump divergence angle, distance from pump waist to crystal, and increasing of absorption coefficient. With increasing of pump power and pump repetition frequency, the thermal focal length would decrease exponentially. For short operating time like 8 min per orbit of space-based laser at relatively low pump repetition frequency (not exceeding 10 Hz), passively cooling of crystal would be preferred for simplification of design, economization of power and volume, and enhancement of reliability. On basis of the theoretical analysis results, a five-side annular laser diode arrays pumped Nd:YAG laser without actively cooling of crystal at 300 K was set up experimentally. The thermal focal length of Nd:YAG was achieved by the beam waist of He-Ne denoting light, beam transformation theory of Gaussian beam propagation through thin lens, and the deduced beam waist of He-Ne light after propagating the Nd:YAG by the beam radius which was obtained by measurement of beam intensity variation with stop aperture variation at different distances. In condition of the total pump power about 6000 W, four group arrays along the crystal, the pump waist diameter 1.2 mm, pump divergence angle 40°, distance from pump waist to crystal 3.5 mm, the pump pulse width 220 ?s?pump repetition frequency 10 Hz, the thermal focal length of Nd (1 at.%):YAG with 6 mm in diameter, and 80 mm in length was about 9.5 m. The experimental result of thermal focal length 9.5m were in basic agreement with the simulated results of 8.443 m.

9513-36, Session PS

Development of a mode-locked fiber laser system for a high finesse enhancement cavity

Rika Suzuki, Takanari Kobayashi, Kazuyuki Sakaue, Masakazu Washio, Akira Endo, Waseda Univ. (Japan)

In recent years, a high finesse optical enhancement cavity technology was widely used as a high repetition rate and high power laser source for such as Higher harmonic generation (HHG) and Laser Compton Scattering (LCS). Optical enhancement cavity enables us to make a very stable focal waist and to increase seed laser power of more than 10000 times by accumulating lasers in the optical cavity.

In this background, we have been studying a high finesse enhancement cavity for photon target of LCS X-ray generation. We have already succeeded in generating high brightness X-rays based on LCS using optical enhancement cavity. However, a high finesse, more than 10000, optical cavity is required the extremely precise length adjustment between an external optical cavity and an incident seed laser oscillator, which is less than 1nm accuracy in the 1000 finesse cavity. Therefore it is very important to develop not only an extremely stable external optical cavity but also a stable seed laser oscillator for an incident laser of an optical cavity.

Thus, we have been developing a mode-locked Yb-doped fiber laser based on Non-Linear Polarization Rotation. Advantages of fiber lasers are compact, economical, flexible, stable, and capable of getting high average power. We have already succeeded in oscillating 69.5mW average power, 449fs pulse duration and 0.58nJ energy at repetition rate of 119MHz resulting in a peak power of 1.3kW. The spectrum band-width was 14.3nm (FWHM), which was enough for a chirp pulse amplification. In this conference, we will report the recent specification of our laser system, results of accumulation experiment in the external optical enhancement cavity, and future prospects.

9513-37, Session PS

Demonstration of an optical enhancement cavity with 10 micron wavelength

Kazuyuki Sakaue, Masakazu Washio, Akira Endo, Waseda Univ. (Japan)

We have been developing a pulsed-laser optical enhancement cavity for laser-Compton scattering (LCS). LCS can produce high brightness X-ray through the collision between relativistic electrons generated from the

accelerator and high power laser photons with a compact facility. In order to increase the number of collisions/sec, high repetition rate accelerator and laser are required. For the laser system, an optical enhancement cavity is the most powerful tool for LCS, thus we have been developing the cavity for storing 1 micron laser pulse. On the other hand, the resulting X-ray energy can be changed by the collision laser wavelength. If we have another optical cavity with different wavelength, the multi-color, quasi-monochromatic, high brightness and compact X-ray source can be realized. Thorefore, we started to develop an optical cavity at 10 micron wavelength with CO2 laser. At this wavelength region, the absoption loss is dominant compared with scattering loss. Thus we carefully chose the optical mirrors for enhancement cavity. We demonstrated a more than 200 enhancement factor with 795 finesse optical cavity at 10 micron CO2 laser. Moreover, 2.3 kW storage in the optical cavity was successfully demonstrated. The design of optical cavity, first experimental results and future prospects will be presented at the conference.

9513-38, Session PS

Multiple pulses and harmonic mode locking from passive mode-locked Ytterbium doped fiber in anomalous dispersion region

Ja-Hon Lin, Hung-Yi Lee, National Taipei Univ. of Technology (Taiwan)

Nowadays, mode-locked fiber laser has been widely used in scientific research and industrial application such as optical communication, ultra-fast probing technique and industrial machining. In order to understand the fiber laser dynamics, it is important to study the soliton operations and multiple soliton formation. Besides, the phenomenon of bound solitons have attracted great attention due to their fundamental importance on realizing the soliton interaction. In this work, we constructed the Ytterbium-doped fiber laser with ring cavity configuration. The mode-locked mechanism was based on the nonlinear polarization evolution (NPE) comprising two quarter-wave plates, one half-wave plate, and one polarization beam splitter (PBS) cube. By adding the two grating pairs with 600 lines/mm groove density inside laser cavity for the group velocity dispersion, the total cavity dispersion was operated within anomalous dispersion region. With proper cavity optimization, the fundamental ML with the 35 MHz repetition rate and 3.3 ps pulsewidth was produced whose optical spectrum reveals the Kelly sideband. After adjusting of the waveplate or increase the pump power, the harmonic mode locking (HML) was generated that revealed the multiple pulses with equal time interval between sequential pulses. In our laser, the 6th HML with the 210 MHz pulse repletion rate can be measured whose time interval between pulse about 4.7 ns. Besides, we also demonstrated the bound states of multiple solitons whose pulse separation between two pulses about several tens of picosecond. At certain pump power and polarization adjustment, the number of solitons and the pulse separation could be controlled so that it would be used in optical communication.

9513-39, Session PS

Thermal effects of liquid direct cooled split disk laser

Huomu Yang, Guoying Feng, Shouhuan Zhou, Sichuan Univ. (China)

Thermal effects is the main barrier of solid state laser to reach high power, high beam quality and high efficiency laser out put. Liquid direct cooled split disk laser, one type of the disk-type laser, is direct cooled on both the larger faces, hence the disk bending was eliminated, furthermore, the distributed method lower the requirement of cooling capacity of unit area on cooling face. Due to these advantages, the liquid direct cooled split disk laser owns the potential to realize high efficiency, high power and good beam quality laser output simultaneously, and has attracted much concentrations.

The width (x), length (y) and thickness (z) of disk gain medium are 2a, 2b and 2l, respectively. the thickness of the cooling channal is 2t. The width of cooling channal is usually tens of times that of thickness, therefore it can be seen as internal flow between two parallel plates. In the entrance of the cooling channal, there is a hydrodynamic entrance region in which the velocity profile develops, it can make influence on the wavefront distortion, therefore, there is usually a supplementary channal for coolant to be fully developed. The coolant studied in this paper is the hydrodynamically fully developed flow.

The thermal management performance of various coolant, such as FC-40, HT-110, D2O and water are compared. The heat transfer coefficients and temperature gap between gian medium and coolant are investigated. It can be seen that D2O owns nearly the same cooling performance of that of water.

The temperature distribution in the gain medium is also investigated. it can be seen that the longitudinal cooling liquid temperature rise have a great influence on the temperature distribution in the gain medium.

9513-40, Session PS

Sub-picosecond laser induced damage test facility for petawatt reflective optical components characterizations

Martin Sozet, Jérôme Néauport, Nadja Roquin, Commissariat à l'Énergie Atomique (France); Laurent Gallais, Institut Fresnel (France); Laurent Lamaignère, Commissariat à l'Energie Atomique (France)

A petawatt laser, called PETAL (PETaWatt Aquitaine Laser), is under construction at the Commissariat à l'Energie Atomique et aux Energies Alternatives. Based on Chirped Pulse Amplication (CPA) technique, it is designed to deliver 500 fs pulses of 3 kJ at a wavelength of 1053nm. The objective of this facility is to perform fundamental physics experiments. To this end, this laser facility uses large size optical components (up to around 1m?) to amplify, compress, transport and focus the laser beam onto a target. In peculiar, damage performance of large size pulse compression gratings, transport mirrors and parabola is one of the main factors that limit the output energy of the facility. Consequently, getting a detailed knowledge of the behavior of these optical components under high fluences in short pulse range and large beam is of major importance.

In this context, a sub-picosecond Laser Induced Damage Threshold test facility called DERIC has been developed. It uses an Amplitude Systemes laser source which delivers Gaussian pulses of 500 fs at 1053 nm. 1-on-1, S-on-1 and RasterScan procedures are implemented to study the behavior of monolayer and multilayer dielectric coatings, used to make the reflective optics of PETAL, under laser irradiation. The deterministic behavior of the laser induced damage of dielectrics materials at this regime and also defect induced damage under irradiation are inspected via an in situ detection. A post-mortem observation of damage sites with a Nomarski microscope is done for a better understanding of the damage processes. Our presentation will first consist in presenting our experimental setup. Then, first results will be shown to exhibit the accuracy of our metrology on various components using 1/1, N/1 and RasterScan procedures and compared to literature.

9513-41, Session PS

Generation of 1.6 ns Q-switched pulses based on Yb:YAG/Cr:YAG microchip laser

Jan Sulc, Helena Jelínková, Czech Technical Univ. in Prague (Czech Republic); Karel Nejezchleb, Vaclav Skoda, CRYTUR spol s.r.o. (Czech Republic)

The highly-stable Q-switched longitudinally diode-pumped microchip laser, emitting radiation at wavelength 1031 nm, was designed and realized. This laser was based on monolith crystal which combines in one piece an active laser part (YAG crystal doped with Yb3+ ions, 10 at.% Yb/Y, 3 mm long) and saturable absorber (YAG crystal doped with Cr3+ ions, 1.36 mm long). The diameter of the diffusion bounded monolith was 3 mm. The initial transmission of the Cr:YAG part was 90 % @ 1031 nm.

The microchip resonator consisted of dielectric mirrors directly deposited on the monolith surfaces. The pump mirror (HT for pump radiation, HR for generated radiation) was placed on the Yb:YAG part. The output coupler with reflection 55 % for the generated wavelength was placed on the Cr3+-doped part. Q-switched microchip laser was tested under CW diode pumping. For longitudinal pumping of Yb:YAG part, a fibre coupled (core diameter 100 um, NA = 0.22) laser diode, operating at wavelength 968 nm, was used. The laser threshold was 3.3 W. The laser slope efficiency calculated for output mean power in respect to incident CW pumping was 17 %. The wavelength of linearly polarized laser emission was fixed to 1031 nm. The generated transversal intensity beam profile was close to the fundamental Gaussian mode. The generated pulse length was equal to 1.6 ns (FWHM). This value was mostly stable and independent on investigated pumping powers in the range from the threshold up to 9.3 W. The single pulse energy was linearly increasing with the pumping power. Close to the laser threshold the generated pulse energy was 45 uJ. For maximum investigated CW pumping 9.3 W the pulse energy was stabilized to 74 uJ which corresponds to the Q-switched pulse peak power 46 kW. The corresponding Q-switched pulses repetition rate was 13.6 kHz. The maximum Yb:YAG/Cr:YAG microchip laser mean output power of 1 W was reached without observable thermal roll-over.

9513-42, Session PS

Research on thermal effects of beam-splitter mirror in high-power laser system

Quan Sun, Yu Ning, Zongfu Jiang, Jun Shao Du, National Univ. of Defense Technology (China)

High-power laser propagation through the inner optical path will produce a significant thermal effect on the beam-splitter mirror which will cause phase aberrations. Based on the three-dimensional transient heat conduction equation and the elastic stress-strain equation, a simulation model of reflector mirror was built with three-dimensional finite element method (FEM). The temperature rises, thermal displacements of two kinds of mirror substrates (spinel and Al2O3 crystal) were especially investigated with different laser intensity, output duration and absorption coefficient. The effects of mirror thermal distortion on laser beam phase aberrations were also evaluated on both reflection and transmission directions. The experiments of high–power laser propagation through two kind materials of beam-splitter mirrors samples with diameters of 100mm and thicknesses of 15mm were carried out to measure the thermal effects induced by the absorbed laser energy. Both two kinds mirror samples were deposited the same film layer of 99.9 percent reflectance. A high power semiconductor laser was expanded to a beam of 80mm diameter, and double Shack-Hartmann wavefront sensors were used to detect both reflection and transmission thermal distortions of the mirror samples. The measurements showed that both reflection and transmission thermal distortions of spinel mirror sample were larger than those of Al2O3 crystal mirror sample. The results of experiments and simulations showed a very good consistency.

9513-43, Session PS

Optical prorerties of laser crystal Cr2+: ZnSe

Yuqin Zhang, Guoying Feng, Jiayu Yi, Sichuan Univ. (China)

The electronic structure and optical properties of Cr2+: ZnSe have been investigated by first-principles calculations on the basis of density functional theory (DFT). First-principles calculation was carried out using the Vienna Ab-initio Simulation Package (VASP). Absorption properties of the chromium doped zinc selenide crystals with various concentrations of the doping impurity in 0.46%–12.5% range were studied. The calculated results of different dopant concentration show that the spectral intensity increases as the doping concentration is increased?while the peak keeps invariant. Good agreement is found between the calculated and the experimental optical results.

9513-44, Session PS

Different mode-locking methods in high-energy all-normal dispersion Yb femtosecond all-fiber lasers

Jan A. Szczepanek, Univ. of Warsaw (Poland); Maria Michalska, Military Univ. of Technology (Poland); Tomasz Karda?, Institute of Experimental Physics, Department of Physics, University of Warsaw (Poland); Czes?aw Radzewicz, Institute of Experimental Physics, Department of Physics, University of Warsaw (Poland) and Institute of Physical Chemistry Polish Academy of Sciences (Poland); Yuriy Stepanenko, Univ. of Warsaw (Poland) and Institute of Physical Chemistry (Poland)

Ultrafast all-fiber oscillators are becoming one of the most rapidly developed laser technologies. Many advantages like: environmental stability, low sensitivity to misalignment, excellent beam quality (intrinsic single transverse mode operation), relatively high pulse energy and great active medium efficiency makes them the best solution for a variety of applications.

Different generation modes classified with respect to the net cavity dispersion can be distinguished in fiber lasers. Our work is focused on the dissipative solitons regime which produces pulses with a large positive chirp. All fiber cavity components used in the setup have positive dispersion in the operating spectral range. Highly stretched pulses are limiting nonlinear effects which can be destructive to stable pulse train formation. Insensitivity to environmental changes such as mechanical perturbations or temperature drift is another highly valued property of new laser designs. In this paper we present the results of the design and study of all-fiber oscillators which have both these properties.

Pulsed work in all-fiber oscillators is commonly achieved by means of passive mode-locking techniques. Material saturable absorber such as a semiconductor saturable absorber mirror (SESAM), graphene or carbon nanotubes can be used to stabilize pulses inside the laser cavity. All these materials have intensity dependent transmission. In all-fiber configurations an artificial saturable absorber - a nonlinear polarization evolution (NPE) is the most common solution. The NPE is based on a nonlinear rotation of elliptically polarized light inside optical fibers. In setups which are built using polarization maintaining fiber only, a Nonlinear Optical Loop Mirror (NOLM) or its modification – a Nonlinear Amplifying Loop Mirror (NALM) are used as a saturable absorber. The transmission of a nonlinear loop mirror is defined by the phase difference between light counter propagating inside the fiber loop made of a fiber coupler (fiber Sagnac interferometer).

In current work we use highly doped Yb fibers as an active medium pumped by a fiber coupled 974 nm laser diode. The operation wavelength of our laser oscillators is 1030 nm. The lasers produce highly chirped pulses which can be recompressed by means of an external optical compressor. In this paper we investigated NPE, NOLM and NALM methods in all-fiber all-normal dispersion cavities. Most attention was paid to all-PM-fiber configurations with NOLM or NALM which are extremely stable. We present self-starting, high energy, dissipative soliton lasers producing pulses with energy of 4.3 nJ and dechirped pulse duration of 150 fs using NALM configuration and 6.8 nJ, 390 fs pulses in configuration with NOLM. An influence of different artificial saturable absorber on output pulse characteristics were studied during experiments. We also discuss the influence of stimulated Raman scattering on laser stability in high energy configurations.

9513-46, Session PS

An intra-cavity device with a discharge-drived CW DF chemical laser

Baozhu Yan, Wenguang Liu, Qiong Zhou, Shengfu Yuan, QiSheng Lu, National Univ. of Defense Technology (China)

In high power laser system, the quality of reflectors is one of the most

important factors affecting the performance of the whole system. On the one hand, the performance parameters of reflectors such as absorption coefficient or thermal distortion determine the beam quality of the output laser. On the other hand, for the high power laser system, the damage threshold of optical thin film coatings is usually lower than the other components, therefore, the damage threshold of reflectors becomes one of the maximum limitation for the improvement of power and the further development of high power laser.

At the present time, there was obviously insufficient in test methods for the reflectors performance. The reflection coefficient, absorption coefficient and scattering coefficient of reflectors can be measured by a lot of test methods such as cavity ring-down method, photothermal deflection method, surface thermal lens method and laser calorimetry. But these methods can not test under high power density radiation. So the measurement data and results can not indicate the real performance in a real laser system exactly. Testing in a real laser system would be expensive and time consuming. Therefore, the test sequence and data would not be sufficient to analyze and realize the performance of reflectors.

To examine the performance of reflectors under high power density radiation, the working principle of intra-cavity was introduced in this paper. Utilizing an output mirror with a low output coupling ratio, an intra-cavity can produce high-power density laser in the resonant cavity on the basis of a relatively small scale of gain medium, and the consumption and cost are very low relatively. Based on a discharge-drived CW DF chemical laser, an intra-cavity device was established. A laser beam of 3kw/cm2 was achieved in the resonant cavity, which was equivalent to the laser beam on reflectors in the real internal optical path. Two pieces of 22.5 degree reflectors and two pieces of 45 degree reflectors can be tested simultaneously. Absorption coefficient and thermal distortion were measured by calorimetry and Hartmann wavefront sensor respectively. Further more, the power density in the resonant cavity can be elevated further by increasing electric power supply, fuel flowrate or using an output mirror with lower output coupling ratio, then, the destroy threshold would be measured. This device was simple, convenient, inexpensive, and can work for a long time. The test results would provide support for process improvement of reflectors.

Conference 9514A: Laser Acceleration of Electrons, Protons, and Ions

Monday - Wednesday 13–15 April 2015

Part of Proceedings of SPIE Vol. 9514 Laser Acceleration of Electrons, Protons, and Ions III; and Medical Applications of Laser-Generated Beams of Particles III

9514-1, Session 1

Injector-booster scheme in laser wakefield acceleration: towards practical accelerators *(Invited Paper)*

Tomonao Hosokai, Osaka Univ. (Japan)

Until recently, generation of quasi-mono-energetic(QME), ultra-short, dense, and low-emittance electron beams have been demonstrated in several experiments on laser wake-field acceleration (LWFA), and the accelerated beam energy has been shown to attained to multi-GeV. These results show the potential of LWFA as a basis for high- performance accelerators. However, the LWFA technique is not accomplished as a practical acceleration technique due to poor repeatability of beam parameters.

In order to find a solution for good repeatability in LWFA we are studying a 2-beam driven staging technique consisting of a stable wave-breaking injector and a stable laser wake-field driver for beam post-processing[1]. This technique has a potential to become a basis for practical accelerators as long as a repeatable electron bunch could be injected into proper phase of the stable post acceleration wake-field.

Firstly, we have developed a repeatable and controllable LWFA injector using a tightly focused Ti:Sapphire laser pulse (30fs-300mJ) and a plasma micro-optics[2]. This injector can produce electron bunches with the energy of below 10MeV (Maxwellian distribution), high charge over 1nC/shot, beam-divergence of below 10mrad, and with the beam pointing stability of below 200μrad. In addition, these beams can be manipulated and steered precisely by the plasma micro-optics.

Secondly, we have developed the stable laser wake-field for post acceleration using a longer Rayleigh lengthened Ti:Sapphire laser pulse (30fs-500mJ), a lower density gas jet target and, again, the plasma micro-optics.

Thirdly, we have conducted 2-beam driven staging acceleration experiments with the two independent wake-fields as above. The produced electron beams have exhibited excellent pointing stability, the divergence better than 2mrad, the total charge of over a few pC/shot, and the maximal energy exceeding 300MeV(QME). These parameters depend strongly on the staging conditions.

Finally, we have constructed a beam transport line of ~8m in length for ultrafast imaging application. The beams have delivered to the very end and focused tightly using a set of Q-magnets. Details of the measurements will be discussed in the talk.

[1] N. Nakanii, et al., PROC of HEDS2012, Apr. 25-27, Yokohama, Japan (2012)

[2] T.Hosokai, et.al., Phys. Rev. Lett. 97, 075004 (2006); T.Hosokai, et.al., Appl. Phys. Lett. 96, 121501 (2010); Y.Mizuta, et.al., Phys. ReV. ST Accel. Beams. 15, 121301 (2012)

9514-2, Session 1

Direct measurement of the electron dephasing in laser wakefield acceleration

Daniel E. Cardenas, Shaoi-wei Chou, Laszlo Veisz, Max-Planck-Institut für Quantenoptik (Germany)

The energy of a laser-wakefield-accelerated electron [1] is limited by, among others, the distance it must propagate until it outruns the plasma wave by half of the plasma wavelength, i.e. the dephasing length L_d [2]. The dephasing length is given approximately by L_d≈(λ_p^3)⁄(λ_0^2), where λ_p and λ_0 are the plasma and laser wavelength, respectively. In order to excite resonantly a plasma wave, the laser pulse duration should match half of the plasma wavelength. In order to excite resonantly a plasma wave, the laser pulse duration should match half of the plasma wavelength. Up to now, no direct or systematic measurement of the electron dephasing has been realized due to quality and reproducibility of the electron bunches or the long durations of the laser pulses (≥ 25 fs) employed to excite the wakefield, which led to dephasing lengths much larger than applied typical acceleration lengths. Taking advantage of the shortness of the pulses delivered by LWS-20 (<5 fs) and LWS-10 (8 fs) [3], dephasing lengths in the order of 100 μm become measureable using a highly precise and tunable injector such as shock-front injection [4]. For a given electron density within the range of 3-15 x10^19 cm-3, by changing the acceleration length, energy-tunable quasi-monoenergetic electron bunches were generated. The peak energy of the electron spectrum depended on whether the acceleration length is shorter, similar or longer than the dephasing length. Fitting the peak energy of the electron spectrum with respect to the acceleration length, yields a maximum accelerating field of (~100-200 GV/m), and most importantly, a dephasing length (~80-300 μm) for each electron density. The latter matches quite well the expected values from the linear theory. The maximum electron energy as a function of the density indicates a rather constant accelerating field. These results give a solid basis to design higher energy accelerators using longer laser pulses.

[1] T. Tajima and J.M. Dawson, Phys. Rev. Lett. 43. 267 (1979)

[2] E. Esarey, C.B. Schroeder, and W.P. Leemans, Rev. Mod. Phys. 81, 1229 (2009)

[3] K. Schmid et al., Phys. Rev. Lett. 102, 124801 (2009)

[4] K. Schmid et al., Phys. Rev. ST Accel. Beams 13, 091301 (2010)

9514-3, Session 1

Observation of collective deceleration of electrons from laser wakefield acceleration

Shao-wei Chou, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); Jiancai Xu, Shanghai Institute of Optics and Fine Mechanics (China); Konstantin Khrennikov, Ludwig-Maximilians-Univ. München (Germany); Daniel E. Cardenas, Laszlo Veisz, Max-Planck-Institut für Quantenoptik (Germany); Stefan Karsch, Ludwig-Maximilians-Univ. München (Germany)

1. Introduction

LWFA electrons have an ultra-short, sub-5 fs temporal structure accompanying with a small transverse initial size due to a bubble-like confining structure in plasma wake. These electron bunches can drive a wake field efficiently inside an underdense plasma and loses their energy. The driven plasma can be utilized as an effective accelerating structure without suffering the dephasing problem in a regular LWFA. This process has also been purposed to have several order of magnitude larger stopping power than conventional solid state beam dump without generating secondary radiation.

Here we report the first time experimental observation of collective decelerating phenomenon driven by LWPA electrons.

2. Experimental setup and results

We used ATLAS laser system at the Max-Planck-Institut für Quantenoptik as the driver. ATLAS is a Ti:Sapphire based 100 TW laser which delivers 25 fs, >2 J pulses with the central wavelength of 800 nm. The pulses were focused with energy of ~0.5 J on target to the spot size ~15 μm FWHM. The target for electron generation included a 300 μm diameter supersonic helium gas jet with a movable razor blade on the top of nozzle to produce a shock front. The abrupt density jump across shock front injected electrons into the plasma wave in a very short distance (few μm) which generated a typical electron energy spread of ~ 3 MeV regardless of peak energy, and also the peak energy was tunable from 10 MeV to a few 100 MeV . As a target for electron deceleration another 1.5 mm supersonic helium gas jet was used with a given density about few times 1018 cm-3. A permanent magnet with scintillation screen observed by a CCD camera detected the electron spectrum. Also, to exclude the situation that the observed electron spectrum was modulated by hydrodynamic interaction between two jets, the absolute gas density distribution has been determined by Rayleigh scattering and interferometry.

The measurement has shown that the electron energy as well as the total bunch charge were dumped almost completely (>90%) right after insertion of second jet. This effect was observed even with several mm separations between two jets. The observed peak deceleration gradient was up to 23.7 GeV/m and 5.1 GeV/m in average.

Under such configuration, both laser depletion length and confocal range are below 500 μm which means the laser pulse was no longer able to drive significant plasma wave after the first nozzle. However, the laser pulse can still fully ionize helium up to several mm away from focus, i.e., it pre-ionizes the background gas in the second jet. The divergence of original electron beam was ~8 mrad and total charge ~30 pC from the first jet which made an ideal short and dense bunch for driving plasma wave in second jet . The electron stopping power of helium due to collision and radiative loss is about 0.4 keV/mm which is negligible compared to our measurement.

Other effects modifying the electron spectrum are also analyzed and discussed. The results shows an excellent agreement with simulation.

9514-4, Session 1

Independent control of laser wakefield-accelerated electron-beam parameters

Donald P. Umstadter, Grigory Golovin, Shouyuan Chen, Univ. of Nebraska-Lincoln (United States); Nathan Powers, KLA-Tencor Corp. (United States); Cheng Liu, Sudeep Banerjee, Jun Zhang, Baozhen Zhao, Kevin Brown, Jared B. Mills, Univ. of Nebraska-Lincoln (United States); Chad Petersen, Univ. of Nebraska-Lincoln (United States); Ming Zeng, Zheng-Ming Sheng, Shanghai Jiao Tong Univ. (China)

We report the results of experiments on laser-wakefield acceleration of electrons, in which stable, quasi-monoenergetic, and tunable (50 to 300 MeV) electron beams were produced. A single high intensity laser pulse was focused onto a single continuous gas jet, which had adjustable density and atomic-composition profiles. Optimal profiles were found that permitted independent control over the mechanisms of electron injection, electron acceleration, and electron phase-space dynamics, and thereby, over the various output parameters of the accelerated electron beams.

9514-5, Session 2

Staging of laser-plasma accelerators
(Invited Paper)

Sven Steinke, Jeroen van Tilborg, Nicholas H. Matlis, Brian H. Shaw, Cameron C. G. R. Geddes, Anthony J. Gonsalves, Kei Nakamura, Daniel E. Mittelberger, Joost Daniels, Lawrence Berkeley National Lab. (United States); Andrew D. Roberts, Minnesota State Univ. (United States); Jean-Luc Vay, Eric H. Esarey, Carl B. Schroeder, Carlo Benedetti, Csaba Toth, Wim P. Leemans, Lawrence Berkeley National Lab. (United States)

9514-6, Session 2

Divergence reduction by adiabatic matching in laser plasma accelerators
(Invited Paper)

Irene Dornmair, Univ. Hamburg (Germany); Klaus Floettmann, Deutsches Elektronen-Synchrotron (Germany); Andreas R. Maier, Univ. Hamburg (Germany)

Plasma accelerators provide large accelerating gradients and thus promise a compact source of highly relativistic electron beams. However, these accelerating gradients are accompanied by strong focusing forces inside the plasma. Matching the beam to these forces and capturing it after the plasma requires extremely strong focusing beam optics, while a mismatch of the beam causes emittance growth. Furthermore, the large divergence after the plasma combined with beam energy spread caused by off-crest acceleration leads to chromatic emittance growth in the drift following the plasma stage.

We present a concept to reduce the divergence after extraction and to relax the beta function needed for matching into the stage by tailoring the plasma density and laser evolution. This also relaxes positioning jitter tolerances and enables emittance conservation throughout the stage. Analytical expressions for ideal plasma and laser profiles at the vacuum-plasma boundaries are derived. They are applied in simulations both in Astra and in the PIC code Warp to an externally injected beam of typical parameters.

9514-7, Session 2

Thermal emittance from laser ionization-induced trapping in plasma accelerators

Carl B. Schroeder, Jean-Luc Vay, Eric Esarey, Stepan Bulanov, Carlo Benedetti, Lawrence Berkeley National Lab. (United States); Lule Yu, Min Chen, Shanghai Jiao Tong Univ. (China); Cameron C. G. R. Geddes, Wim P. Leemans, Lawrence Berkeley National Lab. (United States)

Ultra-low emittance beams can be generated using laser ionization injection into plasma accelerators. In this paper we discuss the minimum obtainable transverse emittance (thermal emittance) of electron beams generated and trapped in plasma-based accelerators (laser- or beam-driven) using ionization injection. The initial transverse phase space distribution following ionization and passage through the ionizing laser is calculated, as well as expressions for the normalized transverse beam emittance, both along and orthogonal to the laser polarization [1]. Results are compared to particle-in-cell simulations. Examples are presented showing that normalized transverse emittances on the order of tens of nm can be generated using the two-pulse, two-color ionization injection method, where the wakefield excitation (using a long wavelength laser pulse) and ionization injection (using a short wavelength laser pulse) are independently controlled [2]. Parameters for a proof-of-principle experiment generating ultralow emittance beams using two-color ionization injection are proposed.

[1] C. B. Schroeder et al., Phys. Rev. ST - Accel. Beams 17, 101301 (2014).

[2] L.-L. Yu et al., Phys. Rev. Lett. 112, 125001 (2014).

9514-8, Session 2

Phase-space dynamics of ionization injection in plasma-based accelerators

Xinlu Xu, Fei Li, Wei Liu, Tsinghua Univ. (China); Joshi Chan, Warren B. Mori, Univ. of California, Los Angeles (United States)

The evolution of beam phase space in ionization injection into plasma wakefields is studied using theory and particle-in-cell simulations.

Starting from the photoionization process, the residual momentum of the electrons is analyzed in different configurations of laser pulses. After the lasers pass them, the electrons conduct complicated longitudinal and transverse motions in the wake. It is found that the injection process involves both longitudinal and transverse phase mixing, leading initially to a rapid emittance growth followed by oscillation, decay, and a slow growth to saturation. An analytic theory for this evolution is presented and verified through particle-in-cell simulations. This theory includes the effects of injection distance (time), acceleration distance, wakefield structure, and nonlinear space charge forces, and it also shows how ultralow emittance beams can be produced using ionization injection methods. In addition, the slice energy spread of the injected beam is also studied and ultralow slice energy spread beams can be produced in transverse injection.

9514-9, Session 3

Laser accelerated ions from near critical gaseous targets *(Invited Paper)*

Michael Helle, Daniel Gordon, Dmitri Kaganovich, U.S. Naval Research Lab. (United States); Yu-hsin Chen, Anthony Zingale, Research Support Instruments, Inc. (United States); Antonio Ting, U.S. Naval Research Lab. (United States)

Efficient laser ions acceleration can be achieved using targets at or in excess of the critical electron plasma density. Typically, this means the use of thin, <?m, solid density targets. These targets can be difficult to fabricate, are subject to contamination, require high laser contrasts, and limit operational repetion rates. Recently a high purity, thin gaseous target has been developed at the Naval Research Laboratory that operates at high repetion rates, with high gradients, and at near critical densities.

We will present experimental results of laser ion acceleration from such a target. The target is created by igniting optically driven, counter-propagating hydrodynamic shocks into the flow of a gas jet in vacuum. The shock fronts are characterized by sharp (10's ?m) density gradients and local density enhancements of ?+1/?-1, where ? is the ratio of specific heats. For molecular hydrogen, this is a factor of 6. The shocks are allowed to collide producing a 70um thick hydrogen gas region with a peak density enhancement of >10. Neutral gas interferometry measurements have verified this behavior.

Using the 10TW TFL laser system at NRL, preliminary results show peak proton energies of ~2 MeV with a Boltzmann like distribution. These results were obtained for a neutral density of 3x1020 cm-3. Assuming fully ionized hydrogen, this corresponds to a plasma density of approximately one-third critical. 3D PIC simulations of this interaction yield comparable proton energies and show characteristics of both electrostatic and inductive contributions to the acceleration process. The electrostatic contribution is due to accelerated electrons escaping from the rear of the target. The inductive accelerating field meanwhile is setup by the strong azimuthal magnetic field produced by electrons accelerating through the back of the target. This mechanism is consistent with Magnetic Vortex acceleration and acts to provide an initial "kick" to the ions. Further experimental results examining various laser parameters, and ion species will be discussed.

*This work is supported by the Naval Research Laboratory Base Program, the Department of Energy, and by NERSC

9514-10, Session 3

Laser ion acceleration in underdense plasmas *(Invited Paper)*

Alessandro Flacco, Lab. d'Optique Appliquée (France)

The propagation of ultrashort laser pulses at relativistic intensity in an underdense Helium plasma is studied in detail, exploring densities in the range of $1%$ to $10%,n_c$.

The plasma is probed to simultaneously reconstruct the evolution in time of electron density and polar magnetic field. Temperature and density variations in the created plasma cylinder results in the formation and evolution of several electron currents, giving birth to a variated and fast evolving scenario.

Magnetic fields analysis appears to be a powerful tool for inferring the properties of the currents in plasmas, revealing the richness of invoked processes and giving crucial physical insights on the interaction dynamics.

Radially accelerated ions have been measured over a wide range of conditions. Both species He+ and He++ have been observed on the transverse direction, at 85 degrees from the laser axis, to a maximum cutoff energy of ~200keV (He++). Analysis of the recorded tracks makes evident the formation of stable and strong modulations in the ion spectra.

9514-11, Session 3

Longitudinal laser ion acceleration in low density targets: experimental optimization on the Titan laser facility and numerical investigation of the ultrahigh intensity limit

Emmanuel d'Humières, Univ. Bordeaux 1 (France); Sophia N. Chen, Ecole Polytechnique (France); Mathieu Lobet, Commissariat à l'Énergie Atomique (France); Massimiliano Sciscio, Dipartimento SBAI, Sapienza, Università di Roma (Italy); Patrizio Antici, INRS Univ. (Canada); Mathieu Bailly-Grandvaux, Univ. Bordeaux 1 (France); Thomas Gangolf, Guilhem Revet, Ecole Polytechnique (France); Joao J. Santos, Univ. Bordeaux 1 (France); Anna-Marie Schroer, Heinrich-Heine-Univ. Düsseldorf (Germany); Oswald Willi, Institut für Laser- und Plasmaphysik Heinrich Heine Universität Düsseldorf (Germany); Vladimir T. Tikhonchuk, Univ. Bordeaux 1 (France); Henri Pepin, Institut National de la Recherche Scientifique (Canada); Julien Fuchs, Ecole Polytechnique (France)

Intense research is being conducted on sources of laser-accelerated ions and their applications [1]. Several experiments on the low density regime of laser ion acceleration [2] were performed in recent years. In this regime, volume effects are expected to dominate, while for solid foils, ion acceleration is directly related to the electron surface density and the number of accelerated ions is limited. Simulations therefore show that it is possible to reach high ion energies with a high number of accelerated ions and a high conversion efficiency [3]. This scheme also leads to less debris than solid foils and is more adapted to high repetition lasers.

Very promising results were recently obtained at LULI [4] and on the LLNL Titan laser in this regime [5]. In both experiments, a first ns pulse was focused on a thin target to explode it and a second laser with a high intensity was focused on the exploded foil. The delay between two lasers allowed to control the density gradient seen by the second laser pulse. The transition between various laser ion acceleration regimes depending on the density gradient length was studied. With a laser energy of a few Joules, protons with energies close to the energies of TNSA accelerated protons were obtained for various exploded foils configurations. In the high energy regime (~180 J), protons with energies significantly higher than the ones of TNSA accelerated protons were obtained when exploding the foil while keeping a good beam quality. These results demonstrate that low-density targets are promising candidates for an efficient proton source that can be optimized by choosing appropriate plasma conditions.

We report on new experiments performed on the Titan laser in 2014 using compact and dense gas jets made available recently by important progresses on nozzle optimization [6]. The experimental optimization of longitudinal laser ion acceleration will be discussed using this setup, which is very promising for several applications of laser ion acceleration.

Scaling the results we obtained on shock acceleration in the low density regime to ultra high intensities that will soon be available on installations like Apollon or ELI is a challenge. Using large scale Particle-In-Cell simulations we have also investigated and modeled the transition to this

regime in which intense beams of relativistic ions can be produced.

[1] A. Macchi et al., Rev. Mod. Phys. 85, 751 (2013)

[2] L. Willingale et al. Phys. Rev. Lett. 96, 245002 (2006); P. Antici et al. New J. Phys. 11, 023038 (2009), C. Palmer et al., Phys. Rev. Lett. 106, 014801 (2011); D. Harberger et al., Nature Physics 8, 95 (2012)

[3] E. d'Humières et al., J. Phys.: Conf. Ser. 244, 042023 (2010), F. Fiuza et al. Phys. Rev. Lett. 109, 215001 (2012), E. d'Humières et al., Phys. Plasmas 20, 023103 (2013).

[4] M. Gauthier et al. Phys. Plasmas 21, 013102 (2014).

[5] E. d'Humières, et al., Plasma Phys. Controlled Fusion 55, 124025 (2013).

[6] F. Sylla et al., Rev. of Sci. Inst. 83, 033507 (2012).

9514-12, Session 3

Observation of monoenergetic protons from a near-critical gas target tailored by a hydrodynamic shock

Yu-hsin Chen, Research Support Instruments, Inc. (United States); Michael Helle, Antonio Ting, Daniel Gordon, U.S. Naval Research Lab. (United States); Mikhail Polyanskiy, Igor Pogorelsky, Marcus Babzien, Brookhaven National Lab. (United States); Zulfikar Najmudin, Imperial College London (United Kingdom)

We present our recent experimental results of monoenergetic ion accelerated from the interaction of an intense CO2 laser pulse with a near-critical gaseous target, with its density profile tailored by a hydrodynamic shock. Previously, it has been shown from both experiments [1, 2] and simulations [3] that a key ingredient to laser-driven, monoenergetic ion beams is the shaping of the plasma density profile – a sharp rise up to a few times of the critical density within several laser wavelengths, followed by a long, exponential-like decay, is desirable. Such density profiles had been previously generated by intrinsic pulse formats such as a train of short pulses [1] or a prepulse [2]. The latter case was observed at the Accelerator Test Facility (ATF) of the Brookhaven National Laboratory where ion acceleration was correlated to a ~100 mJ prepulse 25 ns ahead of the main pulse. It is postulated that proper pre-ionization and heating creates an expanding blast wave in the plasma before the main pulse, which sets up the density profile required for ion acceleration. To properly explore this mechanism, a more controlled way of generating the required density profile instead of a rather uncontrolled prepulse is necessary.

The technique of hydrodynamic shock-assisted gas density shaping was recently developed at the U.S. Naval Research Laboratory, and protons up to 2 MeV with ~100% energy spread were produced [4]. This technique is applied to the present experiment in a different acceleration regime with the 2-TW CO2 laser at ATF. A 5-ns Nd:YAG laser pulse is focused onto a piece of stainless steel foil mounted at the front edge of the gas jet nozzle orifice in vacuum. The ablation launches a spherical shock into the near-critical hydrogen column, which creates a density depression region followed by a sharp density spike at the front edge of the target, with ~6X local density enhancement within ~<100 microns. With the tailored density profile, we have obtained monoenergetic proton beams with good shot-to-shot reproducibility and energies up to 1.5 MeV.

During our experiment, we monitored the energies of the CO2 main pulse and the prepulse. When the prepulse is below the detection limit, monoenergetic protons were recorded only with the presence of the density-shaping shock even for moderate main pulse energy. However, when a prepulse with moderate energy was present together with a very high main pulse energy, accelerated protons with large energy spreads could still be observed even when the hydrodynamic shock was turned off. Evidence of a weak and erratic shock formation by the prepulse can be seen in the density profile diagnostics. This indicates that the presence of a well-formed shock front is essential to the generation of monoenergetic protons in this regime of ion acceleration in near-critical density plasma using a TW CO2 laser.

References

[1] Haberberger et al., Nature Phys. 8, 95 (2012).

[2] Najmudin et al., presented in ATF Users' Meeting 2014.

[3] Fiuza et al., Phys. Rev. Lett. 109, 215001 (2012).

[4] Helle et al., submitted to Proceedings for AAC 2014.

9514-13, Session 3

Laser propagation effects on ion acceleration in near-critical density plasma

Martin King, Haydn W. Powell, Ross J. Gray, David A. Maclellan, Bruno Gonzalez-Izquierdo, Univ. of Strathclyde (United Kingdom); Luca C. Stockhausen, Univ. de Salamanca (Spain); George Hicks, Nicholas P. Dover, Imperial College London (United Kingdom); Dean R. Rusby, Univ. of Strathclyde (United Kingdom) and STFC Rutherford Appleton Lab. (United Kingdom); David C. Carroll, STFC Rutherford Appleton Lab. (United Kingdom); Ricardo Torres, Univ. de Salamanca (Spain); Satyabrata Kar, Queen's Univ. Belfast (United Kingdom); Zulfikar Najmudin, Imperial College London (United Kingdom); Marco Borghesi, Queen's Univ. Belfast (United Kingdom); David Neely, STFC Rutherford Appleton Lab. (United Kingdom); Paul McKenna, Univ. of Strathclyde (United Kingdom)

Ultra-intense laser (>10^20 W/cm^2) interactions with thin solid targets provides a means for the acceleration of ions up to multi-MeV energies over micron scale distances. Typically the main ion acceleration mechanism in intense laser-solid interactions is target normal sheath acceleration. However, recently there has been investigations into more promising mechanisms that can produce high flux, high energy and low energy spread ion beams. These include radiation pressure acceleration [1] (RPA), induced transparency [2] (break-out afterburner BOA) and collisionless shock-wave acceleration [3]. Depending on the thickness and composition of the target as well as the intensity and temporal profile of the laser pulse, more than one mechanism can occur. During the laser-solid interaction, the target plasma frequency can approach the frequency of the laser pulse due to particle expansion and relativistic effects. The target density can therefore decrease to the near-critical density regime such that the target becomes relativistically transparent to the laser light. When this occurs part of the intense laser pulse propagates through the expanded target, albeit in a non-uniform fashion, influencing the expanding electron and ion dynamics. To investigate this behaviour, simulations utilising particle-in-cell techniques have been undertaken for various target compositions and thickness in addition to tailored laser pulse temporal profiles and intensities. The output from these simulations are compared to measurements made during recent experimental campaigns using the Vulcan petawatt laser at the Rutherford Appleton Laboratory. We will show that the maximum energy of the beam of accelerated protons can be enhanced and their spatial-intensity distribution significantly modified by the onset of transparency.

[1] T. Esirkepov et al, Phys. Rev. Lett. 92 175003 (2004)

[2] L. Yin et al, Laser Part. Beams 24 291 (2006)

[3] L.O. Silva et al, Phys Rev Lett, 92, 015002 (2004)

9514-14, Session 4

Radiation pressure acceleration enhanced by carbon nanotube foams: the optimization problem in laser-ion acceleration *(Invited Paper)*

Jörg Schreiber, Ludwig-Maximilians-Univ. München (Germany)

Experiments have shown that the ion energy obtained by laser-ion acceleration can be optimized by choosing either the appropriate pulse duration (J. Schreiber et al., Phys. Rev. Lett. 97, 045005 (2006)) or target

thickness (A. Henig et al., Phys. Rev. Lett. 103, 245003, (2009)). This behavior can be described either by the target normal sheath acceleration (TNSA) model of Schreiber et al. or the radiation pressure acceleration (RPA) model of Bulanov and coworkers (T. Esirkepov et al., Phys. Rev. Lett. 92,175003 (2004)). The starting point of our considerations is that the essential property of a laser system for ion acceleration is its pulse energy and not its intensity. Maybe surprisingly we show that higher ion energies can be reached with reduced intensities.

Of course, these simple models make use of idealized laser parameters (such as a perfect temporal contrast), which in a given laser system may not be achieved right away. With the aid of near-critical plasma based on Carbon-Nanotube Foam (CNF) we are able to manipulate the laser just before it interacts with the ion source. Relativistically induced transparency, self-focusing and self-phase modulation in the CNF results in a laser pulse that is much better suited for laser ion acceleration from nanometer thin Diamond-Like Carbon (DLC) foils which is reflected in a 3fold energy increase of the accelerated ions. Very similar to self-guided laser-wakefield acceleration of electrons, we harvest the nonlinear properties of a plasma to self-match initially imperfect laser pulses for ion acceleration.

9514-15, Session 4

High-repetition laser-driven proton sources

Thomas Sokollik, Noaman Haq, Feng Liu, Xulei Ge, Lule Yu, Shanghai Jiao Tong Univ. (China); Zheng-Ming Sheng, Shanghai Jiao Tong Univ. (China) and Univ. of Strathclyde (United Kingdom); Jie Zhang, Shanghai Jiao Tong Univ. (China)

We will present experiments on laser driven proton acceleration. For most applications using laser driven proton sources the repetition rate as well as the practicability of the target system plays an important role. Although most sub-PW laser systems have repetition rates of 10 Hz, only rarely experiments are done at the full repetition rate. In the future the repetition rate of laser systems will most likely increase even further (partially due to the demands of Laser Wakefield Accelerators [1,2]). Therefore it is important to investigate high repetition target systems and to explore the new possibilities connected with this type of targets.

Currently there are only a limited number of target systems and diagnostics available to support high repetition rates (such as droplet systems [3] and tape drives [4]). In addition, many techniques to optimize the acceleration condition are currently neglected. Online optimization or even optimization using evolutionary algorithms could increase the proton energies and stability. Increasing the shot numbers also allows for detailed study of laser parameter and proton beam correlation.

We will present experiments using a Tape Drive, as the first step towards high repetition target systems. We will show laser proton beam correlation, stability studies as well as proton beam optimizations.

References:

[1] W.P. Leemans, et. al., Nature Physics 2, 696 (2006)

[2] G. Mourou, et. al., Nature Photonics 7, 258 (2013)

[3] T. Sokollik, et.al., Phys. Rev. Lett. 103 (13), 135003 (2009)

[4] AS. Pirozhkov, et al., Proceedings of SPIE, 7354, 735414 (2009)

9514-16, Session 4

Maximum attainable ion energy in the radiation pressure acceleration regime

Stepan Bulanov, Univ. of California, Berkeley (United States) and Lawrence Berkeley National Lab. (United States); Eric H. Esarey, Carl B. Schroeder, Lawrence Berkeley National Lab. (United States); Sergei V. Bulanov, Timur Z. Esirkepov, Masaki Kando, Japan Atomic Energy Agency (Japan); Francesco Pegoraro, Univ. di Pisa (Italy); Wim P. Leemans, Lawrence Berkeley National Lab. (United States)

Radiation Pressure Acceleration (RPA) is a highly efficient mechanism of laser driven ion acceleration, with the laser energy almost totally transferrable to the ions in the relativistic regime. In this regime the RPA of a thin solid density foil is estimated to produce ions with the maximum energy proportional to the laser pulse fluence (F, incident laser energy per unit area) and inversely proportional to the areal density (nel) of the foil (E=F/nel). However this estimate does not take into account the effect of the laser pulse group velocity being smaller than the light vacuum speed. This effect imposes a fundamental limit on the maximum attainable ion energy, i.e., the ion velocity can not exceed the group velocity of the laser. It is shown through the solution of the equations of motion of the solid density foil under the action of the laser pulse with the group velocity smaller than the light vacuum speed, that the maximum ion velocity is limited by the group velocity of the laser .

In the case of a tightly focused laser pulses, which are utilized to get the highest intensity, another factor limiting the maximum ion energy comes into play, the transverse expansion of the target. The RPA of a thin foil by a diffracting laser pulse leads to the termination of the acceleration due to increasing transparency of the expanding foil. Moreover the transverse expansion effects dominate over the group velocity effects in the case of thin foils.

It is shown that these two limitations can be mitigated by the utilization of an external guiding structure for the laser pulse: the composite target consisting of the thin foil followed by a slab of near critical density (NCD) plasma. The NCD slab provides guiding of the laser pulse during the acceleration process, preventing the diffraction of the laser pulse and thus preserving high intensity throughout the acceleration process. The comparison of a single foil RPA and a composite target RPA in Particle-in-Cell simulations shows that in the latter case the ions have the energy several times larger than in the former case, thus greatly increasing the effectiveness of the RPA regime of laser driven ion acceleration. However the group velocity effects in an NCD plasma begin to play more important role than in the case of a single foil target.

This work is supported by the Office of Science of the US DOE under Contract No. DE-AC02-05CH11231 and No. DE-FG02-12ER41798.

9514-17, Session 4

Influence of the strong self-generated magnetic field on ion acceleration during laser-solid target interaction

Chengkun Huang, Sasikumar Palaniyappan, Juan C. Fernández, Los Alamos National Lab. (United States)

The interaction of a high intensity laser with a low areal density solid target (including ultra-thin foils and low density foams) is often accompanied by laser breakout and strong longitudinal electron current channel at the backside of the target. The electron current can generates azimuthal magnetic field exceeding hundreds of MegaGauss, which plays an important role in the dynamics of the electrons near the focal volume or those surrounding the current channel. We present fully kinetic, relativistic Particle-In-Cell simulations that reveal the detail dynamics that lead to enhancement to the ion beam as electrons are magnetically trapped and then released when the laser exits the target. Comparison will be made with recent relevant experiments at the LANL Trident facility. We will also discuss how such interaction can be used to produce high energy ions with smaller energy spread and high conversion efficiency that may be useful for a number of applications.

Work supported by the U.S. Department of Energy through the LDRD program at Los Alamos National Laboratory.

9514-18, Session 4

Simultaneous focussing and post-acceleration of laser accelerated proton beams

Hamad Ahmed, Stayabrata Kar, Queen's Univ. Belfast (United Kingdom); Stephanie Brauckmann, Heinrich-Heine-Univ. Düsseldorf (Germany); Giada Cantono, Queen's Univ. Belfast (United Kingdom); Anna L. Giesecke, Heinrich-Heine-Univ. Düsseldorf (Germany); Fiona M. Hanton, Ciaran L. S. Lewis, Queen's Univ. Belfast (United Kingdom); Andrea Macchi, Istituto Nazionale di Ottica (Italy); Kealan Naughton, Gagik Nersisyan, Queen's Univ. Belfast (United Kingdom); Alex P. L. Robinson, STFC Rutherford Appleton Lab. (United Kingdom); Oswald Willi, Heinrich-Heine-Univ. Düsseldorf (Germany); Matthew Zepf, Marco Borghesi, Queen's Univ. Belfast (United Kingdom)

Since the first observation of proton beam generated in the interaction of intense laser pulses (> 1018W/cm2) with thin foils, significant attention has been devoted to laser-driven acceleration of ions in view of potential applications in science, industry and health care [1]. Proton beams driven by intense lasers via the Target Normal Sheath Acceleration (TNSA) mechanism, have unique properties such as high brightness, laminarity and short burst duration. However, some inherent shortcomings, such as large divergence and broad energy spectra pose significant scientific and technological challenges to the application of these sources. Here, we present a novel target geometry to create a pulsed, traveling charge device for controlling the spectral and angular properties of the proton beams, by exploiting transient self-charging of the target during the interaction [2]. In this target geometry, a helical coil (HC) is attached to the rear surface of the interaction foil aligned to the target normal in such a way that the protons generated from the rear surface of the foil propagate through the HC synchronously with a charge pulse generated during the same interaction. The localised electric field (>109 V/m) generated by the travelling charge pulse acts as both a focusing and an accelerating field. A quasi-collimated and quasi-monoenergetic (~10% energy spread) proton beam of >107 particles at 10 MeV was observed, by employing the TARANIS laser system at Queen's University Belfast. Varying the physical parameters of the coil allows tailoring the process to a desired portion of the spectrum. Particle tracing simulations corroborated the observations of proton beam focusing and post-acceleration. This technique provides a novel platform for producing high-energy collimated ion beams for applications.

Reference:

1. A. Macchi, M. Borghesi and M. Passoni, Rev. Mod. Physics, 85, 751 (2013).

2. K. Quinn et. al., Phys. Rev. Lett., 102, 194801 (2009); J.L. Dubois et. al., Phys. Rev. E, 89, 013102 (2014); S. Kar et. al., Phys. Rev. Lett., 100, 105004 (2008).

9514-19, Session 4

Optimisation of plasma mirror reflectivity and optical quality using double laser pulses

Graeme G. Scott, Central Laser Facility (United Kingdom)

In experimental laser plasma physics, amplified spontaneous emission (ASE) from the laser chain irradiates a target nanoseconds prior to an ultrashort pulse arrival. Whilst the ASE level is often six to ten orders of magnitude less intense than the ultrashort pulse, modern laser systems can exceed focussed intensities of 1021 Wcm-2, meaning that even at a low intensity ratio, or contrast level, the ASE can cause preplasma expansion to occur prior to the main pulse arrival. With the highly nonlinear laser plasma interactions depending sensitively on preplasma conditions, the contrast level must be controlled and the plasma mirror is an optical tool which allows it to be enhanced by more than two orders of magnitude.

When employing a plasma mirror, up to 30 % of the laser energy can be absorbed per interaction, which can make this an unattractive solution to contrast enhancement when investigating phenomena with sensitive energy dependence. This can be a particular problem when double plasma mirrors are required for the necessary contrast enhancement. However, we will present results showing that the plasma mirror reflectivity can be increased to as much as 96 % by introducing a low intensity prepulse, picoseconds prior to the main pulse interaction. One dimensional particle in cell simulations show that the plasma mirror reflectivity enhancement is a result of the main pulse interaction with a finite scale length preplasma created by the prepulse. These results show that a short scale length preplasma of around 0.1 ?m is optimum for peak reflectivity, which is achieved under our experimental condition for an inter pulse time delay of 3 ps.

The main pulse far field is recorded as a function of the inter pulse time delay and it is found that the plasma mirror has a temporal window for usable operation of up to 5 ps after the prepulse interaction. This temporal window is understood in terms of perturbations on the expanding critical surface of the plasma mirror, which govern its optical quality.

9514-20, Session 5

Observing the dynamics of a laser-driven plasma electron accelerator *(Invited Paper)*

Malte C. Kaluza, Abbe School of Photonics (Germany)

When generating relativistic plasmas with high-power laser pulses, small-scale particle accelerators can be realized producing particle pulses with parameters complementary to conventional accelerators. To further improve the stability of these particle pulses and to ultimately be able to tailor the energy spectrum toward the pulses suitability for various applications, the physics underlying the different acceleration scenarios need to be understood as completely as possible.

To be able to resolve the evolution of these acceleration processes, diagnostics well-suited for this plasma environment need to be designed and realized. In this presentation, results from an optical probing technique will be presented [1, 2]. Due to the combination of a multi-TW laser system with a synchronized few-cycle probe pulse, images of few-fs temporal and mm spatial resolution can be taken from a laser-plasma accelerator [3]. The application of this diagnostic has lead to the first time-resolved visualization of the plasma wave with unprecedented temporal and spatial detail. We could observe for the first time the formation, its non-linear evolution, the actual breaking of the plasma wave and ultimately its transformation into one single remaining plasma wave oscillation, also referred to as the plasma bubble [4]. These results will be discussed in detail and compared to the results from multi-dimensional numerical simulations.

References

[1] M. C. Kaluza et al., Physical Review Letters 105, 115002 (2010)

[2] A. Buck et al., Nature Physics 7, 543 (2011)

[3] M. B. Schwab et al., Applied Physics Letters 103, 191118 (2013)

[4] A. Sävert et al., submitted (2014)

9514-21, Session 5

A laser-plasma lens for laser-plasma accelerators

Cédric Thaury, Remi Lehe, Emilien Guillaume, Ecole Polytechnique (France); Andreas Döpp, Ecole Polytechnique (France) and Univ. de Salamanca (Spain); Kim Ta Phuoc, Ecole Polytechnic (France); Agustin Lifschitz, Victor Malka, Ecole Polytechnique (France)

Laser-wakefield accelerators (LWFA) can generate electron beams with hundreds of MeV over only a few millimeters. They have been considered for many applications, including compact colliders (by staging several LWFA), as well as compact synchrotron sources and free-electron lasers (by combining an LWFA with an undulator). Yet, the feasibility of both of these applications partly relies on the ability to focus the electron beam in the device. This transport can be achieved by quadrupole lenses. But, because of the large divergence and energy spread of electron beams accelerated in LWFA, the beam transverse emittance increases steeply in the first centimeters of the transport line [PRSTAB 6, 011302 (2013)]. As a result, the electron beam at the end of the line is useless for most applications.

As they can sustain very high-gradient fields, plasmas are ideal candidates to focus an electron beam over a very short distance. The plasma lens [Particle Accelerators 20, 171 (1987)] was the first focusing system to exploit these plasma fields. However, it is not applicable to electron beams from LWFA, because of the ultrashort duration of these beams (the field is very non-uniform for most electrons from the beam [PoP 21, 043104 (2014)]). Here we propose a new focusing system, the laser-plasma lens, which avoids the drawbacks of the plasma lens.

First, we discuss the theory of the laser-plasma lens. Two configurations are investigated, a single-laser-beam scheme and a two-laser-beam scheme. The single-beam scheme is robust and easy to implement. It is well suited for electron energies around 200 MeV. Conversely, the two-beam scheme, although more complicated to implement, is more promising for multi-GeV beams.

In the second part, we present an experimental demonstration of the laser-plasma lens, in the single-beam scheme. The lens was used as a collimator, leading to the reduction of the divergence by 2.6 for 280 MeV electron beams. This increases by a factor of 7 the length over which the beam can propagate without emittance growth. For high quality electron beams from LWFA, this length could exceed 35 cm, which should be sufficient to transport the beam with a quadrupole lens.

9514-22, Session 5

Experimental demonstration of a tappered laser-plasma accelerator

Emilien Guillaume, Andreas Döpp, Cédric Thaury, Kim Ta Phuoc, Agustin Lifschitz, Julien Gautier, Victor Malka, Lab. d'Optique Appliquée (France)

Laser-wakefield acceleration (LWFA) can accelerate electrons up to a few GeV in a few centimeters-long plasma using a capillary target [Leemans W. et al., Nature Physics 2, 696 - 699 (2006)]. However, such targets have a limited lifetime and require a really precise alignment to inject the laser pulse. A millimeter-long plasma created from a gas jet does not present these disadvantages, but is too short to reach GeV energies. The generation of more energetic electron beams over a few millimeters requires a tapered plasma density with a positive gradient in the direction of the pulse propagation. The virtue of using the tapered density is to mitigate the dephasing effect of the electrons from the wakefield. This technique was studied numerically [Sprangle P. et al., Phys. Rev. E, Vol. 63, 056405 (2001), Hur MS. et al., Phys. Plasmas 18, 033102 (2011)] and experimentally [Kim J. et al., Journal of the Korean Physical Society, Vol. 59, No. 5 (2011)] for a slow upward density gradient. Here we propose to use a sharp upward density transition to rephase the electrons with the wakefield and enhance their energy.

First, we present the experimental scheme that allows for generation of a sharp upward plasma density transition by introducing a knife edge into the gas jet. Such a technique can generate density steps as sharp as the plasma wavelength. This tapered plasma density is then used to generate electron beams of few hundreds of MeV in a 3 mm gas jet. Then, we discuss the experimental demonstration of the electron rephasing process. In the case without shock, self-injection of electrons takes place over more than 1 mm. The head of the electron bunch reaches the decelerating region of the bubble before the end of the jet and is thus decelerated. With the shock, the electron spectrum drastically changes after the bunch crosses the density transition. The bubble size is reduced, and the decelerating region is positively shifted along the laser axis. The electron bunch, which was close to dephasing, finds itself at the tail of the contracted bubble and is rapidly accelerated. The electrons cut-off energy is increased by a factor 1.4 with the shock, from 300 MeV to 420 MeV. This energy boosting technique would allow to reach higher energies in few millimeters-long gas jets.

9514-23, Session 5

Plasma wakefields driven by an incoherent combination of laser pulses

Eric H Esarey, Carlo Benedetti, Carl Schroeder, Wim Leemans, Lawrence Berkeley National Lab (United States)

The wakefield generated in a plasma by incoherently combining a large number of low energy laser pulses (i.e., without constraining the pulse phases) is studied analytically and by means of fully self-consistent particle-in-cell simulations. The structure of the wakefield has been characterized and its amplitude compared with the amplitude of the wake generated by a single (coherent) laser pulse. We show that, in spite of the incoherent nature of the wakefield within the volume occupied by the laser pulses, behind this region, the structure of the wakefield can be regular with an amplitude comparable or equal to that obtained from a single pulse with the same energy. Wake generation requires that the incoherent structures in the laser energy density produced by the combined pulses exist on a time scale short compared to the plasma period. Incoherent combination of multiple laser pulses may enable a technologically simpler path to high-repetition rate, high-average power laser-plasma accelerators, and associated applications.

9514-24, Session 5

Positron acceleration in the doughnut blowout regime

Jorge M. Vieira, José T. Mendonça, Luís O. Silva, Univ. Técnica de Lisboa (Portugal)

Most remarkable plasma based electron acceleration results were reached in strongly non-linear regimes. Positrons, however, can not reach high energies in the non-linear regime because corresponding transverse focusing forces defocus positrons. As a result, the typical acceleration distances are limited to the distance they travel before being defocused. Typically, these distances are orders of magnitude shorter than the distances required for the acceleration of positrons to high energies. As a result, novel plasma based positron acceleration mechanisms would open new research paths for future plasma based colliders. Here we show analytically and through 3D OSIRIS simulations that non-linear wakefields driven by intense and short Laguerre-Gaussian lasers [1] have ideal properties for positron focusing and acceleration [2]. We demonstrate that positron focusing-fields in the doughnut blowout driven by the Laguerre Gaussian laser can be up to an order of magnitude larger than electron focusing in a spherical blowout. In addition, accelerating gradients are similar to those associated with the spherical blowout regime. Three-dimensional simulations then demonstrate stable positron propagation in a doughnut blowout region that can also self-guide the Laguerre-Gaussian laser until its energy has been nearly fully depleted to the plasma. Other realisations of the scheme, using multiple Gaussian laser pulses, will also be explored.

[1] J.T. Mendonça and J. Vieira, PoP 21 033107 (2014)

[2] J. Vieira and J.T. Mendonca, PRL 112 215001 (2014)

9514-25, Session 5

Emittance control of electron and positron beams in laser plasma accelerators

Lule Yu, Shanghai Jiao Tong Univ. (China) and Lawrence Berkeley National Lab. (United States); Carl B. Schroeder, Eric H. Esarey, Jean-Luc Vay, Carlo Benedetti, Lawrence Berkeley National Lab. (United States); Feiyu Li, Min

Chen, Suming Weng, Zheng-Ming Sheng, Shanghai Jiao Tong Univ. (China); Cameron C. G. R. Geddes, Wim P. Leemans, Lawrence Berkeley National Lab. (United States)

The tremendous progress over the last decade in the field of laser-driven plasma-based accelerators has attracted interest in a compact plasma-based electron-positron collider[1,2]. We propose to use a combination of Hermite-Gaussian laser modes to generate a nonlinear ring bubble with a large longitudinal accelerating field and a transverse focusing field suitable for positron beam focusing and acceleration. The nonlinear bubble can provide higher accelerating gradients compared with a linear plasma wake. PIC simulations were used to demonstrate control of the focusing force by changing the relative intensity ratio of the two laser modes, enabling matched beam propagation for emittance preservation. In addition, in order to improve beam phase space characteristicas, and, in particular, to reduce transverse emittance, we proposed to generate ultra-low emittance (10^{?8} m rad), femtosecond electron beams using two-color laser-ionization injection methods [3]. By controlling the amplitude and the duration of the injection pulse, the emittance can be controlled.

Reference:

[1] E. Esarey, C. B. Schroeder, and W. P. Leemans, Rev. Mod. Phys. 81, 1229(2009).

[2] W. P. Leemans and E. Esarey, Phys. Today 62, 44 (2009).

[3] L.-L. Yu, E. Esarey, C. B. Schroeder, J.-L. Vay, C. Benedetti, C. G. R. Geddes, M. Chen, and W. P. Leemans, Phys. Rev. Lett.112, 125001 (2014).

9514-26, Session 6

Laser Generation of Ultra-Short Neutron Bursts From High Atomic Number Converters *(Invited Paper)*

Ishay Pomerantz, Eddie McCary, Alexander R. Meadows, Alexey Arefiev, Aaron C. Bernstein, Clay Chester, Jose Cortez, Michael E. Donovan, Gilliss Dyer, Erhard W. Gaul, David Hamilton, Donghoon Kuk, Arantxa C. Lestrade, Chunhua Wang, Todd Ditmire, Björn M. Hegelich, The Univ. of Texas at Austin (United States)

At the Texas Petawatt laser facility we developed a novel ultra-short pulsed laser-driven neutron source generating an unprecedented output flux [1]. Our results show a dramatic onset of high-energy electron generation from petawatt laser-irradiated plastic targets for targets thinner than a few microns. In this regime, the copious amounts of multi-MeV electrons emitted from the target are utilized to generate photo-neutrons from a metal converter. The neutrons are generated with a <50 ps pulse duration and a flux of 10^18 n/cm^2/s, exceeding any other pulsed or CW neutron source. I will discuss the prospects of ultrafast neutron science and particularly its application in Fast Neutron Resonance Radiography.

[1] I. Pomerantz, et. al, Phys. Rev. Lett. 113, 184801 (2014).

9514-27, Session 6

Laser-driven proton and electron acceleration in high-field plasmonic regime

Luca Fedeli, Andrea Sgattoni, Istituto Nazionale di Ottica (Italy); Giada Cantono, CEA-Ctr. de SACLAY (France); Irene Prencipe, Matteo Passoni, Dipartimento di Energia, Politecnico di Milano (Italy); Ondrej Klimo, Jan Proska, Czech Technical University in Prague · Department of Physical Electronics (Czech Republic); Andrea Macchi, Istituto Nazionale di Ottica (Italy); Tiberio Ceccotti, CEA-Ctr. de SACLAY (France)

Laser-driven sources of high-energy electrons, ion and photons (including both incoherent and coherent XUV emission) have unique properties such as ultrashort duration, large particle numbers and high brilliance, which yields a great potential in several applications. In this context, increasing the laser pulse energy coupling becomes a primary importance goal. Through the interaction of high intensity (>1019 W/cm2) and high contrast (?1012) laser pulses with targets showing a periodic groove on the irradiated surface, we were able to show a marked increase of energy absorption around the incidence angle expected for the resonant excitation of surface wave and the related increase, by a factor of 2.5, of the cutoff energy of TNSA protons [1]. The talk presents our more recent results about proton and electron acceleration in this high field plasmonic regime. In particular, we report the first, to our knowdlege, measurements of an high energy (≈10 MeV) electron beam driven by plasmon surface waves along the target surface.

[1] T. Ceccotti et al, Phys. Rev. Lett. 111, 185001 (2013)

9514-28, Session 6

Proton acceleration in high-intensity laser-plasma interactions from liquid hydrogen jets

Christian Roedel, SLAC National Accelerator Lab. (United States) and Friedrich-Schiller-Univ. Jena (Germany); Sebastian Goede, Will Schumaker, Maxence Gauthier, Luke B. Fletcher, Alessandra Ravasio, Rohini Mishra, Philipp Sperling, SLAC National Accelerator Lab. (United States) and Stanford Institute for Materials and Energy Sciences (United States); Frederico Fiuza, Lawrence Livermore National Lab. (United States) and SLAC National Accelerator Lab. (United States); Siegfried H. Glenzer, SLAC National Accelerator Lab. (United States) and Stanford Institute for Materials and Energy Sciences (United States)

Proton acceleration from the interaction of a femtosecond high power laser with a liquid hydrogen jet is discussed which marks one of the most promising ways for a compact laser-based proton accelerator of high repetition rate. Recent experimental results from the high power laser at MEC/SLAC are presented which have demonstrated laser-proton acceleration at a repetition rate of 1 Hz using Target Normal Sheath Acceleration (TNSA). The proton spectra show an exponential profile with a proton cutoff in the order of 1 MeV. The proton spectra are compared to ion acceleration from thin foils (Al, Co, Au,). It is shown that the maximum proton energy that is achieved with the hydrogen jet is comparable to the proton cutoff from thin metal foils.

Simulations reveal that the maximum ion energy can be strongly enhanced when the maximum plasma density is reduced. For typical laser and target parameters, it is found that the optimum plasma density is around 6nc. Therefore, the laser pulse can burn through the near-critical plasma thus increasing absorption and the accelerating fields.

Moreover, the transition to the regime of Collisionless Shockwave Acceleration (CSWA) is discussed which holds promise of high proton energies with small energy spread. For entering the regime of CSWA with optical high power lasers, the importance of a shaped plasma density will be highlighted.

9514-29, Session 6

Low-temperature resistivity effects on fast electron transport in solids

Paul McKenna, David A. MacLellan, Univ. of Strathclyde (United Kingdom); David C. Carroll, STFC Rutherford Appleton Lab. (United Kingdom); Ross J. Gray, Univ. of Strathclyde (United Kingdom); Alex P. L. Robinson, STFC Rutherford Appleton Lab. (United Kingdom); Michael

Desjarlais, Sandia National Labs. (United States); Haydn W. Powell, Univ. of Strathclyde (United Kingdom); Nicola Booth, Graeme G. Scott, STFC Rutherford Appleton Lab. (United Kingdom); Matthias Burza, Lund Univ. (Sweden); Xiaohui Yuan, Shanghai Jiao Tong Univ. (China); David Neely, STFC Rutherford Appleton Lab. (United Kingdom); Claes-Goran Wahlstrom, Lund Univ. (Sweden)

The physics of the transport of large currents of fast, relativistic electrons in dense matter underpins numerous applications of high power lasers, including the properties of beams of sheath-accelerated ions, the generation of intense X-rays sources and the fast ignition approach to inertial confinement fusion. An ability to completely change the transport pattern could have radical implications for these applications. We have recently demonstrated that completely new types of fast electron transport patterns can be generated by understanding and controlling the target electrical resistivity evolution at temperatures as low as a few eV [1-4]. We have also shown that lattice structure plays an important role in defining the electrical resistivity of materials irradiated by intense, sub-picosecond laser pulses, and that the resulting resistive magnetic field and feedback on the fast electron beam transport are strongly affected.

We report on a new experimental and numerical investigation into the effects of lattice melt on the properties of resistive magnetic fields and fast electron transport in solids which are isochorically pre-heated using laser-accelerated protons [5]. Tailoring the heating profile enables the resistive magnetic fields which strongly influence the current propagation to be manipulated. We demonstrate that the divergence, spatial-intensity profile and symmetry of the fast electron beam can be actively manipulated by tailoring temperature and resistivity gradients within the target.

[1] P. McKenna et al, Phys. Rev. Lett. 106, 185004 (2011)

[2] D. A. MacLellan et al., Phys. Rev. Lett, 111, 167588 (2013)

[3] D. A. MacLellan et al., Laser Part. Beams, 13, 0263-0346 (2013)

[4] D. A. MacLellan et al., Plasma Phys. Control. Fusion, 56 084002 (2014)

[5] D. A. MacLellan et al., Phys. Rev. Lett, At press (2014)

9514-30, Session 6

Investigation of collective electron dynamics in relativistically transparent laser-foil interactions

Ross J. Gray, David A. MacLellan, Bruno Gonzalez-Izquierdo, Haydn W. Powell, Univ. of Strathclyde (United Kingdom); David C. Carroll, Central Laser Facility (United Kingdom); Christopher D. Murphy, The Univ. of York (United Kingdom); Luca C. Stockhausen, The Ctr. for Ultrashort Ultraintense Pulsed Lasers (Spain); Dean R. Rusby, Graeme G. Scott, Central Laser Facility (United Kingdom); Robbie Wilson, Univ. of Strathclyde (United Kingdom); Nicola Booth, Daniel R. Symes, Steven J. Hawkes, Central Laser Facility (United Kingdom); Ricardo Torres, The Ctr. for Ultrashort Ultraintense Pulsed Lasers (Spain); Marco Borghesi, Queen's Univ. Belfast (United Kingdom); David Neely, STFC Rutherford Appleton Lab. (United Kingdom); Paul McKenna, Univ. of Strathclyde (United Kingdom)

The interaction of an intense laser pulse with a solid target produces high energy electrons at the target-vacuum boundary. For sufficiently high laser intensities and thin foil targets, the target electrons become highly relativistic and rapidly expand into vacuum, lowering the peak electron density. The relativistic increase in the electron mass increases the critical density of the plasma. The combination of these two factors can result in the target electron density decreasing below the relativistically-corrected critical density at a given point in the laser pulse, thereby enabling the remainder of the laser pulse to propagate through the target and in the process interact with the bulk target electrons.

In this work we present a measured asymmetry in the collective dynamics of ponderomotively-driven electrons in the interaction of an ultraintense laser pulse with a relativistically transparent target. The 2D profile of the beam of accelerated electrons is shown to change from an ellipse aligned along the laser polarization direction in the case of limited transparency, to a double-lobe structure aligned perpendicular to it when a significant fraction of the laser pulse co-propagates with the electrons. We further demonstrate control over the collective electron dynamics by changing the laser-pulse length and intensity. The temporally-resolved dynamics of the interaction are investigated via particle-in-cell simulations. The results provide new insight into the collective response of charged particles to intense laser fields over an extended interaction volume, which is important for a wide range of applications, and in particular for the development of promising new ultraintense laser driven ion acceleration mechanisms involving ultrathin target foils.

9514-31, Session 6

Analytical nonlinear model of the relativistic laser-ion acceleration

Yongsheng Huang, China Institute of Atomic Energy (China)

A nonlinear analytical solution is proposed to describe the relativistic ion acceleration with the local Maxwell-J€uttner relativistic distribution electrons. With our model, the potential is finite naturally and has an upper limitation proportional to the square root of the electron temperature. The divergent potential in the non-relativistic case is the linear items of the Taylor expansion of that obtained relativistic one here. The energy distribution of ions and the dependence of the ion momentum on the acceleration time are obtained analytically. Maximum ion energy has an upper limitation decided by the finite potential difference. The analytical results may also suitable for BOA mechanism of ion acceleration.

9514-32, Session 7

ultrahigh brilliance multi-MeV gamma-ray beam from nonlinear Thomson scattering *(Invited Paper)*

Gianluca Sarri, Queen's Univ. Belfast (United Kingdom)

We report on the generation of a narrow divergence (2.5 mrad), multi-MeV (EMAX = 18 MeV) and ultra-high brilliance (> 2 10^19 photons s^-1 mm^-2 mrad^-2 0.1% BW) gamma-ray beam from the scattering of an ultra-relativistic laser-wakefield accelerated electron beam in the field of a relativistically intense laser (dimensionless amplitude a0 = 2). The spectrum of the generated gamma-ray beam is measured, with MeV resolution, seamlessly from 6 MeV to 18 MeV, giving clear evidence of the onset of non-linear Thomson scattering. The photon source has the highest brilliance in the multi-MeV regime ever reported in the literature.

9514-33, Session 7

Betatron radiation from laser-plasma accelerators *(Invited Paper)*

Felicie Albert, Lawrence Livermore National Lab. (United States)

To meet the increasing requirements of examining and understanding high-energy-density (HED) science phenomena on extremely short space- and timescales, it is necessary to develop novel and accessible light sources. We are developing one of the most promising applications of laser-wakefield accelerators—betatron radiation—to probe HED plasmas with unprecedented time resolution. This unique broadband, collimated (<30 mrad) source of hard x-rays (1–100 keV), with sub-ps pulsewidths, is produced by electrons accelerated and wiggled in the wake of a high intensity laser pulse in a plasma. When a short laser pulse

with an intensity I > 1018 W/cm2 is focused inside a plasma, the laser ponderomotive force expels the plasma electrons away from the strong intensity regions to form an ion bubble in the wake of the pulse. Electrons trapped at the back of this structure are accelerated and wiggled by the focusing forces to produce broadband, synchrotron-like radiation in the keV energy range. Studies have implied that betatron x-rays have a source size of a few microns, a divergence of less than 100 mrad, a pulse duration of less than 100 fs, and a broadband spectrum in the keV energy range. Betatron x-rays are also directly related to the electrons emitting them, and thus the radiative properties of the source can be a diagnostic of the LWFA acceleration process. We will review betatron radiation experiments performed with various high intensity lasers such as Titan and Callisto at the LLNL Jupiter Laser Facility and others.

9514-34, Session 7

Laser wakefield acceleration of electrons for radiation generation

Anatoly M. Maksimchuk, Zhen Zhao, Keegan Behm, Univ. of Michigan (United States); Jonathan J. Wood, Jason Cole, Imperial College London (United Kingdom); Vladimir V. Chvykov, Univ. of Michigan (United States); Stuart P. D. Mangles, Zulfikar Najmudin, Imperial College London (United Kingdom); Victor P. Yanovsky, Alexander G. R. Thomas, Karl M. Krushelnick, Univ. of Michigan (United States)

Experiments using the Hercules laser at the University of Michigan have shown that control of the electron beam from Laser Wakefield Acceleration can be used in order to optimize the generation of betatron x-ray radiation. This can be achieved by: i) extending the interaction length to increase the overall flux, ii) use of ionization injection to increase the lower energy x-rays, iii) off-axis injection of electrons in a density gradient to produce a very-monoenergetic and divergent "ring" of high energy electrons which increases the flux of x-rays by about an order of magnitude. Preliminary measurements of dynamic x-ray phase contrast imaging and time resolved x-ray absorption spectroscopy will also be discussed.

9514-35, Session 7

Analysis of electron injection in Laser Wakefield Acceleration using betatron emission in capillary tubes

Frédéric G. Desforges, Bhooshan S. Paradkar, Univ. Paris-Sud 11 (France); Martin Hansson, Lund Univ. (Sweden); Thomas L. Audet, Jinchuan Ju, Univ. Paris-Sud 11 (France); Isabel M Gallardo-González, Bastian Aurand, Department of Physics, Lund University (Sweden); Patrick Lee, Laboratoire de Physique des Gaz et Plasmas (France); Lovisa Senje, Anders Persson, Lund Univ. (Sweden); Sandrine Dobosz-Dufrénoy, CEA-Ctr. de SACLAY (France); Olle Lundh, Lund Univ. (Sweden); Gilles Maynard, Univ. Paris-Sud 11 (France); Pascal Monot, CEA-Ctr. de SACLAY (France); Jean-Luc Vay, Lawrence Berkeley National Lab. (United States); Claes-Göran Wahlström, Lund Univ. (Sweden); Brigitte Cros, Univ. Paris-Sud 11 (France)

Laser Wakefield Acceleration (LWFA) of electrons is a promising scheme for the development of compact accelerators and bright, short-wavelength radiation sources. In LWFA, a plasma wave, driven in a plasma with electron number density larger than 1018 cm-3 by an intense short pulse laser (T ≈ 40 fs and I0 ? 1018 W/cm?), traps and accelerates electrons to relativistic energies. The accelerated electrons wiggle in the transverse field of the plasma cavity and radiate x-ray beams with brightness comparable to synchrotron X-ray sources. The number of X-ray photons produced depends on the nonlinear evolution of the laser beam and the plasma density, and is closely related to the dynamics of the electrons trapped in the plasma cavity.

The analysis of the X-ray beam provides a method to investigate the injection of electrons into the plasma cavity. We have used it to study the dynamics of electron injection in the plasma wave in the case of pure hydrogen and compared it to the case of a mixture with 1% nitrogen.

By performing an experiment inside long dielectric capillary tubes, the emitted radiation can be analyzed through a method similar to pinhole imaging. Using this technique, it can be shown that ionization-induced injection occurs in our experimental conditions at a lower value of intensity than the threshold for self-injection. With the help of numerical simulations, we demonstrate that early injection of ionization-induced trapped electrons in the ion cavity suppresses the self-injection of electrons.

9514-36, Session 7

X-Ray imaging of ultrafast magnetic reconnection driven by relativistic electrons

Anthony Raymond, Andrew McKelvey, Calvin A. Zulick, Victor Chykov, Anatoly M. Maksimchuk, Alexander G. R. Thomas, Louise Willingale, Univ. of Michigan (United States); Vladimir Yanovsky, Univ. of Szeged (Hungary); Karl M. Krushelnick, Univ. of Michigan (United States); Will Fox, Amitava Bhattacharjee, Princeton Plasma Physics Lab. (United States)

Magnetic reconnection (MR) events driven by relativistic electrons are observed between two high intensity laser/plasma interaction sites producing relativistic electron outflows. The two laser focuses were on average 20um FWHM containing 50TW of power each, delivered with a split f/3 paraboloid onto copper foil targets at a focused intensity of 10^19 W/cm^2 with the HERCULES laser system. Cu K-alpha emissions from the interactions were imaged with a spherically bent Quartz crystal with a 2d=3.082A lattice spacing, and by motorizing one half of the paraboloid vertically the focal separation was varied between 0-200um.

Splitting the beam halves revealed an enhanced region between the foci with the highest K-alpha signal intensity at an inter-beam separation of 150um, evidencing inflow from relativistic electron driven MR. A filtered LANEX screen was imaged to search for outflow/jet electrons along the plane of the target surface and normal to the axis defined by the two spots, demonstrating relativistic electrons with E>150keV and with spatial profile nonuniformities potentially directly originating from reconnection events; varying target geometries were used to investigate the resulting effects on the spatial electron profiles. 2D and 3D PIC simulations were conducted to better understand and model the measured electron outflow dynamics.

9514-37, Session 7

Development of single-shot ultrafast electron diffraction system using laser wakefield accelerated electrons

Nobuhiko Nakanii, Tomonao Hosokai, Shinichi Masuda, Alexei G. Zhidkov, Osaka Univ. (Japan) and Japan Science and Technology Agency (Japan); Naveen Pathak, Kenta Iwasa, Naoki Takeguchi, Yoshio Mizuta, Hiroki Nakahara, Jin Zhan, Keiichi Sueda, Osaka Univ. (Japan); Michiaki Mori, Hideyuki Kotaki, Masaki Kando, Japan Atomic Energy Agency (Japan); Tomokazu Sano, Osaka Univ. (Japan); Kazuto Arakawa, Shimane Univ. (Japan); Ryosuke Kodama, Osaka Univ. (Japan)

Ultrafast fundamental processes on fs time scale are significant in a wide range from biology to material sciences and ultrafast electron diffraction

(UED) affords access to these processes. Laser wakefield acceleration (LWFA) has a great potential to produce high-quality ultrashort electron bunches due to the huge electric field with ultrashort wavelength. We are developing single-shot UED system consisted of stable ultrashort electron source based on 2-pulse-driven staged LWFA and its beamline with conventional beam optics to observe irreversible ultrafast phenomena of material.

The staged LWFA has wave-breaking injector and long linear wakefield created by co-axial laser two pulses with different focal lengths. The linear wakefield makes the energy spread of the injector beam narrow by phase rotation scheme. We have developed the stable and controllable injector beam using a short-focused(f/3.5) pulse and the clear wakefield using the long-focused(f/20) pulse individually. The pointing stability achieved to be less than 0.5 mrad rms by using transient plasma micro optics (TPMO) technique. Moreover, quasi-monoenergetic electron beams with the energy from a few MeV to hundreds MeV have generated in the experiment of 2-pulse-driven staged LWFA.

Due to the stable beam generation, the beam optics of conventional accelerators can be used for LWFA. We have designed and constructed the SS-UED beamline, which is consisted from four quadruple magnets for beam focusing and pinhole for energy selection to obtain high spatial resolution in UED. We have performed transport test of electron beam from LWFA in the beamline. The beams have reached and focused tightly on the screen at ~ 7 m from the source and UED experiment is started. We will report the status of these developments and UED experiments.

9514-38, Session PS

Spectra of plasmas of Ru, Rh, Pd and Mo produced with nanosecond and picosecond laser pulses

Ragava Lokasani, Czech Technical Univ. in Prague (Czech Republic); Elaine Long, Univ. College Dublin (Ireland); Paul Sheridan, UCD (Ireland); Patrick B Hayden, Fergal O'Reilly, Padraig Dunne, Univ. College Dublin (Ireland); Jiri Limpouch, Czech Technical Univ. in Prague (Czech Republic); Akira Endo, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Gerard D. O'Sullivan, Univ. College Dublin (Ireland)

With the invention of the laser in 1960, this strong, oscillating electromagnetic radiation from a high energy Q switched lasers can be used to remove electrons from atoms as atoms exposed to laser light lose one or more electrons and become ions. We have investigated the spectral behaviour of laser produced plasmas of Mo, Ru, Rh and Pd in the spectral region from 2.5 to 13 nm and their use as sources for beyond EUV and soft x-ray region. The spectra produced by Nd:YAG lasers which delivered up to 330mJ in 170Ps and 600mJ in 7ns, respectively, laser pulses were focused on solid targets of Mo, Ru, Rh and Pd housed in a stainless steel vacuum chamber. The chamber was pumped to a pressure 1.6*10-6 m.bar. Spectra were recorded using a 0.25-m flat field grazing-incidence spectrograph equipped with a variable groove spaced grating with an average value of 1200 grooves/mm and a thermoelectrically cooled CCD camera with 2048 pixels in the spectral direction. This spectrograph covers the range from 2.5 to 13nm. The lasers irradiated the target at two different angles, parallel to target and at 450 to target normal. For each illumination angle, spectra were also recorded at two angles. Intense emission was observed in the 2-8 nm spectral region resulting from unresolved arrays due to 3d-4p, 3d-4f and 3p-3d transitions. These transitions in a number of neighbouring of ion stages were identified by comparison with Cowan code calculations and previous results from spectral studies especially on the elements Mo and Pd. The experimental result shows that strong emission can be observed at 6.x region for Ru, Rh and Pd.

9514-39, Session PS

Physics of laser-plasma electron acceleration in high-Z gases

Emilien Guillaume, Andreas Döpp, Agustin Lifschitz, Cédric Thaury, Kim Ta Phuoc, Francois Sylla, Victor Malka, Lab. d'Optique Appliquée (France)

Laser-plasma accelerators have successfully reached higher electron energies in the past few years, up to the GeV range [Kim HT. et al., Phys. Rev. Lett. 111, 165002 (2013)], but some applications need much lower energies, in the MeV range. Laser wakefield acceleration in pure argon [Mori M. et al., Physical Review Special Topics Accelerators and Beams 12, 082801 (2009)] or nitrogen plasmas was recently identified as a promising way to produce electron beams with energies below few tens of MeV's [Pak A. et al., Phys. Rev. Lett. 104, 025003 (2010)] with high charges. This acceleration technique is based on ionization injec- tion and trapping of electrons in a plasma created from a high Z gas with multiple ionization states. This injection method allows to generate heavy- charged electron beams (up to 1 nC), which behave differently from beams with low charge (few dozens of pC). We present here the experimental and numerical study of the physics of electron acceleration in a nitrogen plasma.

First, we present the two acceleration regimes which were identified from the experimental study, for a low density and a high density nitrogen plasma. At low electron density, the electron spectrum was found to have a flat shape in the few dozens of MeV range. For higher electron densities, the spectrum is closer to a thermal one, but drops slower than a Maxwellian one. The main trends of the spectrum dependency with the gas density found in the experiment are retrieved in the simulations. The particular spectrum shape at low density is associated with the generation of a wakefield by the electron bunch itself when leaving the gas jet.

It was also observed that the general shape of the spectra does not vary much with the laser energy. This unexpected feature - usually the amplitude of the wakefield strongly depends on the laser energy - is also found in the simulations. They indicate that this is a beamloading effect of the electron beam due to the injection of large amounts of electrons with the ionization injection process.

9514-40, Session PS

Simulations of ion acceleration from ultrathin targets with the VEGA Petawatt laser

Luca C. Stockhausen, The Ctr. for Ultrashort Ultraintense Pulsed Lasers (Spain); Ricardo Torres, Enrique Conejero, Univ. de Salamanca (Spain)

The acceleration of ions via laser-plasma interactions has been studied extensively in the recent years. Besides the Target Normal Sheath Acceleration, in which protons are accelerated through a large charge-separation field at the rear side of an overdense plasma, other promising mechanisms have emerged. Radiation Pressure Acceleration (RPA), based on the momentum transfer from photons to electrons, offers a much better scaling and produces tens of MeV ions. Other schemes at the onset of relativistically induced transparency like the Breakout Afterburner (BOA), where the interaction changes from surface-dominated to volumetric, have also emerged. Both RPA and BOA dominate for ultrathin overdense targets in the range of nanometres. Such targets require delicate handling and an ultrahigh contrast to prevent destruction by the pre-pulse.

The Pulsed Laser Centre (CLPU) is a new laser facility located in Salamanca (Spain), open to national and international users for experiments ranging from attosecond physics to laser-plasma interactions. Its main system, VEGA, is a multi-stage CPA Ti:Sapphire laser which, in its final phase, will be able to reach petawatt peak powers in ultrashort pulses of 30 fs (up to 30 joules) with a pulse contrast of 1:10^10 at 1 ps. The extremely low level of pre-pulse intensity makes this system ideally suited for studying the laser interaction with ultrathin (? 10 nm)

targets.

Prior to performing the first experiments at petawatt power, we have used the fully-relativistic PIC code OSIRIS [1] to carry out 2D simulations of the acceleration of ions in ultrathin solid targets under the unique conditions provided by VEGA.

Here we present the results of the 2D simulations performed with laser intensities up to 10^22 W/cm2 impinging normally on 5 – 40 nm thick overdense plasmas (up to 1000 nc) consisting of protons or C6+ ions, with different polarizations and pre-plasma scale lengths.

We show how signatures of the radiation pressure dominated regime, such as layer compression and bunch formation as imprinted in the species density profiles, are only present with circular polarization. By actively shaping the laser pulse and density gradient of the plasma, we demonstrate an enhancement in peak energy up to tens of MeV and monoenergetic features. On the contrary linear polarization at the same intensity level causes the target to blow up at an early stage of the interaction, resulting in much lower energies and broader spectra.

One limiting factor of Radiation Pressure Acceleration is the development of Rayleigh-Taylor like instabilities at the interface of the plasma and photon fluid. This results in the formation of 'bubbles' in the spatial profile of laser-accelerated proton beams. These structures were previously evidenced both experimentally and theoretically [2]. We have performed 2D simulations to characterize this bubble-like structure and report on the dependency on laser and target parameters.

[1] Fonseca et al. Lec. No. in Com. Sc. 2331, Springer (2002)

[2] Palmer et al. PRL 108, 225002 (2012)

9514-41, Session PS

Bunch modulation in LWFA blowout regime

Jirí Vyskocil, Czech Technical Univ. in Prague (Czech Republic) and Institute of Physics of the ASCR, v.v.i. (Czech Republic); Jorge M. Vieira, Luís O. Silva, Univ. Técnica de Lisboa (Portugal); Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Laser wakefield acceleration (LWFA) is a method capable of producing high quality electron bunches interesting for many applications ranging from coherent light sources to high energy physics. The blow-out regime of LWFA provides excellent accelerating structure able to maintain small transverse emittance and energy spread of the accelerating electron beam if combined with localized injection. In simulations of the injection process, the tail of the injected electron beam shows transverse modulations. These modulations are studied here using 3D Particle-in-Cell simulation with the OSIRIS code. A short laser pulse propagates in a pre-formed matched plasma density channel trapping background electrons into a positively charged bubble, and accelerating them. The injected electron bunch exhibits a modulation in the form of collective oscillations roughly on the order of the driving laser pulse's wavelength. The modulation takes a "corkscrew" shape when circular polarization is used, and a zig-zag line shape in case of linear polarization. Electrons injected at the back of the bunch come form a similar angular position at the time when they interact with the laser pulse. The front of the bunch is not modulated. The origin of the modulation seem to be linked to the phase of the driving pulse, and it tends to disappear as the bunch propagates further.

9514-42, Session PS

High-repetition rate relativistic electron beam generation from intense laser solid interactions

Thomas G. Batson, John A. Nees, Bixue X. Hou, Alexander G. R. Thomas, Karl M. Krushelnick, Univ. of Michigan (United States)

Relativistic electron beams have applications spanning materials science, medicine, and homeland security. Recent advances in short pulse laser technology have enabled the production of very high focused intensities at kHz rep rates. Consequently this has led to the generation of high flux sources of relativistic electrons – which is a necessary characteristic of these laser plasma sources for any potential application. In our experiments, through the generation of a plasma with the lambda cubed laser system at the University of Michigan (a 5 x 1018 W/cm2, 500 Hz, Ti:Sapphire laser), we have measured electrons ejected from the surface of fused silica and Cu targets having energies in excess of an MeV. The spectrum of these electrons, as well as the spatial divergence of the resulting beam, was also measured with respect to incident laser angle, prepulse timing and focusing conditions. While taken at a high repetition rate, the pulse energy of the lambda cubed system was consistently on the order of 10 mJ. In order to observe scaling of electron energy with laser pulse energy, the experiment was repeated on the petawatt-scale, 2 x 1022 W/cm2 HERCULES laser system at the University of Michigan. The use of HERCULES also offered the opportunity to observe electron energy as a function of the intensity contrast of the pulse through the implementation of plasma mirrors, which have been shown to reduce ASE to a level of 10-15. In addition, the experimental results are compared to the energy spectrum generated through particle in cell simulations.

9514-43, Session PS

Computer simulation of PIC method of intense laser pulse interaction with multicluster-plasma targets

Evgenia Echkina, Lomonosov Moscow State Univ. (Russian Federation); Sergei V. Bulanov, Japan Atomic Energy Agency (Japan); Igor Inovenkov, Lomonosov Moscow State Univ. (Russian Federation); Timur Z. Esirkepov, Yuji Fukuda, Koichi Yamakawa, James Koga, Japan Atomic Energy Agency (Japan)

A number of salient phenomena have been observed in the laser irradiation of cluster targets. These include the Coulomb explosion of the clusters, enhanced emission of x rays, generation of energetic electrons and energetic ions. There are indications that some strong nonlinear interaction of laser and clusters do occur upon the intense short pulse irradiation. The laser interaction with clusters is far stronger than that of the same intensity laser with other preparations of the same materials such as gas and/or usual plasma and solid with planer surface structure.

A cluster medium is characterized by its material (the charge state Z, and density, size (the radius, assuming circular structure), surface and internal structure(for example, multilayer coating using different materials), packing function, spatial configuration or distribution of clusters (order or random distribution). In relation to the interaction with laser field, following parameters such as cluster size to wavelength, collisionless skin depth to cluster size. A difference of cluster medium from conventional plasmas is in variety of controllable parameters which characterize the interaction. Such a large number of parameters widens applications utilizing the laser-cluster interaction. In this work we analyze the laser -cluster interaction in order to understand the cluster fusion. For this purpose by using our two - dimensional (2D) particle - in - cell (PIC) number code we investigate the ultra short high irradiance laser pulse interaction with targets where the multicluster cloud is imbedded in an underdense plasma or the clusters are located in a vacuum region preceding the plasma layer. Single bunch formation of an electron beam generated from nonlinear laser wakefields was also shown in numerous PIC simulations. The wake wave breaking occurs when the laser pulse pushes the plasma electrons both in the forward and sideways directions. As a result the wakewave takes the form of a plasma cavity.

?ne characteristic of high intensity laser-plasma interactions is the formation of an electron density cavity moving with the group velocity of the laser pulse. The cavity's transverse size is determined by the laser pulse width and its length is of the order of the relativistically strong Langmuir wave wavelength. In this limit, the wavelength depends on the amplitude of the Langmuir wave, which in turn depends on the laser pulse intensity. On the other hand the high intensity laser pulse is subject to self-focusing which changes its intensity. Therefore, the difference in the laser intensity influences not only the wake amplitude but also the wake position relative to the laser pulse. This is considered to lead to

variations in the features of the electron acceleration in addition to the increase and decrease of the electron energy. Here we systematically study the interaction of a short-pulse moderate to high intensity laser with an underdense plasma slab. Also discussed are the properties of the fast electron distribution in phase space, aiming at a better understanding of the formation of their energy spectrum. We consider the terawatt – petawatt range laser pulse interaction with a sub millimeter underdense plasma slab.

9514-44, Session PS

Generation of utrafast X-ray pulses using 20 TW laser system at PALS Facility

Vojtech Horny, Czech Technical Univ. in Prague (Czech Republic); Jaroslav Nejdl, Michaela Kozlova, Karel Bohacek, Miroslav Krus, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Ondrej Klimo, Czech Technical Univ. in Prague (Czech Republic)

Research facility PALS (Prague Asterix Laser System) is equipped with the 20 TW Ti:sapphire laser system. This system can deliver laser pulses with the duration of 40 fs and total energy of 0.8 J. Such a pulse can be focused up to intensities 1019Wcm-2 (a0 ≈ 2). Electron beams with the energy in hundreds of MeV can be produced using the interaction of such a laser pulse with the underdense gas medium via laser wake field acceleration (LWFA) mechanism in a bubble regime. During the acceleration the injected electrons have inherited transverse momentum. It leads to transverse oscillations during the acceleration process. Electron trajectories are sine-like with increasing wavelength. Oscillations of accelerated electron bunch lead to X-ray radiation. Numerical simulations via 2D particle-in-cell method claim the generation of the ion cavity, where the electron bunch is accelerated to the energy up to 700 MeV. Electron oscillations were investigated, trajectories of injected electron macroparticles were tracked. It was proven that electron oscillates in so called wiggler regime generating X-ray betatron radiation with critical energy up to 6 keV. The first experimental campaign carried out at the PALS facility aiming at characterization of LWFA electron beam and generated betatron radiation was performed in early 2015. Interaction of the laser with supersonic gas jet was investigated using femtosecond interferometry and Thomson scattering. A standard magnetic electron spectrometer was used to characterize the electron beam. To characterize the X-ray radiation a back-illuminated charge-coupled device was used to measure the X-ray beam profile and the spectrum via single photon detection.

9514-45, Session PS

Ultra-short pulse duration, high temporal contrast, high repetition rate multi-TW/ PW laser systems development

Franck Falcoz, Amplitude Technologies (France); Stephane Branly, Thales Optronique S.A.S. (France); Pierre- Mary Paul, Luc M. Vigroux, Gilles Riboulet, Amplitude Technologies (France)

During the past years, the growing interest for research areas such as the creation of short scale length high density plasmas from solid target [1], has driven the development of high energy, high peak power laser systems. High filed Physics, in particular, laser-driven electron and ions acceleration, now requires laser intensities greater than 1022 W/cm? on target [2]. The expectations for the Laser system characteristics have grown with the increase of the output energy (>30 J). Therefore, the laser community takes now a great care on the topic of spatial and temporal qualities of the delivered beams.

For more than a decade, Amplitude Technologies is one the major actor in the development of these High Energy Ultra-fast lasers.

In this communication, we report the development of the latest generation of compact ultra-intense laser systems with unprecedented capabilities at this energy level: compressed pulse energy > 4J, Pulse duration as short as 16 fs and high temporal contrast ASE < 10-12, leading to peak powers greater than 250 TW at 5 Hz.

We will also describe the high performances obtained on the last PetaWatt laser manufactured (VEGA laser source at CLPU facility and DRACO in HZDR Dresden). We will emphasize the high level of performances on the laser/optical specifications point of view, but also on the Men Machine Interface (MMI) aspects (supervision, control-command, automated safeties) and finally on the complete characterization of the laser pulse/beam (spatial and temporal real-time diagnostics, metrology...).

Conference 9514B: Medical Applications of Laser-Generated Beams of Particles: Review of Progress and Strategies for the Future

Monday 13–13 April 2015

Part of Proceedings of SPIE Vol. 9514 Laser Acceleration of Electrons, Protons, and Ions III; and Medical Applications of Laser-Generated Beams of Particles III

9514-50, Session 10

Solid hydrogen target for laser driven proton acceleration *(Invited Paper)*

Jean-Paul Perin, CEA Grenoble (France)

There is a great interest for fundamental research but also for applied research, in producing energetic protons. These protons can be used for example in the field of thermonuclear inertial confinement fusion research or in medical domains as proton therapy.

One mean to obtain a beam of energetic protons consists in focusing a high intensity laser on a target. Various physical mechanisms of laser-driven ion acceleration have been investigated to date. The mechanism most investigated experimentally is the Target Normal Sheath Acceleration (TNSA) when ions are accelerated at the rear side of thin target in a quasi-electrostatic sheath formed by fast electrons propagating from the target front side 3,4 .

A suitable target for this application is a thin ribbon of solid H2.

In this context, the low temperature laboratory of the CEA developed a cryostat able to produce a continuous film of solid H2 of some tens of microns in thickness and one millimeter in width. A new extrusion technique is used, without any mobile part. Thermodynamic properties of the fluid are used to achieve this goal. The principle is as follow: Once the experimental cell is totally filled with solid H2, the inlet valve is closed and the top of the cell is heated up. The pressure increases and pushes the solid H2 placed at the bottom of the cell through a calibrated hole.

The construction of new high power laser facilities (e.g. high repetition rate petawatt-class lasers at ELI-Beamlines5) will clearly enable numerous prospective applications based on secondary sources of energetic particles. In particular the use of the proposed solid hydrogen cryogenic target along with these emerging laser technologies will allow demonstrating future medical applications such as hadron therapy 6,7. In fact, in recent years pilot experiments of cancer cell irradiation have already been realized8. The possibility to use other gases than hydrogen (e.g. deuteron) suitable for different applications is also envisioned in the future.

3 S.P. Hatchett et al., Phys. Plasmas 7, 2076 (2000).

4 A. Maksimchuk et al., Phys. Rev. Lett. 84, 4108 (2000).

5 http://www.eli-beams.eu

6 K.W.D. Ledingham et al., British J. Radiology 80, 855 (2007).

7 D. Margarone, P. Cirrone , G. Cuttone, G. Korn, 2nd ELIMED Workshop and Panel, Vol. 1546, AIP Proceedings (2013) ISBN: 978-0-7354-1171-5

8 A. Yogo, T. Maeda, T.Hori et al., Appl. Phys. Lett. 98, 053701 (2011).

9514-51, Session 10

Innovative beam transport solutions and dosimetry for laser-driven ion beams

Valentina Scuderi, Institute of Physics Czech Academy of Science ELI-Beamlines project (Czech Republic) and INFN-LNS (Italy); Pablo G. Cirrone, Francesco P. Romano, Giacomo Cuttone, Istituto Nazionale di Fisica Nucleare (Italy); Marco Borghesi, Queen's Univ. Belfast (United Kingdom); Giacomo Candiano, Istituto Nazionale di Fisica Nucleare (Italy); Domenico Doria, Queen's Univ. Belfast (United Kingdom); Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Mario Maggiore, Rosanna Manna, Istituto Nazionale di Fisica Nucleare (Italy); Lorenzo Manti, Univ. degli Studi di Napoli Federico II (Italy) and Complesso Univ. di Monte Sant'Angelo (Italy); Valentina Marchese, Istituto Nazionale di Fisica Nucleare (Italy); Daniele Margarone, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Giuliana Miluzzo, Agatino Musumarra, Francesco Schillaci, Antonella Tramontana, Istituto Nazionale di Fisica Nucleare (Italy)

Over the last decades, charged particle acceleration using ultra-intense and ultra-short laser pulses has been one of the most attractive topics in the relativistic laser-plasma interaction research. One of the biggest challenges consists in using high intensity laser-target interaction to generate high-energy ions for multidisciplinary and, in particular, medical applications. High interest of the scientific community towards optically accelerated ion beams stems from the fact that conventional ion accelerators, beam transport lines and gantry systems are complex and expensive. On the other hand, more compact laser-based accelerators might significantly increase the availability of high-energy ion beams and provide particle therapy to a wider range of patients.

In this framework, the purpose of the international ELIMED network consists in demonstrating that laser-driven high-energy proton beams can be used for multidisciplinary applications investigating, particularly, new approaches to hadron-therapy. Indeed, the kick-off for medical applications and radiobiological investigations will be given once laser-accelerated proton beam transport, selection and dosimetric systems will be tested and their reliability will be demonstrated. Recently, we started to design and develop a beam transport line prototype able to deliver laser-driven proton beams suitable for multidisciplinary applications.

A focusing element consisting of four magnetic quadrupoles is currently under construction at LNS (Catania). The purpose of this element is to reduce the initial angular divergence of the optically accelerated ions improving the transmission efficiency of the entire transport system. A prototype of the key component of the whole beam line, the Energy Selector System, able to control and select in energy the laser-driven proton beams, has been already developed and characterized with mono-energetic proton beams at LNS (Catania) and LNL (Legnaro). The ESS prototype has been also tested with laser-driven proton beams available at TARANIS laser facility, Queen's University of Belfast (UK).

Furthermore, a Faraday cup prototype for absolute dosimetry with high dose rates and intense beams has been designed and preliminary tested at PALS laser facility in Prague.

Design, development and characterization of the first prototypes for beam transport, selection and dosimetry will be presented. Moreover, preliminary Geant4 Monte Carlo simulation results regarding the beam-line and the dosimetric devices will be discussed.

9514-52, Session 10

DNA repair dynamics following irradiation using laser-driven ion beams with ultra-high dose rates

Fiona M. Hanton, Domenico Doria, Deborah Gywnne, Clare Scullion, Kealan Naughton, Pankaj Chaudhary, Queen's Univ. Belfast (United Kingdom); Lorenzo Romagnani, Ecole Polytechnique (France); Satyabrata Kar, Queen's Univ. Belfast (United Kingdom); Giuseppe Schettino, National Physical Lab. (United Kingdom); Paul

Mckenna, Univ. of Strathclyde (United Kingdom); Kevin M. Prise, Marco Borghesi, Queen's Univ. Belfast (United Kingdom)

Hadrontherapy overcomes the limitations that exist within conventional X - ray radiotherapy by delivering dose with superior precision, due to finite range and maximum dose deposition at the Bragg peak. Despite the clear advantages that hadrontherapy offers, there remains a major limitation in the number of patients treated annually, due to the huge cost and size of facilities required for this type of treatment. The idea of future facilities based on laser driven ion accelerators has been proposed as a way of reducing complexity and cost of these infrastructures.

The most significant difference between laser-driven ion and conventional ion sources is the beam mode and duration; as laser-driven ion sources deposit dose with an ultra-high dose rate exceeding 109 Gys-1. The radiobiological effect of these ultra-high dose rates are virtually unknown and need to be carefully assessed prior to any medical use.

The Astra-Gemini laser system at the Rutherford Appleton Laboratory was used in an investigation into the radiobiological effect of using proton and carbon ion beams of multi MeV/ nucleon energies with respective dose rates of 1010 and 109 Gys-1. In a single shot we were able to obtain clinically relevant doses leading to an investigation into DNA damage formation and associated repair kinetics in normal human fibroblasts cells (AG01522) exposed to laser-driven ions using the 53BP1 immunofluorescence technique.

9514-53, Session 11

Development of the pulse powered gantry system for laser driven proton therapy *(Invited Paper)*

Umar Masood, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); Michael Bussmann, Thomas E. Cowan, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Wolfgang Enghardt, OncoRay - National Ctr. for Radiation Research in Oncology (Germany) and Technische Univ. Dresden (Germany) and Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Thomas Herrmannsdörfer, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Kerstin M. Hofmann, Technische Univ. München (Germany); Leonhard Karsch, OncoRay - National Ctr. for Radiation Research in Oncology (Germany) and Technische Univ. Dresden (Germany); Florian Kroll, Ulrich Schramm, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Michael Schürer, OncoRay - National Ctr. for Radiation Research in Oncology (Germany) and Technische Univ. Dresden (Germany); Jan J. Wilkens, Technische Univ. München (Germany); Jörg Pawelke, OncoRay - National Ctr. for Radiation Research in Oncology (Germany) and Technische Univ. Dresden (Germany)

In radiation therapy, proton beams due to their superior dose profile over photon and electron beams may provide higher dose-conformity and healthy tissue sparing. But due to huge costs and size ion beam therapy (IBT) is limited to only a few centers worldwide. The laser-driven ion acceleration process may provide an alternative to conventional IBT. However, laser-driven beams are characterized by intense particle bunches with peak dose rates exceeding conventional values by several orders of magnitude but with low repetition rate, broad energy spread and large divergence. These features are very different from conventional beams from synchrotron/cyclotron, thus require innovative solutions to develop Laser-based Ion Beam Therapy (LIBT) for clinical application. The presented work is a result of the ongoing joint translational research project onCOOPtics of several institutions in Germany aiming to establish LIBT for proton beams and the status of the project will be presented.

In addition to laser accelerator development for reaching therapeutic proton energies (up to 230 MeV) an optimized transport beamline, preferably a 360o rotatable gantry, is required for dose delivery to patient tumor volumes. For the purpose, a compact gantry system based on pulsed magnets has been designed. This gantry features an incorporated laser-particle acceleration chamber and an integrated energy selection system. We also introduce an innovative beam scanning system for broad energetic wide laser-driven beams for efficient dose delivery.

Furthermore, in conventional IBT, 3D treatment planning software (TPS) is used to calculate tumor conformed homogeneous dose distributions for any given patient data. For any treatment plan, clinical parameters, i.e. dose conformity, dose homogeneity, healthy tissue sparing etc., determine the quality of the plan. Conventional TPS uses mono-energetic beams for dose calculations; however, in LIBT low repetition laser-driven beams could deliver doses efficiently if broad energies are deposited over larger tumor sub-volumes simultaneously for keeping short treatment times. This demands a new 3D TPS, which has been developed to explore new dose delivery and treatment planning strategies for laser-driven beams. The evaluation of treatment plans, calculated with our 3D TPS with beam parameters from the before mentioned gantry system, shows laser-driven beams could deliver plans with high quality.

The 3D TPS combined with our pulsed gantry system provide a comprehensive solution for LIBT. The necessary realization of pulsed gantry magnets is being continued. LIBT is a promising compact alternative yet requires substantial development towards clinical application.

Acknowledgment: This work is supported by the German Ministry of Education and Research (BMBF) under grant numbers 03ZIK445, 03Z1N511 and 03Z1O511 and DFG cluster of excellence Munich-Centre for Advanced Photonics.

9514-54, Session 11

Pulsed power magnets for laser-driven proton therapy gantry systems

Leonhard Karsch, Technische Univ. Dresden (Germany) and OncoRay - National Ctr. for Radiation Research in Oncology (Germany); Michael Bussmann, Thomas E. Cowan, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Wolfgang Enghardt, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); Thomas Herrmannsdörfer, Florian Kroll, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Umar Masood, Michael Schürer, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); Jörg Pawelke, Technische Univ. Dresden (Germany) and OncoRay - National Ctr. for Radiation Research in Oncology (Germany); Ulrich Schramm, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

Purpose: Radiation therapy is an important modality in cancer treatment. Conventional photon beam facilities are compact and widespread. The use of ion beams with the inverse depth dose distribution has physical and radiobiological advantages compared with the photon beams. But worldwide only few ten ion beam facilities are exisiting caused by the large size and high investment costs. In addition to the accelerator a rotating beam gantry system is necessary for the clinically required individual irradiation direction for patients. Due to the high rigidity of ion beams, already common proton gantry systems have a diameter of 11 m and a length of 9 m. The use of laser ion acceleration promises reduced costs and size by smaller accelerators and gantry systems. The pulsed nature of laser driven ion beams allow more compact gantry systems by using pulsed power magnets. Hereby the large energy spread of laser-driven ion beams demands for a gantry which allows an integrated energy selection to reduce the energy spread to clinically required bandwidth.

Methods: Pulsed power magnets will establish the magnet field only over a short time, which is sufficient for passing short ion bunches. Equipped with a high power steering electronic (current pulse generator) the field strength of pulsed, ironless magnets may rise up to 50 T in stable and reproducible conditions. A gantry system will need different types of magnets: solenoid, dipole and quadrupole. In a first step, a prototype of each of the magnet types has been designed and realized. In a second

step, these prototype magnets have been tested and characterized at a well-defined pulsed proton beam at a conventional tandem accelerator.

Results: Typical magnet pulse durations achieved with the prototype of each magnet and of a steering electronic are in the order of 1 ms, which can be considered stable and uniform while the passing of laser-driven ion bunches through it. The solenoid is working and focuses a parallel 10 MeV proton beam of about 1.5 cm diameter to a spot with FWHM of 1 mm. The dipole bends the proton beam by an angle of 45 degrees with user controlled magnetic field. Also a first pulsed beamline combining solenoid and dipole have been successfully tested and show the expected optical ion beam features like the possible energy selection by dispersion. First tests of the quadrupole prototype show also promising results.

Discussion and Outlook: While the pulsed solenoid is already in routine use at laser driven proton beams, improved designs for dipole and quadrupole are in progress. With the improved magnets experiments will be performed in the experimental bunker of the conventional clinical proton therapy facility at OncoRay in Dresden extending these studies to proton beams of up to 230 MeV energy. In parallel experiments with laser-driven beams are foreseen.

Acknowledgment: This work is supported by the German Ministry of Education and Research (BMBF) under grant numbers 03ZIK445, 03Z1N511 and 03Z1O511.

9514-55, Session 12

Laser-wakefield accelerators for medical phase contrast imaging: Monte Carlo simulations and experimental studies

Silvia Cipiccia, David Reboredo-Gil, Univ. of Strathclyde (United Kingdom); Fabio A. Vittoria, Univ. College London (United Kingdom); Gregor H. Welsh, Peter A. Grant, David W. Grant, Enrico Brunetti, S. Mark Wiggins, Univ. of Strathclyde (United Kingdom); Alessandro Olivo, Univ. College London (United Kingdom); Dino A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

X-ray phase contrast imaging (XPCI) is a very promising method of dramatically enhancing the contrast of images of small weakly absorbing objects and soft tissue, which may lead to significant advancements in medical imaging toward a high-resolution, low-dose technique. The coded aperture technique developed at the University College of London shows that a high transverse coherence X-ray beam is not a requirement, compared with conventional techniques[1].

The interest for XPCI is giving rise to a demand for effective simulation methods. Monte Carlo codes have proven to be a valuable tool in the study of XPCI including coherent effects[2].

Laser-plasma wakefield accelerators (LWFAs) are a new concept of very compact particle accelerator[3]. Using plasma as an accelerating medium, the accelerating gradient of a LWFA is in excess of 1 GV/cm which makes them a thousand times more compact than conventional accelerators.

In a LWFA a high intensity laser (>10^18W/cm^2) focused on plasma generates plasma waves. Electrons surfing the waves are accelerated to very high energy (>100 MeV) in extremely short distances[4-6]. During the acceleration electrons undergo transverse oscillations which result in the emission of betatron radiation in a narrow cone along the propagation axis[7]. Betatron radiation based on LWFAs is a bright compact X-ray source[8,9] which is promising for applications such as in medical imaging.

The application potentials and limits of the betatron radiation depend on key properties such as source size, spectrum and divergence.

We investigate here the potential of LWFA-based betatron sources for medical XPCI and their resolution limits both in free space propagation and using the coded aperture technique. Numerical simulations using the FLUKA Monte Carlo code are compared to experimental results.

1. P. R. T. Munro et al. Opt Express 18 19681-19692 (2010).

2. S. Cipiccia et al. Opt Express 22 23480-23488 (2014).

3. T. Tajima & J. M. Dawson. Phys. Rev. Lett. 43 267-270 (1979).

4. S. P. D. Mangles et al. Nature 431 535-538 (2004).

5. C. G. R. Geddes et al. Nature 431 538-541 (2004).

6. J. Faure et al. Nature 431 541-544 (2004).

7. A. Rousse et al. Physical Review Letters 93 135005 (2004).

8. S. Kneip et al. Nature Physics 6 980-983 (2010).

9. S. Cipiccia et al. Nat Phys 7 867-871 (2011).

9514-57, Session 13

Production (y, np) of copper-62 medical radioisotope using monoenergetic electron beams from a laser-plasma wakefield accelerator *(Invited Paper)*

Panos Lepipas, Univ. of Strathclyde (United Kingdom) and Univ. of Glasgow (United Kingdom); Sally L. Pimlott, Univ. of Glasgow (United Kingdom) and NHS (United Kingdom); Silvia Cipiccia, S. Mark Wiggins, Peter A. Grant, David Reboredo-Gil, David W. Grant, Univ. of Strathclyde (United Kingdom); David O'Donnell, Univ. of Glasgow (United Kingdom); Gregor H. Welsh, Univ. of Strathclyde (United Kingdom); Dima Maneuski, Univ. of Glasgow (United Kingdom); Gregory Vieux, Enrico Brunetti, Univ. of Strathclyde (United Kingdom); David G. Ireland, David J. Wyper, Univ. of Glasgow (United Kingdom); Dino A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

The laser-plasma wakefield accelerator (LWFA), that is a compact source of quasi-monoenergetic, high energy electron beams has the potential to provide an alternative method for the production of medical radioisotopes. Many studies have been carried out towards this direction in an attempt to reduce dependence on aging reactors which along with cyclotrons are the main sources of medical isotopes. The importance of radioisotopes in medicine can be understood by their wide usage in diagnostic and therapeutic modalities. Between the most sensitive, non-invasive methods for detecting and evaluating abnormalities in molecular systems in-vivo are the positron emission tomography (PET) and single photon emission computed tomography (SPECT). Both techniques are based on radioisotopes and find applications in many neurological disorders and cost effective management of a range of cancers. Therapeutic applications of isotopes include brachytherapy, which uses implanted radioactive "seeds" to irradiate cancerous tumours and targeted alpha therapy including radioimmunotherapy where monoclonal antibodies are conjugated to radionuclides, thereby providing a specific internal radiotherapy.

In this study a LWFA has been applied in a demonstration of radioisotope production. High energy bremsstrahlung photons are created when the LWFA electron beam (energy 130 MeV, energy spread 10%, charge 5 pC) is transported using a quadruple magnet triplet onto a tantalum converter. They are then directed on a natural zinc target to stimulate (gamma,np) photonuclear reactions for the production of the positron emitter copper-62. This differs from previous LWFA studies that investigated (gamma,n) reactions on a Cu-63, in the case of Cu-62 production. (gamma,np) reactions are preferable as parent and daughter separation is much easier when atomic numbers are different. The relatively high pulse repetition rate of 1 Hz allowed the produced activity of copper-62 to peak at 18 kBq. The findings of this experiment are in good agreement with FLUKA Monte Carlo simulations that take into account self-absorption of hard X-rays in the target. Favourable scaling towards single patient doses based on near-future LWFA technological advancement is also presented.

In the pursuit of new production methods a study in collaboration with TRIUMF centre (Canada's nuclear and particle research facility) is planned*. The rare medical isotope actinium-225, an alpha-emitter with therapeutic applications, will be collected and purified in a novel experiment. The method consists of the bombardment of a uranium target (UCx multiple foils) by 500 MeV cyclotron produced protons. The fragment-products are to be extracted from the target with laser ionisation and accelerated, actinium-225 ions will then be selected by a mass spectrometer and directed to a collection chamber.

*Results of the upcoming experiment are expected before the date of the conference

9514-58, Session 13

Methodology to improve resolution in multiple configuration sensors

Hua Liu, Science and Technology on Electro-Optic Control Lab. (China)

For break the optical diffraction limit, and achieve an improved resolution, based on single molecule microscopy in modern domain, a method of continuous multiple configuration, with a micro lens array and core optics is attempt to establish model by novel principle on resonance energy transfer and high accuracy localization, by which the system resolution can be improved with a level of a few nanometers. A comparative study on traditional vs modern methods can demonstrate that the dialectical relationship and their balance is important, among Merit function, Optimization algorithms and Model parameterization. The effect of system evaluated criterion that MTF, REA, RMS etc. can support our arguments qualitatively . The results can develop new products.

Conference 9515: Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers

Monday - Wednesday 13–15 April 2015

Part of Proceedings of SPIE Vol. 9515 Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers II

9515-1, Session 1

The Nexawatt *(Keynote Presentation)*

Christopher Barty, Lawrence Livermore National Lab. (United States)

No Abstract Available

9515-2, Session 1

Extreme light: the first steps towards zeptosecond and zettawatt science *(Keynote Presentation)*

Gérard A. Mourou, Ecole Polytechnique (France)

The possibility to amplify laser to extreme peak power offers a new paradigm unifying the atomic and subatomic worlds, to include nuclear physics, high-energy physics, astrophysics and cosmology. After the description of a technique to generate zeptosecond pulses, of exawatt to zettawatt power in the x-ray and gamma-ray regimes, we will enunciate the applications. They will include giant particle acceleration to the level of TeV/cm providing a means for to go beyond the high-energy standard model and contribute to apprehend cosmic acceleration and revealing dark matter.

9515-4, Session 2

ELI Beamlines: status of user facility development *(Invited Paper)*

Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

No Abstract Available

9515-5, Session 2

ELI ALPS status *(Invited Paper)*

Károly Osvay, ELI-HU Nonprofit Kft. (Hungary)

No Abstract Available

9515-6, Session 2

Extreme Light Infrastructure-Nuclear Physics (ELI-NP): status and perspectives *(Invited Paper)*

Victor Zamfir, Horia Hulubei National Institute of Physics and Nuclear Engineering (Romania)

No Abstract Available

9515-7, Session 2

Three to become one: ELI entering its era as one unified international user facility *(Invited Paper)*

Wolfgang Sandner, ELI Delivery Consortium International Association (AISBL) (Belgium)

No Abstract Available

9515-3, Session 3

Laser-based nuclear photonics *(Invited Paper)*

Christopher Barty, Lawrence Livermore National Lab. (United States)

No Abstract Available

9515-8, Session 3

PW-class lasers as future drivers: from medical imaging to compact XFELs *(Invited Paper)*

Florian J. Grüner, Ludwig-Maximilians-Univ. München (Germany)

Laser-driven plasma wakefield acceleration holds the potential for very compact sources for brilliant X-rays. Candidates are Thomson backscattering, generating hard X-rays for medical imaging, and Free-Electron-Lasers (FELs), with single-molecule imaging as their most prominent application. In both cases, the acceleration process needs to deliver high-charge electron beams with minimum energy spread. In this talk I will present design studies for both future applications and discuss the need for lasers in the PW-regime.

9515-9, Session 3

Laser-wakefield betatron radiation for biological imaging *(Invited Paper)*

Nelson C. Lopes, Instituto Superior Técnico (Portugal)

Laser-wakefield accelerators have been proven as a compact source of ultra-short bunches of relativistic electrons. A short laser pulse can be focused to a diameter close to its longitudinal size (e.g. 20 micron FWHM) reaching an intensity of 1019 W/cm2. When this “light bullet” hits a plasma with the adequate electron density to sustain electron waves with wavelength matching the laser spot diameter a relativistic cavitation bubble with almost no electrons is formed in the plasma. This bubble like plasma structure surrounds the laser pulse and guides it until the laser pulse energy is consumed or the gas finishes. Electrons can be trapped by this structure and accelerated to energies above 500 MeV in less than one centimeter. Those electrons oscillate in the radial field of the plasma structure resulting in the emission of betatron radiation with a few milliradian divergence and broadband photon energies with a synchrotron like spectra with critical energies typically in the 1- 50 KeV range. This radiation has a source size of a few microns and is bright enough for single shot imaging (typically > 109 photons with 5 – 9 KeV).

A betatron imaging setup was built at Astra-Gemini laser facility for an experiment dedicated to demonstrate the adequacy of this light source for biological imaging. Electron bunches with energies of 1 GeV where produced in a 1 cm long helium gas target by laser pulses with energy of 10 J and duration of 45 fs focused to a spot size of 25 micron by a F/20 off-axis-parabola. The experimental parameters where optimized to produce a small source size bright x-ray betatron beam. We have performed two imaging modalities: phase-contrast imaging of soft-tissue samples (millimeter thick prostate slices) using radiation in the range 5-9 KeV and absorption-contrast imaging of trabecular bone samples using radiation in the range 5-50 KeV. The phase-contrast result in images of the prostate tissues where the architecture of the tissues is clearly visible with resolution comparable to what is possible using histology techniques. The absorption-contrast imaging of the bone sample with different angles made possible the tomographic high-resolution reconstruction of the sample. These studies indicate the usefulness of these sources for biological research and clinical applications. They also show that 3D imaging can be made possible with this source in a fraction of the time that it would take with a x-ray tube.

9515-10, Session 3

High field physics at ALLS: from electron acceleration to X-ray coherent imaging *(Invited Paper)*

Jean-Claude Kieffer, Institut National de la Recherche Scientifique (Canada)

No Abstract Available

9515-11, Session 3

High order harmonics from relativistic laser plasmas

Sergei V. Bulanov, Timur Esirkepov, James Koga, Alexander Pirozhkov, Kiminori Kondo, Masaki Kando, Japan Atomic Energy Agency (Japan)

High-order harmonic generation (HHG) of high intensity ultra-short laser pulses by means of laser produced plasmas are discussed. Since with plasma targets there is no limitation on applicable laser intensity the generated harmonics can be substantially intense. Recent results of experiments and computer simulations on the HHG are briefly reviewed. Main attention is paid to the analysis of basic mechanisms of HHG from overdense and underdense plasma targets irradiated by relativistically intense laser pulses.

9515-12, Session 3

Laser driven pulsed `X-ray radar' for penetrative imaging

Lucy A. Wilson, STFC Rutherford Appleton Lab. (United Kingdom); Robert M. Deas, Defence Science and Technology Lab. (United Kingdom); Dean R. Rusby, Univ. of Strathclyde (United Kingdom); Aaron Alejo, Queen's Univ. Belfast (United Kingdom); Peter P. Black, Sarah E. Black, Defence Science and Technology Lab. (United Kingdom); Marco Borghesi, Queen's Univ. Belfast (United Kingdom); Ceri M. Brenner, STFC Rutherford Appleton Lab. (United Kingdom); Jonathan Bryant, Imperial College London (United Kingdom); Robert J. Clarke, John L. Collier, Justin Greenhalgh, Cristina Hernandez-Gomez, STFC Rutherford Appleton Lab. (United Kingdom); Satyabrata Kar, Queen's Univ. Belfast (United Kingdom); David Lockley, Defence Science and Technology Lab. (United Kingdom); Robert M. Moss, Defence Science and Technology Lab. (United Kingdom) and Univ. College London (United Kingdom); Zulfikar Najmudin, Imperial College London (United Kingdom); Matt Whittle, Defence Science and Technology Lab. (United Kingdom); Jonathan J. Wood, Imperial College London (United Kingdom); Paul McKenna, Univ. of Strathclyde (United Kingdom); David Neely, STFC Rutherford Appleton Lab. (United Kingdom) and Univ. of Strathclyde (United Kingdom)

X-ray backscatter imaging is currently used in a range of technologies from portal security, where it is used to scan airline passengers, vehicles and containers to industrial inspection, studing the internal structure of low density materials and for applications requiring single sided imaging. Currently, the application of this imaging technique to the detection of landmines is limited due to the surrounding sand or soil strongly attenuating the 10s to 100s of keV X-rays required for backscatter imaging.

Here we will present a new approach using a 140MeV short - pulse (<100fs) electron beam generated by laser Wakefield acceleration to probe the sample. High energy electrons are able to penetrate to greater depths in a sample; these electrons will then produce X-rays via bremsstrahlung emission which then backscatter and are attenuated as they travel back through the sample before being detected. The greater penetration depth of the high energy electrons combined with the single pass of the X-ray emission through the target allows for greater depths to be imaged.

The electrons were produced using the Gemini laser system at the Rutherford - Appleton laboratory by focusing a 10±1J, 55±5fs laser pulse in a supersonic gas jet using an f/20 of axis parabolic mirror. Helium with a 5% nitrogen gas mix was used to allow for ionisation injection. An electron density of 3.9x1018cm-3 ± 0.1x1018cm-3 was found to give most uniform, consistent and high flux electron beams.

A variety of detector and scintillator configurations are examined, with the best time response seen from an absorptive coated BaF2 scintillator with a bandpass filter to remove the slow scintillation emission components. An X-ray backscatter image of an array of different density and atomic number items is demonstrated. This is the first time a backscatter imaging technique using a laser generated electron beam to generate X-ray emission n the imaging target has been demonstrated. The use of a compact laser Wakefield accelerator based system to produce a high charge; short pulse length beam of high energy electrons makes this technique feasible for applications in the field.

9515-13, Session 4

Technology development toward rep-rated, kJ-class, 10 PW lasers *(Invited Paper)*

Todd Ditmire, The Univ. of Texas at Austin (United States)

No Abstract Available

9515-14, Session 4

ELI Beamlines: development of next generation short-pulse laser systems *(Invited Paper)*

Bedrich Rus, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

No Abstract Available

9515-15, Session 4

Scaling high energy petawatt laser systems to high repetition rate *(Invited Paper)*

Constantin L. Haefner, Lawrence Livermore National Lab. (United States)

No Abstract Available

9515-16, Session 4

High-field sciences explored with the upgraded J-KAREN-P:current status and perspective

Masaki Kando, Sergei V. Bulanov, Timur Zh. Esirkepov, Yuji Fukuda, Yukio Hayashi, Masato Kanasaki, Hiromitsu Kiriyama, James K. Koga, Akira Kon, Kiminori Kondo, Hideyuki Kotaki, Yuji Mashiba, Michiaki Mori, Mamiko Nishiuchi, Koichi Ogura, Alexander S. Pirozhkov, Akito Sagisaka, Hironao Sakaki, Hirotaka Tanaka, Japan Atomic Energy Agency (Japan)

The previous J-KAREN laser was a Ti:sapphire laser system with chirped pulse amplification (CPA) at the Kansai Photon Science Institute, Japan Atomic Energy Agency. J-KAREN could deliver a laser energy of 8 J on target with the pulse duration of 40 fs. Thanks to the double CPA, the laser system had a high contrast ratio of 1011. The focused intensity was 10^21 W/cm^2 with the f/2 optic and its value has been confirmed by the achievement of electron energy from an irradiated thin foil. The upgraded J-KAREN (J-KAREN-P) is ongoing to deliver petawatt laser pulses on target and aiming the peak irradiance of 10^22 W/cm^2. We focus on the system performance on target and will conduct two pilot experiments to test our system. The two experiments are 200 MeV proton acceleration using a thin foil and 1 keV high-order harmonics generation from a gas jet target. The preliminary experiments of both of them have been successfully conducted at our institute with the power of 200 TW and 20 TW, respectively. The above parameters can be obtained if we increase the peak power to petawatt.

In the presentation we will show the current status and perspective to explore high field sciences using J-KAREN-P.

In addition we will show the possible experiments such as gamma-ray flash from the thin foils, heavy ion acceleration, electron acceleration, and ion generation from clusters.

9515-17, Session 4

Focal spot of femtosecond laser pulse under tight focusing condition

Tae Moon Jeong, Gwangju Institute of Science and Technology (Korea, Republic of) and ELI Beamlines (Czech Republic); Stefan Weber, Bruno J. Le Garrec, Daniele Margarone, ELI Beamlines (Czech Republic); Tomás Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Georg Korn, ELI Beamlines (Czech Republic)

As an effort to efficiently increase a peak intensity of a high power laser, a tight focusing geometry is frequently considered by utilizing a low f-number focusing optic. In this talk, we present a method developed for describing the focal spot of a femtosecond laser pulse which is formed in the spatio-temporal region under low f-number (f/# ≤ 1) focusing conditions. In the method, transverse and longitudinal electromagnetic (EM) fields for a monochromatic wave are calculated in the focal plane and its vicinity, and then, in order to precisely describe the femtosecond focal spot in the spatio-temporal domain, calculated monochromatic EM fields are coherently superposed with a given amount of spectral bandwidth and phase. The accuracy and validity of the method are tested and compared to results obtained with Fourier transform method under high f-number conditions. The changes of the femtosecond focal spot under tight focusing conditions are described in the spatio-temporal domain.

9515-18, Session 4

Final EDP Ti: sapphire amplifiers for ELI Project

Vladimir Chvykov, ELI - ALPS (Hungary); Mikhail Kalashnikov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Károly Osvay, ELI-HU Nonprofit Kft. (Hungary)

For the new generation of the ultra-high power lasers with tens of PW of output power the kJ- energy level has to be reached. . Large aperture laser amplifiers, are subjected to severe losses due to Transverse Amplified Spontaneous Emission (TASE), and Transverse Parasitic Generation (TPG). It was demonstrated that Extracting During Pumping (EDP) can significantly reduce parasitic losses due to both TASE and TPG making EDP-based final laser amplifiers be an excellent candidate for the new generation of CPA-laser systems. The EDP-method was applied at several Ti:Sapphire booster amplifiers of a PW-scale, and has allowed output energies in excess of 72 J with the current record power of 2 PW reached in a single channel. The capability of EDP-amplifiers to reduce the TASE-losses was demonstrated using an exemplary design. With existing technology EDPCPA-systems are able to achieve kJ-level output energy and several kJ if larger crystals for amplifiers are provided.

In this paper we study the concept of EDP amplification for the 10-100PW level laser systems. In the three pillars of ELI, several PW-class lasers have been planned to build. The HF PW laser of ELI-ALPS (and the L2 laser of the ELI-Beamlines) with 2 PW peak power and <20 fs pulse duration, while the L4 of the ELI-BEAMLINES as well as the ELI-NP lasers aiming at 300 J / 10 PW lasers. The 200 PW laser facility is still on the roadmap of the ELI consortium.

The design of EDP – duty amplifiers required to achieve the mentioned above parameters was done and will be reported. For numerical simulations we used the method especially elaborated for the geometry of Ti:Sa amplifiers. Main parameters for the ELI-ALPS amplifier are as follows: the diameter of the pump area and the crystal are 8 and 9 cm, the pump energy – 170 J, the input and the output energy are 10 J and 90 J. The dependence of calculated TASE losses for this crystal with thickness of 3cm (purple) and 2cm (blue) measured on the moment of the pump arrival will be presented. The losses for the EDP-amplifier can be reduced from 70 to less than 5%. The calculated main parameters for ELI-BEAMLINES and ELI-NP amplifiers are: the diameter of the pump area and crystal - 19 and 20 cm, the pump energy – 960 J, the input and the output energy – 60 and 600 J, the losses with the EDP technology can be made also under 5%. Besides that, the design of EDP Ti:Sa power amplifiers for a 200 PW class system required for the forth-high intensity pillar of the ELI facility will be presented.

9515-19, Session 4

Technology development and prospects for multi-10PW OPCPA pumped by OMEGA EP *(Invited Paper)*

Jonathan D. Zuegel, Univ. of Rochester (United States)

Optical parametric chirped-pulse amplification (OPCPA) pumped by multikilojoule, Nd:glass lasers is a promising approach to produce ultra-intense pulses (>1023 W/cm2) that can be used to study ultrarelativistic phenomena. Scalable technologies are being developed and demonstrated to prepare for a future upgrade of the OMEGA EP Laser System to pump an optical parametric amplifier line (EP-OPAL) and realize a high-energy, multi-10-PW system. The goal is a system capable of achieving ultrahigh intensities (1.5 kJ, 20 fs, 75 PW, ~1024 W/cm2) for experiments that can also integrate picosecond infrared and/or

nanosecond ultraviolet laser pulses from OMEGA EP beamlines.

An EP-OPAL conceptual design includes an ultra-broadband front end to produce chirped pulses that are amplified in a three-stage, high-energy OPCPA beamline using highly deuterated potassium dihydrogen phosphate (DKDP) crystals to produce up to 2.5-kJ stretched pulses. All-reflective vacuum spatial filters image relay ultra-broadband pulses between OPCPA stages and deliver them to a four-grating compressor operating in vacuum. EP-OPAL on-target energy is limited by damage thresholds of short-pulse optics and a compressed beam size that can be delivered without major modifications to the OMEGA EP target area structure or target chamber. Compressed pulses are delivered to a novel, two-stage focusing system to provide a range of focal spot sizes and flexibility in choosing the direction of the focused beam, while also improving the temporal contrast of the on-target pulse. Direct, single-stage focusing with an off-axis parabolic mirror is also an option.

OPAL technology development includes: demonstrating an ultra-broadband seed source with ultrahigh temporal contrast; developing nanosecond-pumped OPCPA amplifiers that can be scaled to kilojoule pulse energies; and proving optical and diagnostic systems for transporting, compressing, focusing, and measuring pulses to achieve nearly transform-limited and diffraction-limited performance with the required damage thresholds. These efforts are being accomplished in a mid-scale system (7.5 J, 15 fs) that will serve as a prototype front end for EP-OPAL. Concepts to address each of these challenges will be presented along with a plan to implement technology so that progressively higher EP-OPAL system performance and experimental capabilities can be delivered as each of these technical challenges is met.

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0001944, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

9515-20, Session 5

Spin dynamics in relativistic light-matter interaction

Heiko Bauke, Max-Planck-Institut für Kernphysik (Germany); Sven Ahrens, Max-Planck-Institut für Kernphysik (Germany) and Illinois State Univ. (United States); Christoph H. Keitel, Max-Planck-Institut für Kernphysik (Germany); Rainer Grobe, Illinois State Univ. (United States) and Max-Planck-Institut für Kernphysik (Germany)

Employing novel light sources such as the ELI-Ultra High Field Facility, for example, which envisage to provide field intensities in excess of 10^20 W/cm^2 and field frequencies in the x-ray domain [1, 2], light-matter interaction in the relativistic regime may be probed experimentally. Relativistic quantum mechanics predicts various new phenomena to occur in this regime [3, 4] including spin effects [5–9]. In this contribution, we are going to analyze theoretically various setups of electrons in strong electromagnetic fields, which show distinct spin dynamics.

Relativistic quantum mechanics has to be employed to study these phenomena. However, there is no universally accepted operator to describe the electron's spin degree of freedom. Thus, we first investigate the properties of different proposals for a relativistic spin operator and show that most candidates are lacking essential features of proper angular momentum operators [10, 11]. Only the so-called Foldy-Wouthuysen and the Pryce operators qualify as proper relativistic spin operators.

The various spin operators predict different expectation values when electrons interact with electromagnetic potentials. In this way, one may distinguish between the proposed relativistic spin operators by experimental means. In particular, ground states of highly charged hydrogen-like ions can be utilized to identify a legitimate relativistic spin operator experimentally.

A further process that we study in more detail is the coupling of the spin angular momentum of light beams with elliptical polarization to the spin degree of freedom of free electrons [12, 13]. It is shown that this coupling, which is of similar origin as the well-known spin-orbit coupling, leads to electron-spin precession. The spin-precession frequency is proportional to the product of the laser-field's intensity and its spin density. To derive the correct spin-precession frequency relativistic corrections to the Pauli equation, which account for the light's spin density, have to be taken into account. The quantum mechanical interactions of the electron's spin with the laser's rotating magnetic field, which may be characterized by the nonrelativistic Pauli equation, and with the laser's spin density, which results via the relativistic corrections, counteract each other. As a result, a net electron-spin rotation remains with a precession frequency that is much smaller than the frequency predicted by a nonrelativistic theory, although the involved electromagnetic field strengths may be nonrelativistic.

[1] M. Altarelli, R. Brinkmann, M. Chergui, W. Decking, B. Dobson, S. Düsterer, G. Grübel, W. Graeff, H. Graafsma, J. Hajdu, J. Marangos, J. Pflüger, H. Redlin, D. Riley, I. Robinson, J. Rossbach, A. Schwarz, K. Tiedtke, T. Tschentscher, I. Vartaniants, H. Wabnitz, H. Weise, R. Wichmann, K. Witte, A. Wolf, M. Wulff, and M. Yurkov, eds., The European X-Ray Free-Electron Laser Technical design report, DESY XFEL Project Group European XFEL Project Team Deutsches Elektronen-Synchrotron Member of the Helmholtz Association, Hamburg, 2007.

[2] G. Mourou, N. Fisch, V. Malkin, Z. Toroker, E. Khazanov, A. Sergeev, T. Tajima, and B. Le Garrec, "Exawatt-zettawatt pulse generation and applications," Opt. Commun. 285, pp. 720–724, Mar 2012.

[3] F. Ehlotzky, K. Krajewska, and J. Z. Kami ?nski, "Fundamental processes of quantum electrodynamics in laser fields of relativistic power," Rep. Prog. Phys. 72(4), p. 046401, 2009.

[4] A. Di Piazza, C. Müller, K. Z. Hatsagortsyan, and C. H. Keitel, "Extremely high-intensity laser interactions with fundamental quantum systems," Rev. Mod. Phys. 84, pp. 1177–1228, Aug 2012.

[5] M. W. Walser, D. J. Urbach, K. Z. Hatsagortsyan, S. X. Hu, and C. H. Keitel, "Spin and radiation in intense laser fields," Phys. Rev. A 65, p. 043410, Apr 2002.

[6] F. Faisal and S. Bhattacharyya, "Spin asymmetry in an intense-field ionization process," Phys. Rev. Lett. 93, p. 053002, Jul 2004.

[7] G. Brodin, M. Marklund, J. Zamanian, and M. Stefan, "Spin and magnetization effects in plasmas," Plasma Phys. Controlled Fusion 53, p. 074013, May 2011.

[8] S. Ahrens, H. Bauke, C. H. Keitel, and C. Müller, "Spin dynamics in the Kapitza-Dirac effect," Phys. Rev. Lett. 109, p. 043601, Jul 2012.

[9] M. Klaiber, E. Yakaboylu, C. Müller, H. Bauke, G. G. Paulus, and K. Z. Hatsagortsyan, "Spin dynamics in relativistic ionization with highly charged ions in super-strong laser fields," J. Phys. B: At., Mol. Opt. Phys. 47, p. 065603, Mar 2014.

[10] H. Bauke, S. Ahrens, C. H. Keitel, and R. Grobe, "What is the relativistic spin operator?," New Journal of Physics 16(4), p. 043012, 2014.

[11] H. Bauke, S. Ahrens, C. H. Keitel, and R. Grobe, "Relativistic spin operators in various electromagnetic environments," Phys. Rev. A 89, p. 052101, May 2014.

[12] H. Bauke, S. Ahrens, C. H. Keitel, and R. Grobe, "Electron-spin dynamics induced by photon spins." accepted for publication in New Journal of Physics, 2014.

[13] H. Bauke, S. Ahrens, and R. Grobe, "Electron-spin dynamics in elliptically polarized light waves." accepted for publication in Phys. Rev. A, 2014.

9515-21, Session 5

Gamma-ray generation in the interaction of two tightly focused laser pulses with a low-density target composed of electrons

Martin Jirka, Ondrej Klimo, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Stefan Weber, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Sergei V. Bulanov, Timur Zh. Esirkepov, Japan Atomic Energy Agency (Japan); Georg Korn, Institute of Physics of the

ASCR, v.v.i. (Czech Republic)

With the continuing development of laser systems, new important and so-far unexplored fields of research related to interaction of ultra-intense laser beams with matter are opening. At intensities of the order 10^22 W/cm^2, electrons may be accelerated in the electromagnetic field of the laser wave and achieve such a high energy that they can enter the regime affected by the radiation reaction. Due to the non-linear Thomson and Compton scattering the accelerated electrons may emit photons. The interaction of emitted photons with the laser field may result in effective generation of electron-positron pairs by means of the Breit-Wheeler process.

In this work we study the influence of laser pulse polarization on gamma-ray generation during interaction of two colliding and tightly focused laser pulses with an low density target composed of electrons. It is focused on evolution of electron trajectories and key parameters ? and ? in the laser field. These interactions are studied using 2D PIC simulations. It is shown that in the case of circularly polarized and tightly focused laser beams, electrons are not following circular trajectories at the magnetic node of the standing wave established in the focus, which leads to lowering the radiation emission efficiency.

9515-22, Session 5

The Non-Linear Compton Scattering in Plasma Obtained Using a Novel Analytical Solution of The Strong-Field Klein-Gordon Equation

Erez Raicher, The Hebrew Univ. of Jerusalem (Israel); Shalom Eliezer, Univ. Politécnica de Madrid (Spain) and Soreq Nuclear Research Ctr. (Israel); Arie Zigler, The Hebrew Univ. of Jerusalem (Israel)

The quantum dynamics of electrons in strong laser fields are commonly described by the familiar Volkov solution. This solution is valid for vacuum dispersion relation, i.e. it is not adequate in plasma or in a standing wave formed by counterpropagating laser beams. Partial generalization of the solution was addressed by the authors in previous publications [1,2]. In this work we report the derivation of a general solution of Klein-Gordon equation in the presence of an electromagnetic field in plasma. Significant differences between Volkov and our solution are demonstrated and their possible influence on the emission processes as well as on the macroscopic dynamics of the plasma are discussed.

[1] E. Raicher, and S. Eliezer Phys. Rev. A 88, 022113 (2013).

[2] E. Raicher, and S. Eliezer, A. Zigler Phys. Plasmas. 21, 053103 (2014).

9515-23, Session 5

Proposal for an LSW experiment (light shining through walls) at ELI-Beamlines

Bruno J. Le Garrec, Jakub Grosz, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

The most promising approach for detecting WISPs is to use their small coupling to photons, which detection is easy, even at the single particle level. This is what is done in "light shining through the wall" experiments [1], which are based on the probability that a photon may be converted into a WISP, which would traverse a light-tight wall without interacting, then have a chance of being converted back into a photon with the same frequency and direction as the original one. Because of the smallness of the WISPs-photon couplings, it is valuable to use the highest photon fluxes available together with a high magnetic field. This has been successfully done with the kJ laser LULI 2000 in 2007 [2] to search for an axion-like particle which detection had been claimed by the PVLAS collaboration [3]. The high energy laser approach was proven the most efficient to discard this result.

In the near future, another interesting hidden-sector particle can be searched for on laser facilities, namely a hidden-sector photon (HP), also called paraphoton or dark photon. Indeed, the recent WMAP-7 [4] observations and interpretations hint for an extra neutrino-like particle (the total number of neutrino species is found to be 4.34 ± 0.87 with 68% Confidence Level), which could be accounted for by a hidden photon with a mass ? and a HP-photon coupling ? in the parameters range accessible with laser shots.

A former proposal has been made during one of the IZEST meeting for using the LIL facility (LMJ prototype): the upper four beams of the LIL facility are delivering up to 80 kJ in a long pulse mode (20 ns) at 1? which is equal to 4,2 10+22 photons per shot. A detailed design of the experiment including the diagnostic part has been made with the help of Cecile Robilliard .

At ELI-Beamlines, there will be a 1.5-kJ laser (L4) running at 1 shot per mn. This beamline will be mostly devoted to particle acceleration and plasma physics. Nevertheless, any of the transport sections between two mirrors can be used as the before-the-wall part of a LSW experiment. The real advantage is to use all the shots that are delivered to the target chamber. One possible solution is to have a dedicated LSW experiment inside one of the experimental rooms that would take advantage of the "high repetition rate" of 1 shot per minute when compared to LIL rep-rate (1 shot per day).

There are three major requirements for the design of the experiment:

1. Get a long and straight beam path of real photons,

2. Block the beam with a physical wall,

3. Detect particles after propagating the same distance after the wall than the distance real photons did propagate before the wall.

References

[1] J. Redondo and A. Ringwald, "Light shining through walls", DESY 10-175, MPP-2010-149 arXiv:1011.3741v1 [hep-ph].

[2] C. Robilliard et al., Phys. Rev. Lett. 99, 190403 (2007).

[3] E. Zavattini et al., Phys. Rev. Lett. 96, 110406 (2006).

[4] E. Komatsu et al., Astrophys. J. Suppl. Ser. 192, 18 (2011).

9515-24, Session 5

Influence of the radiation reaction force on ultraintense laser driven ion acceleration in the classical radiation dominated regime

Remi Capdessus, Paul McKenna, Univ. of Strathclyde (United Kingdom)

The development of multi-petawatt-class lasers, such as the extreme light infrastructure (ELI) project, will enable new frontiers in laser-plasma research to be explored experimentally [1]. These new laser facilities will provide laser peak intensities beyond 1023 W/cm?. Amongst the many research topics to be explored using these new facilities is radiation reaction physics and how this influences the motion of ultrarelativistic electrons, and subsequently ions, in strong electromagnetic fields. Here we consider how radiation reaction affects laser-driven ion acceleration in the classical radiation dominated regime. This means that the characteristic frequency of the emitted synchrotron radiation is much less than the kinetic energy of the associated radiating electron. We consider the case of a Gaussian laser pulse profile interacting with a deuteron plasma with initial density equal to ~10nc. The laser amplitude range in this study is such that strong classical radiation damping occurs, whilst QED effects are negligible [2]. For laser intensities above 1023 W/cm?, the radiation reaction effects depend strongly on the thickness of the target. In the case of thin targets undergoing relativistic induced transparency, radiation reaction enhances the energy transfer to ions, by acting on electrons expanding backwards towards the incoming laser light. A significant part of the electron kinetic energy is lost to radiation, modifying the plasma expansion. However, for thick targets, the situation is contrary. The laser field interacts with the plasma and ponderomotively pushes the electrons forward, creating a charge separation field which can attain the same magnitude than the laser field [3]. The electrostatic field plays an important role on electron acceleration, enhancing the backward electron motion and increasing the energy converted into intense synchrotron radiation. As a result, less laser energy is transferred to ions (reducing the piston efficiency). Analytical estimates in 1D have been performed to account for the classical radiation losses on the classical piston velocity [4,5]. The 2D effects are also analysed. 1D and 2D simulations have been performed with a relativistic Particle-In-Cell code accounting for the classical radiation reaction force [2]. Our classical approach is also compared and discussed with a QED approach [6].

References

[1] A. Macchi et al. Rev. Mod. Phys., 85, 751 (2013).

[2] R. Capdessus et al. Phys. Rev. E 86, 86036401 (2012)

[3] R. Capdessus et al. Phys. Rev. Lett. 110, 215003 (2013)

[4] T. Schlegel et al. Phys. Plasmas 16, 083103 (2009);

[5] A. P. L. Robinson et al., Plasma Phys. Control. Fusion 51 024004 (2009).

[6] C. P. Ridgers et al., Phys. Rev. Lett., 108, 165006 (2012)

9515-25, Session 5

Optimized multibeam configuration for observation of QED cascades

Evgeny G. Gelfer, Alexander M. Fedotov, Nikolay Narozhny, Arseny Mironov, National Research Nuclear Univ. MEPhI (Russian Federation); Igor Kostyukov, Vladimir Bashmakov, Institute of Applied Physics (Russian Federation)

Observation of QED cascade production in laser experiments would be important for both fundamental physics and experimental testing of QED principles. Numerical simulations provided by previous works [1] indicated that the threshold intensity required for cascade development probably exceeds the intensity that would be available with such upcoming facilities as ELI Beamlines. In this presentation, we optimize the beam polarization in a multibeam setup, thus suggesting a field configuration that reduces both the threshold power and the intensity necessary for cascade production.

Hard photon emission and pair photoproduction in an intense laser field start when the quantum parameter (electron proper acceleration expressed in Compton units) becomes of the order of unity [2]. As was shown previously, for slow particles this quantum paramerer is initially growing as a square of time on the scale smaller than the laser period (this is an `acceleration mechanism' introduced in [3]). This allows for self-sustainable cascades, for which the energy and the quantum parameter of particles are retained from the laser field back due to the acceleration mechanism.

We derive general expression for the coefficient of initial square growth of the quantum parameter in an arbitrary electromagnetic field. Next, we apply this formula to a planar multibeam setup and find optimal polarization of the beams, providing the most rapid growth of the quantum parameter. Finally, we confirm our choice by numerical simulations and find that cascades can be observed in the case of 8 focused beams of the Gaussian shape [4] with angular aperture around Pi/2 [5] colliding at the target if the total laser power is 8 PW and the intensity is 6*10^23$W/cm^2. Such parameters of the beams are believed to be attainable with the new generation of laser facilities, particularly with ELI Beamlines.

[1] N.V. Elkina et al, Phys. Rev. STAB 14, 054401 (2011); E.N. Nerush and I.Yu. Kostyukov, Nucl. Instr. and Methods A 653, 7 (2011); R. Duclous, J.G. Kirk, and A.R. Bell, Plasma Physics and Controlled Fusion 53 015009 (2011); C. P. Ridgers et al, Phys. Rev. Lett. 108, 165006 (2012).

[2] A. I. Nikishov, V. I. Ritus, Sov. Phys. JETP 19, 529 (1964); ibid. 25, 1135 (1967); V. N. Baier, V. M. Katkov, Phys. Lett. 25A, 492 (1967).

[3] A.M. Fedotov et al, Phys. Rev. Lett. 105, 080402 (2010).

[4] N.B. Narozhny, M.S. Fofanov, JETP 90, 753 (2000); A.M. Fedotov, Laser Physics 19, 214 (2009).

[5] S.-W. Bahk et. al. Opt. Letters, 29, 2837 (2004); V. Yanovsky, et. al., Opt. Express 16, 2109 (2008).

9515-26, Session 6

Status of European XFEL and plans for start of operation *(Invited Paper)*

Thomas Tschentscher, European XFEL GmbH (Germany)

The European X-Ray Free-Electron Laser (European XFEL) is currently under construction in the Hamburg metropole area, Germany. First electrons have been generated in the laser-driven injector and commissioning of the accelerator with beam will commence in summer 2015. The production and installation of the main accelerator, provided to a large extent through contributions by partners from a large number of countries, is in full swing. The 91 undulator segments to be installed for the various FEL sources have been produced, tested and await installation. The challenging x-ray optics and diagnostics elements are under procurement and first components have been installed in the tunnels. The design of the science instruments is largely complete and installation has started. This important activity will continue until start of operation. Further important developments concern the x-ray detectors, synchronized optical lsers, sample environments and the data acquisition and storage systems. By summer 2016 the accelerator construction and installation will be completed and commissioning with beam will be started at an electron energy of initially 17.5 GeV. By the end of 2016 the electron beam and undulators will be ready for first generation of FEL radiation. In 2017 the commissioning of electron beam, undulator and FEL operation, and of the science instruments will continue. The three FEL sources and the six science instruments will be taken into operation in the sequence SASE1 – SASE3 – SASE2 over a period of about four to six months. In parallel, in 2017 first user experiments will be performed. Full performance of accelerator, FEL radiation and science instruments shall be reached in 2018. It is currently planned to increase the hours for accelerator operation dedicated to the user program from 1000 hrs in 2017, over 2000 hrs in 2018, to the final 4000 hrs in 2019. In the presentation the current layout of the facility and science instrument will be shown. An outlook to the commissioning of the facility and the initial science program is provided.

9515-27, Session 6

World's largest high energy petawatt laser LFEX as a users facility *(Invited Paper)*

Hiroshi Azechi, Hiroyuki Shiraga, Osaka Univ. (Japan)

No Abstract Available

9515-28, Session 6

Bella Laser: status update *(Invited Paper)*

Wim P. Leemans, Lawrence Berkeley National Lab. (United States)

No Abstract Available

9515-29, Session 6

Research activities on high-intensity laser and high-field physics at CoReLS *(Invited Paper)*

Tae Moon Jeong, Gwangju Institute of Science and Technology (Korea, Republic of)

The Center for Relativistic Laser Science (CoReLS) is developing a

femtosecond 4-PW Ti:sapphire laser system. In this talk, the current status of the laser development and the related research on high-field physics will be presented.

9515-30, Session 7

High-energy processes in extremely strong laser pulses *(Invited Paper)*

Christoph H. Keitel, Max-Planck-Institut für Kernphysik (Germany)

With current and anticipated new facilities laser physics in the GeV regime is becoming feasible. Theoretical progress on high-energy physics with such facilities will be discussed in this talk. Recent results will include examples like plasma-based generation of single few-cycle high-energy ultrahigh-intensity laser pulses and Higgs boson generation with extremely intense laser pulses.

[1] M. Tamburini, A. Di Piazza, T.?V. Liseykina, and C.?H. Keitel, Phys. Rev. Lett. 113, 025005 (2014) [2] Jian-Xing Li, K. Z. Hatsagortsyan, and C. H. Keitel, Phys. Rev. Lett. 113, 044801 (2014).

[3] S. Meuren, K. Z. Hatsagortsyan, C. H. Keitel, A. Di Piazza, arXiv:1407.0188 [hep-ph] (2014) [4] S. Müller, C. H. Keitel, C. Müller, Phys. Lett. B 730, 161-164 (2014)

9515-31, Session 7

Robust signatures of quantum radiation reaction and ultrashort gamma-ray pulses with an electron beam in a focused laser pulse

Jian Xing Li, Karen Z. Hatsagortsyan, Christoph H. Keitel, Max-Planck-Institut für Kernphysik (Germany)

We have investigated radiation-reaction effects in the interaction of an electron bunch with a superstrong focused ultrashort laser pulse in the quantum radiation-dominated regime. In dependence of the laser-pulse duration we find signatures of quantum radiation reaction in the radiation spectra, which are characteristic for the focused laser beam and visible in the qualitative behavior of both the angular spread and the spectral bandwidth of the radiation spectra. The signatures are robust with respect to the variation of the electron and laser-beam parameters in a large range. Qualitatively, they differ fully from those in the classical radiation-reaction regime and are measurable with presently available laser technology. Furthermore, we show a method for the creation of high-quality ultrashort gamma-ray pulses in nonlinear Compton scattering which employs both radiation reaction and tightly focusing of the laser field.

9515-32, Session 7

High-energy recollision processes of laser-generated electron-positron pairs

S. Meuren, Karen Z. Hatsagortsyan, Christoph H. Keitel, Antonino Di Piazza, Max-Planck-Institut für Kernphysik (Germany)

The non-linear regime of QED is entered if the electric field strength reaches the critical value, which corresponds to a laser intensity of (1). Even if near-future laser facilities like ELI, CLF or XCELS will not reach this threshold, the critical field of QED can be even exceeded in the rest frame of an highly energetic particle at those facilities. In (2) we have shown that by combining petawatt laser systems with GeV photons (obtainable via Compton backscattering), probabilities for electron-positron pair production of the order of 10% are feasible. Once a pair is produced, the classical equations of motion predict that the electron and the positron are further accelerated by the laser field and (under certain circumstances) brought to a recollision (3). In (4) we have given the first ab initio quantum calculation for such recollision processes and demonstrated that they are in the realm of quantum field theory encoded in electron-positron loop Feynman diagrams. By investigating the polarization operator in a plane-wave laser field, we have identied the contribution describing recollisions, which differs qualitatively and quantitatively from the one describing radiative corrections. As a consequence, recollision processes may signicantly alter the tree-level predictions of QED in a strong laser field and could play a role for next-generation laser parameters.

[1] A. Di Piazza, C. Müller, K. Z. Hatsagortsyan, and C. H. Keitel, Rev. Mod. Phys. 84, 1177 (2012).

[2] S. Meuren, K. Z. Hatsagortsyan, C. H. Keitel, and A. Di Piazza, (2014), arXiv:1406.7235.

[3] M. Y. Kuchiev, Phys. Rev. Lett. 99, 130404 (2007).

[4] S. Meuren, K. Z. Hatsagortsyan, C. H. Keitel, and A. Di Piazza, (2014), arXiv:1407.0188.

9515-33, Session 7

The effect of QED processes on ion acceleration and other applications of 10PW-class lasers

Christopher P. Ridgers, The Univ. of York (United Kingdom)

Next generation high-intensity lasers, such as several of those comprising the Extreme Light Infrastructure (ELI), will push laser plasma interactions into an entirely new regime. At the extreme intensities projected to be reached by these facilities (>5x10^22Wcm^-2) nonlinear quantum electrodynamics processes play a critical role in the plasma dynamics. The promising application of these lasers as a source of energetic ions is crucially dependent on this plasma dynamics. Specifically, the radiation pressure of the pulse is sufficient to drive the ions to ~GeV energies, but this radiation pressure is reduced by the absorption of laser energy and its conversion to a critical density pair plasma which impedes the pulse as it propagates towards the target. We will re-examine radiation pressure driven ion acceleration to account for these effects. We will also determine the effect of QED processes on other potential applications of next generation 10PW class lasers, re-examining the generation of energetic electrons and coherent high-harmonics in the new regime.

9515-34, Session 7

Lepton plasma diagnostics and antimatter physics : challenges for PW-class facilities

Ladislav Drska, Czech Technical Univ. in Prague (Czech Republic)

New generation of high-intensity laser systems culminating in the ELI facility paves the way to breakthrough possibilities in basic physics research. This paper aimes to present some results of a feasibility study of such effort taking account of real parameters of ELI pillars. In the introduction, some preparatory information will be provided: (1) Contemporary lepton physics and antimatter research. (2) Dawn of laser leptonics , its potential for basic physics studies. *

Comprehensive diagnostics of plasmas produced by high-intensity lasers is a key demand for their research . In this part of the presentation, some novel potential forms of diagnostics for high-intensity systems will be analyzed: (1) Possibilities of plasma diagnostics using positrons / positronium (electron pair production as a signature of high-intensity processes, problems of active plasma diagnostics using positrons / positronium). (2) Nuclear pyrometry and active muon / muonium plasma diagnostics (muon supported pyrometry of extremely hot plasma systems, concepts of active plasma diagnostics via muon / muonium beams). *

Research of gravitational characteristics of antimatter may be viewed as a test of general relativity theory and could bear importantly on the formulation of quantum theory of gravity. This part of the talk will include the following topics: (1) Laser-based supportive activities in non-hadronics antimatter studies (synergy of accelerator and laser approaches, laser as a suitable producer / tool for non-hadronic antimatter species). (2) Antimatter gravity with slow leptons as a prospective task for the UHI laser facility (specific problems related to positronium/muonium-based gravity studies challenges and obstacles of potential experiments via PW-class lasers).

9515-35, Session 7

Compton scattering: exploring the weakly quantum regime with 1-10 PW lasers

Marija Vranic, Thomas Grismayer, Joana L. Martins, Instituto Superior Técnico (Portugal); Ricardo A. Fonseca, Instituto Superior Técnico (Portugal) and Univ. de Lisboa (Portugal); Luis O. Silva, Instituto Superior Técnico (Portugal)

Currently available petawatt laser systems can provide intensities of 10^21 ? 10^22 W / cm^2 with the pulse duration of about 30 fs. ELI is aiming at multi-PW and a pulse that allows for longer interaction (100-150 fs). This opens new possibilities to experimentally observe radiation reaction and study the electron distribution evolution for a relativistic beam undergoing Compton scattering.

A powerful tool that supports theoretical studies of laser-matter interactions and helps design of experiments are particle-in-cell (PIC) codes. However, appropriate quantum corrections must be taken into account for studies at extreme intensities: OSIRIS contains a classical radiation reaction module based on the Landau&Lifshitz equation and a Quantum electrodynamics (QED) module that includes discrete photon emission (non-linear Compton scattering) and Breit-Wheeler electron-positron pair production.

While classical radiation reaction is a continuous process, in QED, radiation is a stochastic process that impacts the particle trajectory in a distinct manner. The two pictures reconcile in the limit when the emitted photons have much smaller energy compared to the emitting electrons. The most pronounced QED signature is on the energy spread of the electron beam: classical radiation reaction always tends to decrease it [1], whereas with the stochastic QED emission can also enlarge it. Detailed studies using the QED module revealed an upper limit to the maximal attainable energy spread that depends on laser intensity and the electron beam average energy. The experimental signatures in the context of future ELI parameters will be discussed.

[1] M. Vranic et. al., Phys. Rev. Lett. 113, 134801(2014)

9515-36, Session 7

Motion of a charge in a superstrong electromagnetic standing wave

Timur Zh. Esirkepov, Sergei V. Bulanov, Japan Atomic Energy Agency (Japan)

With the advent of super-intense multi-petawatt lasers, it will become possible to probe quantum electrodynamics (QED) effects at the focus of two counter-propagating laser pulses, where a standing electromagnetic wave is formed. While an electron rotating in a circularly polarized wave cannot attain the Schwinger limit due to an electron-positron avalanche development [1], an oscillation along a transverse axis in a linearly polarized wave has much higher threshold for such avalanches and can attain the Schwinger limit [2].

Recently it was found [3] that electrons in a sufficiently intense standing wave are compressed toward, and oscillate synchronously at, the antinodes of the electric field. This opens new possibilities for the generation of high energy, directed, and collimated radiation and particle beams.

Here we investigate electron trajectories in circularly and linearly polarized standing waves, taking into account the radiation reaction in Landau-Lifshitz form [4] and QED effects moderating the radiation reaction [5]. With a relatively weak radiation reaction the electron performs a random walk like motion encompassing many spatial periods of a standing wave. As the radiation reaction grows, the electron trajectory becomes trapped in a quasi-regular motion near the electric field antinodes and quasi-chaotic motion near the nodes. We study the stability of the trapping effect with respect to the standing wave perturbations.

[1] A. R. Bell and J. G. Kirk, Phys. Rev. Lett. 101, 200403 (2008).

[2] S. S. Bulanov, et al., Phys. Rev. Lett. 105, 220407 (2010).

[3] A.Gonoskov, et al., Phys. Rev. Lett. 113, 014801 (2014).

[4] L. D. Landau and E. M. Lifshitz, The Classical Theory of Fields.

[5] C. P. Ridgers, et al., Phys. Rev. Lett. 108, 165006 (2012).

9515-37, Session 8

Extreme laser power from external enhancement in high finesse Fabry-Perot cavities: application to high-flux X- or ?-Ray production through Compton scattering *(Invited Paper)*

Eric Cormier, Univ. Bordeaux 1 (France)

No Abstract Available

9515-38, Session 8

Seeded QED cascades in ultra-intense counter-propagating lasers: theory and multidimensional QED-PIC simulations *(Invited Paper)*

Thomas Grismayer, Marija Vranic, Joana L. Martins, Ricardo A. Fonseca, Luis O. Silva, Instituto Superior Técnico (Portugal)

Plasma physics in extreme fields requires taking into account Quantum Electrodynamics. Out of the possible mechanisms, pair production seeded by an electron is likely to be the most dominant at lower intensities. We have included the two-step process (non linear Compton scattering + Breit-Wheeler) in a massively parallel PIC code (using the Osiris 2.0 framework) via a Monte Carlo module, focusing on implementing in a self-consistent manner and multi-dimensions the interaction of the intense fields with the pair plasma dynamics.

As an illustration we have investigated the pair cascades seeded by electrons in counter-propagating lasers pulses for ELI parameters. The self-consistent modeling of these scenarios is challenging since some localized regions of ultra-intense field will produce a vast number of pairs that may cause memory overflow during the simulation. To overcome this issue, we have developed a merging algorithm that allows merging a large number of particles into fewer particles with higher particle weights while conserving local particle distributions.

This algorithm is crucial to investigate the laser absorption in self-generated pair plasmas. During the interaction, the laser energy is converted into pairs and photons and the absorption become significant when the plasma density reaches the critical density. With the results of 2D and 3D PIC-QED simulations, we will present the growth rates of the pair cascades and their dependence on the initial intensity of the lasers and on the polarisation. A simple analytical model for pair cascade will be compared with the numerical results. We will additionally show the respective fraction of laser energy transferred into pairs and photons for various configurations. Finally the various mechanisms contributing the laser absorption will be discussed.

9515-39, Session 8

Interaction of photons traversing a slowly varying electromagnetic background: numerical simulation of vacuum self-emission *(Invited Paper)*

Ben King, Plymouth Univ. (United Kingdom); Patrick Boehl, Hartmut Ruhl, Ludwig-Maximilians-Univ. München (Germany)

When two electromagnetic fields counterpropagate, they are modified due to mutual interaction via the polarized virtual electron-positron states of the vacuum. By studying how photon-photon scattering effects such as birefringence and four-wave mixing evolve as the fields pass through one another, we find a significant increase during overlap when both electromagnetic variants can be nonzero. The results have particular relevance for calculations based on a constant field background.

9515-40, Session 8

Steering laser plasma simulations towards reliable predictions: how to use accelerated computing for particle accelerators

Michael Bussmann, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

No Abstract Available

9515-41, Session 9

Particle acceleration with the Dresden PW lasers *(Invited Paper)*

Ulrich Schramm, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

No Abstract Available

9515-42, Session 9

Laser plasma accelerators for near-term applications *(Invited Paper)*

Victor Malka, Ecole Nationale Supérieure de Techniques Avancées (France); Cédric Thaury, Ecole Polytechnique (France); Emilien Guillaume, Lab. d'Optique Appliquée (France); Andreas Döpp, Ctr. de Laseres Pulsados (Spain); Remi Lehe, Ecole Nationale Supérieure de Techniques Avancées (France); Agustin Lifschitz, Ecole Polytechnique (France); L. Truong Phuoc, Ecole européenne de Chimie, Polymères et Matériaux (France)

Laser-plasma accelerator allows to produce in compact and reliable way high quality electron beam with an ultra short duration. It could make free electron lasers available to a broad scientific community, and push further the limits of electron accelerators for high-energy physics purpose. The unique femtosecond nature of the bunch makes it a promising tool for the study of ultra-fast phenomena. The maturity of this research allows to consider the use of the electron beam for applications in domain such as medicine for cancer imaging and for cancer treatment, or such security for non destructive imaging of dense matter. For other important applications, its transport with conventional electrons lenses degrades drastically the beam parameters. This problem can be solved, by using a laser-plasma lens, with field gradients, that are five orders of magnitude larger than in conventional optics. We demonstrate a reduction of the divergence by nearly a factor of three, which should allow for an efficient coupling of the beam with a conventional beam transport line.

9515-43, Session 9

Recent development and future perspectives in laser-driven ion acceleration *(Invited Paper)*

Marco Borghesi, Queen's Univ. Belfast (United Kingdom)

No Abstract Available

9515-44, Session 9

Petawatt laser pulses for proton-boron high gain fusion without problem of nuclear radiation *(Invited Paper)*

Heinrich Hora, The Univ. of New South Wales (Australia); Paraskevas Lalousis, Foundation for Research and Technology-Hellas (Greece); Lorenzo Giuffrida, Daniele Margarone, Georg Korn, Institute of Physics of the ASCR, v.v.i., ELI Beamlines (Czech Republic); Shalom Eliezer, Univ. Politécnica de Madrid (Spain) and Soreq REsearch Center, Yavne (Israel); Geroge H Miley, Univ. of Illinois at Urbana-Champaign (United States); Stavros Moustaizis, Technical Univ. of Crete (Greece); Gerard Mourou, Ecole Polytechnique (France)

Fusion of 11B with protons (HB11) resulting in 3 alpha particles each of energy 2.9 MeV are a long years desire because they result in less radioactivity than burning coal per generated energy and therefore has not any problem with nuclear radiation. However, HB11 reactions are known to be extremely more difficult than DT fusion when using nanosecond laser pulses with hydrodynamic compression and thermal ignition. A drastic change resulted by using >PW-picosecond laser pulses with non-thermal direct conversion of laser energy into ultrahigh accelerated plasma blocks using nonlinear (ponderomotive) forces as calculated 1978 and measured by Sauerbrey 1996 in agreement with the theoretical prediction [1]. These picoseconds laser pulses of very high power can for the first time inititiate fusion flames in solid density fuel according to Bobin and Chu. A significant success for HB11 fusion with ps laser pulses was discovered by Laboune et al [2] with subsequent 100 times higher gains even by using only by non-ideal laser pulses [3] not too far away from the highest gains of DT fusion by lasers. The block ignition of HB11 with PW-ps laser pulses was shown to be similar to DT [4] (and not extremely more difficult). When secondary reactions were included for HB11 and a cylindrical trapping of the reaction by the now available 10 kilotesla magnetic fields [5], a high gain reaction is expected with 30 Petawatt laser pulses [6]. The theory is generalized by including the double layer [7] mechanism [8] for the initiation of the fusion flame to ignite uncompressed fuel.

[1] H. Hora, J. Baziak et al 14, 972701 (2007)

[2] C.Labaune et al Nature Communications 4, 2506 (2013)

[3] Korn, G. D. Margarone and A. Picciotto Boron-Proton Nuclear Fusion Enhancement Induced in Boron-doped Silicon Targets by Low-contrast Pulsed Lasers. IZEST ELI-NP Conference Paris, 17-18 Sept. (2014). A. Picciotto et al. Phys. Rev. X 4, 031030 (2014)

[4] H. Hora, Laser and Particle Beams 27, 207 (2009)

[5] S. Fujioka et al. Sci. Reports 3, 1170 (2013)

[6] P. Lalousis, H. Hora and S. Moustaizis, Laser and Particle Beams 32, 409 (2014)

[7] H. Hora, P. Lalousis and S. Eliezer, Phys. Rev. Letters 53, 1650-1652 (1984).

[8] S. Eliezer, N. Nissim, J.M. Martinez Val, K. Mima and H. Hora, Laser and Particle Beams 32, 211-217 (2014).

9515-45, Session 9

Design and development of the user station of HELL: beam transport, characterization and shielding

Gabriele Maria Grittani, Alberto Fasso, Miroslav Krus, Tadzio Levato, Daniele Margarone, Martin Precek, Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and ELI Beamlines (Czech Republic)

In the framework of the ELI-Beamlines project, HELL will be an electron beam-line with a dual aim: explore innovative concepts of laser driven electron acceleration and deliver a stable and reliable electron beam to external users, according to their specific needs. Because of this, it is crucial to identify the possible applications and their respective range of parameters. In order to accomplish this goal, Monte Carlo simulations of electron radiography and dose deposition curves in different objects are performed and are compared and discussed with experimental data. Once identified those parameter spaces, a beam transport line, beam diagnostics and a dedicated shielding are studied and presented. Finally, a possible design of the user station is presented, along with a picture of the different configurations depending on the electron beam to be delivered.

9515-46, Session 9

Stabilization of laser-driven accelerators and scaling to higher energies

Victor Malka, Ecole Nationale Supérieure de Techniques Avancées (France)

To produce high quality electron beam with laser plasma accelerators, it is crucial to control electrons injection process in a very small volume, of about one micrometer radius, in a well-defined position of the plasma wakefield. To do so different injection schemes have been proposed such as self-injection, colliding laser pulses injection, ionization injection or gradient injection. In addition to these schemes that have been demonstrated experimentally by many groups, other injection schemes have been also proposed theoretically and are under consideration for experiments. From the experimental data, such as energy spread, energy and charge, the laser to electron energy efficiency that can be evaluated and can be used to estimate the required laser parameters for scaling a machine of relevance for high energies physics purpose. The many questions that are still open with the many problems that need to be solved will be discussed in order to evaluate the pertinence of the laser plasma accelerators approach for high energy physics applications.

9515-47, Session 10

Plasmas at the extreme with ultraintense lasers and beams *(Invited Paper)*

Luis O. Silva, Univ. Técnica de Lisboa (Portugal)

No Abstract Available

9515-48, Session 10

Photonuclear reactions and radiography with laser-accelerator-based Thomson X-rays *(Invited Paper)*

Donald P. Umstadter, Sudeep Banerjee, Grigory Golovin, Univ. of Nebraska-Lincoln (United States); Ping Zhang, Daniel Haden, Univ. of Nebraska-Lincoln (United States); Shouyuan Chen, Cheng Liu, Jun Zhang, Baozhen Zhao, Kevin Brown, Jared B. Mills, Univ. of Nebraska-Lincoln (United States); Chad Petersen, Cameron Miller, Univ. of Nebraska-Lincoln (United States); Shaun Clarke, Sara A. Pozzi, Univ. of Michigan (United States)

The laser-driven Thomson scattering light source generates x-rays by the scattering of a high-energy electron beam off a high-intensity laser pulse. We have demonstrated that this source can generate collimated, narrowband x-ray beams in the energy range 0.1-12 MeV. In this work, we discuss recent results on the application of this source for radiography and photonuclear studies. We will show that using 6-9 MeV photon beams we can distinguish shielded high-Z materials. The unique characteristics of the source make it possible to do this with the lowest possible dose and in a low-noise environment. We will also discuss recent experimental results that study nuclear reactions above the threshold for photodisintegration and photofission. The tunable nature of the source permits activation of specific targets while suppressing the signal from background materials.

9515-49, Session 10

Laser-driven multicharged heavy ion beam acceleration

Mamiko Nishiuchi, Hironao Sakaki, Timur Zh. Esirkepov, Katsuhisa Nishio, Tatiana A. Pikuz, Anatoly Y. Faenov, Alexander S. Pirozhkov, Akito Sagisaka, Masato Kanasaki, Koichi Ogura, Hiromitsu Kiriyama, Hiroyuki Koura, Masaki Kando, Japan Atomic Energy Agency (Japan); Tomoya Yamauchi, Kobe Univ. (Japan); Yukinobu Watanabe, Kyushu Univ. (Japan); Sergei V. Bulanov, Kiminori Kondo, Kenichi Imai, Japan Atomic Energy Agency (Japan); Shoji Nagamiya, RIKEN (Japan)

More than three decades has been passes since the observation of the acceleration of protons to high kinetic energy in plasmas by the interaction between high-intensity laser pulses and thin-foil targets [1]. Because of the peculiar characteristics of the beam, many possible fields of applications have been proposed, including a compact injector for the conventional accelerator, especially for heavy ions [2]. The investigation of the laser-driven proton beam is extensively carried out in past decade.. However, the investigation of the heavy ion acceleration is less paid attention to. This is simply because proton, originates from the surface contaminant layer of the target surface is accelerated relatively easily for its largest Q/M and the achieved on-target intensity of the laser was not high enough to make the heavy atoms to have high Q/M. For the acceleration of heavy ions by the laser, making the Q/M ratio of heavy ions as high as possible at enough short time than the laser pulse width is the key issue.

We have achieved on target intensity of 1021Wcm-2 with 200TW, less than 10J of energy, by controlling the temporal and spatial pulse shape, for the purpose of the heavy atoms originate from the target to be stripped efficiently at the beginning phase of the laser pulse. As a result, the heavy ions with almost fully stripped charge state are accelerated efficiently by the quasi-static electric field which is sustained during the rest of the laser pulse irradiation.

Here we demonstrated almost fully stripped aluminum and iron ion acceleration up to 12 MeV/u and 16 MeV/u (total energy of 324 MeV and 1GeV), which is, to our knowledge, far the highest energy ever reported for the case of acceleration of the heavy ions produced by the 200TW class Ti:sapphire laser system called J-KAREN [3] with laser energy less than 10J.

The up-grade of the J-KAREN laser system is now going on for further exploring the high intensity laser-plasma interaction. The status of the up-grade and the prospects of the upgraded J-KAREN system will be reported.

Reference

[1] R.A.Snavely M. H. Key, S. P. Hatchett, T. E. Cowan,1 M. Roth, T.W. Phillips, M. A. Stoyer, E. A. Henry,T. C. Sangster, M. S. Singh, S. C. Wilks, A. MacKinnon, A. Offenberger, D.M. Pennington, K. Yasuike, A. B. Langdon, B. F. Lasinski, J. Johnson, M. D. Perry, and E. M. Campbell, “Intense High-Energy Proton Beams from Petawatt-Laser Irradiation of Solids”, Phys.

Rev. Lett., 85, 2945 (2000).

[2] A.V. Korzhimanov, E. S. Efimenko, S.V. Golubev, and A.V. Ki, "Generating High-Energy Highly Charged Ion Beams from Petawatt-Class Laser Interactions with Compound Targets", Phys. Rev. Lett. 109, 245008 (2012).

[3] H. Kiriyama, M. Mori, Y. Nakai, T. Shimomura, H. Sasao, M. Tanoue, S. Kanazawa, D. Wakai, F. Sasao, H. Okada, I. Daito, M. Suzuki, S. Kando, K. Kondo, A. Sugiyama, P. R. Bolton, A. Yokoyama, H. Daido, S. Kawanishi, T. Kimura, and T. Tajima, Opt. Lett. 35, 1497 (2010).

9515-50, Session 10

Numerical investigations on a compact magnetic fusion device for studing the effect of external applied magnetic field oscillations on the nuclear burning efficiency of D-T and p-11B fuels

Stavros Moustaizis, Technical Univ. of Crete (Greece); Paraskevas Lalousis, Foundation for Research and Technology-Hellas (Greece); Heinrich Hora, The Univ. of New South Wales (Australia); Jean Larour, Philippe Auvray, Ecole Polytechnique (France); Philippe Balcou, Jean-Eric Ducret, Univ. Bordeaux 1 (France); Philippe Martin, Commissariat à l'Énergie Atomique (France)

The burning process of high density (about 10^18cm-3), high temperature (tens of keV) plasma trapped by a high mirror-like magnetic field in a Compact Magnetic Fusion (CMF) device is numerically investigated.. The initial high density and high temperature plasma in the CMF device is produced by ultrashort high intensity laser beam interaction with clusters or thin foils, and two fuels, D-T and p-11B are studied. The spatio-tempral evolution of D-T and p-11B plasmas, the production of alphas, the generated electric fields and the high external applied magnetic field are described by a 1-D multi-fluid code. The initial values for the plasma densities, temperatures and external applied magnetic field (about 100 T) correspond to high ? plasmas. The main objectives of the numerical simulations are: to study the plasma trapping, the neutron and alpha production for both fuels, and compare the effect of the profile of the external applied magnetic field on the nuclear burning efficiency for the two fuels. The comparisons and the advantages for each fuel will be presented. The proposed CMF device and the potential operation of the device within the ELI-NP pillar will be discussed.

9515-51, Session 10

Reduction of angular divergence of laser-driven ion beams during their acceleration and transport

Martina Záková, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Jan Psikal, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Daniele Margarone, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Mario Maggiore, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and Istituto Nazionale di Fisica Nucleare (Italy); Georg Korn, Institute of Physics ASCR, v.v.i. (FZU), ELI-Beamlines Project, 182 21 Prague (Czech Republic)

Laser plasma physics is a field of big interest because of its implications in basic science, fast ignition, medicine (i.e. hadrontherapy), astrophysics, material science, particle acceleration etc.

More than 150 MeV protons accelerated from a target plasma produced by a high intensity, short laser pulse (in relativistically transparent regimes) were experimentally observed. With continuing development of laser technology, greater and greater energies are expected, therefore projects focusing on various applications are formed, i.e. ELIMAIA (ELI Multidisciplinary Applications of laser-Ion Acceleration). One of the main characteristic and crucial disadvantage of ion beams accelerated by ultra-short intense laser pulses is their large divergence, not suitable for the most of applications. In this paper two ways how to decrease beam divergence are proposed. Firstly, impact of different design of targets on beam divergence are studied using 2D Particle-in-cell simulations (PIC). Namely, various types of targets cover flat foils, curved foils and foils with diverse microstructures. Obtained results show that the particle beam accelerated from a curved foil has lower divergence compared to the beam from a flat foil. In addition, the foil with microstructures shows a different focusing effect depending on number and size of its microstructures and also on the position of the laser focus center (between or across microstructures). Moreover, energy spectrum of accelerated ions (maximum protons energies of tens MeV) and absorption of laser pulse energy are compared for various targets. Secondly, another proposed method for the divergence reduction is using of a magnetic solenoid. The trajectories of the laser-accelerated particle beam passing through the solenoid are modeled in a simple Matlab program. Results from PIC simulations are employed to compute emittance Twiss parameters which are used as input in the program. The divergence is controlled by changing the length of the coil, optimizing the magnetic field inside the solenoid and installing an aperture in front of the device.

9515-52, Session 10

Enhanced ion acceleration by using femtosecond laser pulses at the third harmonic frequency

Jan Psikal, Ondrej Klimo, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Stefan Weber, Daniele Margarone, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Jiri Limpouch, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Relativistically induced transparency regime has been already achieved experimentally by the expansion of ionized solid target during laser-target interaction for relatively longer laser pulses (about 500 fs), but not for ultrashort pulses (about 30 fs), where the expansion is not significant, and, thus, too high laser intensity (close to 10^(23) W/cm^(2)) is required. However, when ultrashort intense laser pulse at higher harmonic frequency irradiates a thin solid foil, the target may become relativistically transparent for significantly lower laser pulse intensity compared with the irradiation at fundamental laser frequency. The relativistically induced transparency results in an enhanced heating of hot electrons as well as increased maximum energy of accelerated ions and their numbers. When fundamental laser frequency is converted to the third harmonics, we observed the increase of maximum energy of accelerated protons and numbers of high energy protons by factor of 2 in our two-dimensional particle-in-cell simulations. Lengthening of the laser pulse due to frequency conversion should not decrease the energy and numbers of accelerated protons. The proposed scheme enables to accelerate protons to energies over 250 MeV by ultrashort laser pulse of maximum intensity below 10^(22) W/cm^(2) irradiating 200 nm thick solid foil.

9515-53, Session PS

Magnetic reconnection research with petawatt-class lasers

Yanjun Gu, Ondrej Klimo, Deepak Kumar, Yue Liu, Sushil Singh, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Sergei V. Bulanov, Timur Zh. Esirkepov, Japan Atomic Energy Agency (Japan); Stefan Weber, Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Magnetic reconnection is regarded as a fundamental phenomenon in space and laboratory plasmas. It converts magnetic energy to kinetic energy of plasma particles through the topological rearrangements of the magnetic field lines. Magnetic reconnection is believed to play an important role in the solar systems, such as solar flares and coronal mass ejections. Observations of rapid energy release in solar flare and the global convection pattern within the magnetosphere are strongly suggestive that reconnection must be occurring. With the development of laser technology, high power laser facilities have made great progress in recent decades. Ultra powerful pulse with TW and PW are available now. As a result, the laser-matter interaction enters regimes of interest for laboratory astrophysics such as magnetic reconnection. J. Y. Zhong et al. reported the experiment about X-ray source emission by reconnection outflows. Two intense lasers with long pulse duration are focused on the solid Aluminum target to generate hot electrons. In this paper, we employed a hydrogen foam target with near critical density to investigate the reconnection. Two parallel ultra intense pulses are injected into the target. By the effect of laser wakefield acceleration, two strong electron beam are generated and both of them induce a magnetic dipole structure. With the expansion of the dipole, magnetic field annihilation occurs in the center part of the target. The induced electric field and particle acceleration are detected in the simulations as the evidence for magnetic reconnection. The effects from the separation distance between two laser pulses and laser intensity to magnetic reconnection are also discussed.

9515-54, Session PS

Evolution of relativistic solitons in underdense plasmas

Yue Liu, Ondrej Klimo, Yanjun Gu, Deepak Kumar, Sushil Singh, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Sergei V. Bulanov, Timur Zh. Esirkepov, Japan Atomic Energy Agency (Japan); Stefan Weber, Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

When the highly intense laser pulse radiates collisionless plasmas, various relativistic nonlinear effects occur such as relativistic self-focusing, relativistic induced transparency of an overdense plasma, and the formation of the relativistic solitons. Relativistic solitons are observed behind laser pulse with oscillating electromagnetic field confined in the expanding cavity in the distribution of the electron and ion densities. We show the formation and evolution of the relativistic solitons in a collisionless cold plasma with two dimensional particle-in-cell simulations. Such a kind of solitons will evolve into postsolitons if the time scale is longer than the ion response time. Postsolitons are elementary components of relativistic electromagnetic turbulence in laser-plasma interaction. Generally, a substantial part of the pulse energy is transformed into solitons during the soliton formation. This fairly high efficiency of electromagnetic energy transformation can play an important role in the interaction between the laser pulse and the plasma. The energy transformation among the laser pulse, relativistic soliton as well as the fast particles has also been studied. In homogeneous plasmas, the solitons stay close to the region where they are generated for a long time and dissipate due to the interaction with fast particles eventually. While the laser pulse propagates through inhomogeneous plasmas, the solitons will be accelerated along the plasma density gradient towards lower density. The comprehensive research on basic properties of soliton and postsoliton in plasmas are presented in terms of the particle momenta, electromagnetic field as well as the energy dissipation of the solitons. We also discuss the effects of laser and plasma parameters on the soliton evolution, such as the different plasma components, laser pulse duration, plasma temperature and so on.

9515-55, Session PS

Radiochromic film diagnostics for laser-driven ion beams

Jan Kaufman, Daniele Margarone, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Giacomo Candiano, Istituto Nazionale di Fisica Nucleare (Italy); I Jong Kim, Tae Moon Jeong, Gwangju Institute of Science and Technology (Korea, Republic of); Jan Psikal, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Francesco Romano, Pablo G. A. Cirrone, Istituto Nazionale di Fisica Nucleare (Italy); Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

The self-developing radiochromic films represent a clear step in processor-less laser-driven ion beam diagnostics. The films have found their use in various kinds of applications, primarily in modern radiotherapy though they can also be used for laser-driven particle beams. In fact, in an environment of frequent high power electromagnetic pulses, such an electronics-free diagnostics is highly desirable. An appropriately put together stack of alternating film and shielding layers inserted in the path of the particle beam (in this case ions) provides vital beam characteristics such as maximum energy, particle number and divergence. An ion passing through the stack leaves a mark on each of the films it has passed until it is finally stopped. With a proper calibration one can use deconvolution to isolate single ion energy groups associated with each film layer where the energy range of each group is determined by the stack design. The strength of this technique lies in its simplicity. Moreover it serves as a complementary diagnostics to other usually employed diagnostics such as Thomson parabola spectrometer.

9515-56, Session PS

Quadrupole lens free multiple profile monitor emittance measurement method

Miroslav Krus, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

The quadrupole lens free multiple profile emittance measurement method is a new adaptation of the standard multiple profile monitor method for electron beam emittance measurement which was tested at (sub) PW class laser facilities. This single shot technique allows to obtain the emittance from beam profile radii fit by means of Twiss (Courant-Snyder) parameters. LANEX scintillating screens (due to their high yield of visible photons) were used as profile monitors. However, on the other hand, the screen is a source of multiple Coulomb scattering which can influence the beam profile on the following screens at relatively low electron energies. Nevertheless, the contribution of the multiple scattering can be effectively subtracted from the signal by e.g. Bayes unfolding. For high energy beams (> 0.5 GeV), the multiple scattering contribution is negligible. The presented diagnostics is easy to be implemented into standard experimental setups without any special requests for alignment procedure. Moreover, it can be especially useful in the optimization phase of the laser plasma accelerator where beam fundamental parameters (energy, energy spread, divergence, pointing) typically fluctuate shot-to-shot.

9515-57, Session PS

Towards the effect of transverse inhomogeneity of electromagnetic pulse on the process of ion acceleration in the RPDA regime

Kirill V Lezhnin, F. F. Kamenets, V. S. Beskin, Moscow Institute of Physics and Technology (Russian Federation); Masaki Kando, Timur Zh. Esirkepov, Sergei V. Bulanov, Japan Atomic Energy Agency (Japan)

Studies of the high energy ion generation in the interaction between an ultra-intense laser pulse and a small overdense targets, are of fundamental importance for various research fields ranging from the developing the ion sources for thermonuclear fusion and medical applications to the investigation of high energy density phenomena in relativistic astrophysics. Depending on the laser and target parameters different regimes of acceleration appear – from acceleration at the target surface called the Target Normal Sheath Acceleration (TNSA) through the Coulomb explosion to radiation pressure dominance acceleration (RPDA) regime. In the present paper, we discuss the RPDA regime under the conditions when a transverse inhomogeneous laser pulse irradiates a MLT(mass limited target) positioned not precisely at the laser pulse axis. This situation naturally occurs due to a finite pointing stability of the laser systems. As a result the transverse component of the radiation pressure leads to the displacement of the irradiated target in the off-axis direction. Apparently, after a finite interval of time the target leaves the laser pulse preventing from the further ion acceleration. On the ground of a theoretical model of relativistic mirror we calculate the acceleration time and hence the achieved ion energy dependence on the laser pulse amplitude and transverse size and on the initial displacement of the target from the laser axis. According to recently published papers, various instabilities of the target plasma appear in the RPDA regime, for instance, the Rayleigh-Taylor-like instability leads to the target modulation forming the low density bubbles and high density clumps resulting in the broadening of the accelerated ion energy spectrum. In order to elucidate the kinetic, nonlinear and instability effects we carry out the PIC simulations of the finite waist laser pulse interaction with the MLT by using the REMP code. When the target is irradiated by the Gaussian laser pulse it is pushed away from the pulse by the ponderomotive pressure of electromagnetic radiation, while in the case of super-Gaussian profile the central part of the target may undergo self-contraction provided its initial of-axis displacement is small enough. The 2D particle in cell simulations affirm the theoretical calculations at large initial coordinate of the target in the vertical direction, ?y0 . If the target is positioned in the vicinity of the axis, the self-modulation of the laser pulse in transverse direction prevents the target from sleapage out off the acceleration phase providing the fast ion collimation. The results obtained can be used for determining the required laser-target alignment parameters and/or diagnostics of the ion acceleration by the laser radiation pressure with mass limited targets, widely used in the experiments.

Conference 9516: Integrated Optics: Physics and Simulations

Monday - Wednesday 13–15 April 2015

Part of Proceedings of SPIE Vol. 9516 Integrated Optics: Physics and Simulations II

9516-1, Session 1

Towards an automated design framework for large-scale photonic integrated circuits *(Invited Paper)*

Sergei Mingaleev, VPI Development Ctr. (Belarus); André Richter, VPIphotonics GmbH (Germany); Eugene Sokolov, VPI Development Ctr. (Belarus); Cristina Arellano, Igor Koltchanov, VPIphotonics GmbH (Germany)

The complexity of modern photonic integrated circuits (PICs) is rapidly approaching the order of 1000 components per chip. Efficient design of large-scale PICs requires the development of a new generation of photonic circuit simulators. Ideally, the design framework for large-scale PICs should resemble the one developed for electronic circuits (ECs). However, there are fundamental differences between PICs and ECs which make this task very challenging. First of all, building blocks (BBs) of ECs are all interconnected by electrical wires, each described by a voltage and current, whereas PICs contain, in addition, optoelectronic and photonic devices with optical ports, coupled to each other by guided modes of channel optical waveguides and described by complex-valued envelope amplitudes. ECs are efficiently described in terms of the modified nodal analysis (MNA) approach. Thus, attempts have been made to apply an extension of this method for modeling PICs as well. However, this appears to be a difficult task, mainly because even a simple linear photonic device must be modeled as a non-linear element in terms of MNA. This makes the method not scalable to large-scale PICs. Consequently, new scalable system-level simulation techniques capable of modeling electronic, optoelectronic, and photonic devices on the same circuit, are argued to be developed.

We present with VPIcomponentMaker Photonic Circuits a simulator trying to address the demand, and outline our recent achievements and encountered challenges. We show that large-scale PICs consisting of only passive BBs can be very efficiently modeled using a frequency-domain scattering matrix (S-matrix) assembly technique. Importantly, we extended this approach to model both, passive photonic and linear electronic circuits. We demonstrate that although the S-matrix approach is numerically less efficient than MNA when applied to purely electronic circuits, it enables modeling of electronic circuits with exactly zero or infinite values of resistance, and thus predicting effects of component failures. Further, it natively supports various forms of controlled sources, transmission lines and S-parameters. Most importantly, it provides a uniform scalable framework for modeling both, electronic and photonic circuits. We also illustrate that modeling large-scale PICs with a mix of passive/linear and active/nonlinear BBs is not feasible by applying simulation approaches operating in frequency- or time-domain only, and present our scalable time-and-frequency-domain modeling (TFDM) approach with its unique simulation capabilities.

Within this work we also highlight that an automated design framework should provide a seamless integration of circuit-level and device-level simulations, and illustrate this approach for the combination of VPIcomponentMaker Photonic Circuits and VPImodeDesigner. Further, we present our approach to supporting low cost access generic-foundry models. It includes specialized libraries of foundry-specific BBs and allows to design and optimize PICs for a chosen foundry, estimate fabrication yields, export mask layouts and check DRC rules (via the link with MaskEngineer from PhoeniX Software), and, finally, fabricate designed PICs at a chosen foundry.

9516-2, Session 1

Passive and electro-optic polymer photonics and InP electronics integration *(Invited Paper)*

Ziyang Zhang, Alejandro Maese Novo, David de Felipe, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany); Vasilis Katopodis, Panos Groumas, National Technical Univ. of Athens (Greece); Agnieszka Konczykowska, III-V Lab. (France) and Thales Research and Technology (France) and CEA-LETI (France); Jean-Yves Dupuy, III-V Lab. (France) and Thales Research and Technology (France) and CEA-LETI (France); Antonio Beretta, Alberto Dede, LINKRA S.r.l. (Italy); Eric R. Miller, Raluca Dinu, Giulio Cangini, GigOptix, Inc. (United States); Antonello Vannucci, LINKRA S.r.l. (Italy); Norbert Keil, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany); Hercules Avramopoulos, Christos Kouloumentas, National Technical Univ. of Athens (Greece)

Hybrid photonic integration allows components to be developed at their best-suited material platforms without sacrificing the overall performance due to yield compromises. In the past few years a polymer-enabled hybrid integration platform has been established, comprising 1) passive polymers for constructing low-loss waveguide networks, manipulating the polarization of light and providing wavelength agility; 2) electro-optic (EO) polymers for building low-complexity and low-cost Mach-Zehnder modulators (MZMs) with extremely high modulation bandwidth; 3) InP components for light sources, detectors and high-speed electronic drivers, DEMUX circuits and etc.; 4) ceramic RF board for electronic signal links and termination within the package. On this platform, fully packaged optoelectronic modules have been successfully demonstrated, including 100 Gb/s, 2?100 Gb/s, and wavelength tunable 100 Gb/s optical transmitters, all adopting simple data format (NRZ OOK) and validated for datacenter optical interconnect applications.

Furthermore, a 4M transmission concept has been recently proposed with unprecedented potential for flexibility and spectral efficiency. On top of the capability to adaptively handle varying data rates (multi-rate), different modulation formats (multi-format) and transmission reaches (multi-reach), such a transmitter features a built-in “redundancy” in the optical circuit design and can aggregate the data capacity into a smaller number of large data flows or distribute it into a larger number of small data flows (multi-flow), depending on the incoming traffic. The EO polyboard, providing 4? MZMs with 65 GHz bandwidth, is sandwiched between two passive polyboards consisting of a multitude of elements that provide wavelength agility, polarization diversity and multi-flow control. In this work, we focus on the development of the passive polyboard including the tunable lasers, thermo-optic switches (TOS), polarization splitters (PS), and polarization rotators (?/2 plate). The optical interface with EO polyboard, electrical interface with ceramic RF board and InP electronic components will also be introduced.

9516-3, Session 1

Rethinking the surface of optical waveguides *(Invited Paper)*

Andrea I. Melloni, Politecnico di Milano (Italy)

The interface between the core and the cladding of optical waveguides exhibits a number of physical phenomena that do not occur in the bulk of the material itself. For this reason, the behavior of nanoscale devices is expected to be conditioned, or even dominated, by the nature of their surface. Roughness-induced losses, backscattering and crosstalk between

adjacent waveguides, together with surface states absorption impact on the optical and electrical properties of the waveguides and must be considered in the design of any integrated optoelectronic device. The detrimental effects and the possibility of their exploitation are carefully reviewed.

9516-4, Session 1

Simulation of self-organized waveguides for self-aligned coupling between micro- and nano-scale devices

Tetsuzo Yoshimura, Tokyo Univ. of Technology (Japan)

Optical interconnects based on high-index-contrast nano-scale waveguides have received major attention. One of the challenges of using these nano-scale waveguides is optical coupling between the nano-scale waveguides used in large-scale integrated circuits and the micro-scale waveguides used in multi-chip modules or printed circuit boards. To date, edge couplings using mode converters and grating couplings combined with tapered waveguides have been developed. The former realizes low-loss in-plane coupling with losses of less than 1 dB. However, the cost of the optical coupling tends to increase because of the process complexity involved and the high chip dicing/alignment accuracy requirements. The second method enables optical coupling cost reduction. However, it is difficult to apply to in-plane coupling structures, and is not suitable for coarse wavelength division multiplexing because of its narrow spectral bandwidth characteristics.

In this work, we propose an optical coupling technique based on the reflective self-organized lightwave network (R-SOLNET), where optical devices with different core sizes are connected. Two optical devices to be connected, such as optical fibers, waveguides, or light modulators, are placed in a photo-induced refractive-index increase (PRI) material such as a photopolymer with a refractive index that increases upon exposure to a write beam or luminescence. The optical device with the narrower core has a luminescent target on the core edge. When a write beam is introduced into the PRI material from the optical device with the wider core, it is absorbed by the luminescent target, and this is followed by emission of luminescence from the target. Then, in the area where the write beam and the luminescence overlap, the refractive index increases more rapidly than it does in the surrounding region. The write beam and the luminescence thus attract each other and finally merge into one through a self-focusing process, resulting in formation of a self-aligned coupling waveguide of R-SOLNET between the differently-core-sized optical devices.

To investigate the applicability of the R-SOLNET to self-aligned optical coupling, the growth of the R-SOLNET between a 3-um-wide waveguide and a 600-nm-wide waveguide, on the core edge of which a luminescent target has been deposited, is simulated by the finite-difference time-domain (FDTD) method. The two waveguides are placed together, with gap sizes ranging from 16 to 64 um, in a PRI material. When a 400 nm wavelength write beam is introduced from the micro-scale waveguide, 470 nm luminescence is generated by the luminescent target. A waveguide is then gradually self-organized between the two waveguides, even when a lateral misalignment of 600 nm exists between them, and provides a self-aligned optical coupling with a coupling loss of 1.5–1.8 dB. This indicates that the self-organized waveguide can be used as an optical solder to connect a micro-scale waveguide to a nano-scale waveguide. The optimum writing time required to attain the minimum coupling loss increases with increasing lateral misalignment. The dependence of the optimum writing time on the misalignment is reduced with increasing gap distance, and the dependence almost vanishes when the gap distance is 64 um, thus enabling unmonitored optical solder formation.

9516-5, Session 2

Nonlinear Optical Signal Processing in High Figure of Merit CMOS Compatible Platforms *(Invited Paper)*

David J. Moss, RMIT Univ. (Australia); Roberto Morandotti, INRS-EMT (Canada)

Nonlinear photonic chips have succeeded in generating and processing signals all-optically with performance far superior to that possible electronically - particularly with respect to speed. Although silicon-on-insulator has been the leading platform for nonlinear optics, its high two-photon absorption at telecommunications wavelengths poses a fundamental limitation. This talk will review some of the recent achievements in novel CMOS-compatible platforms for nonlinear optics, including amorphous silicon, Hydex glass and SiGe, highlighting their potential as well as the challenges to achieving practical solutions for many key applications. These material systems have opened up many new capabilities such as on-chip optical frequency comb generation and ultrafast optical pulse generation and measurement from the near IR to the mid-IR..

9516-6, Session 2

High-speed and low-power silicon-organic hybrid modulators for advanced modulation formats *(Invited Paper)*

Matthias Lauermann, Stefan Wolf, Robert Palmer, Sebastian Köber, Philipp C. Schindler, Karlsruher Institut für Technologie (Germany); Thorsten Wahlbrink, Jens Bolten, Anna Lena Giesecke, AMO GmbH (Germany); Michael Koenigsmann, Matthias Kohler, Dimitri Malsam, Keysight Technologies Deutschland GmbH (Germany); Delwin L. Elder, Larry R. Dalton, Univ. of Washington (United States); Juerg Leuthold, Karlsruher Institut für Technologie (Germany) and Swiss Federal Institute of Technology (Switzerland); Wolfgang Freude, Christian Koos, Karlsruher Institut für Technologie (Germany)

Efficient electro-optic IQ modulators operating at high speed are important elements for terabit/s telecommunication links and optical interconnects. As key requirements, the devices must combine small footprint and high electro-optic bandwidth with low drive voltages and therefore low power consumption. Silicon photonics is a particularly attractive platform for realizing such devices, leveraging mature CMOS processing and enabling high-density integration of photonic devices along with electronic circuitry. Silicon as an optical material, however, falls short of certain properties that are indispensable for high-performance devices. In particular, unstrained bulk silicon does not feature any second-order optical nonlinearity due to crystal symmetry, and current all-silicon photonic modulators have to rely on the plasma dispersion effect, where modulation is achieved by injecting or depleting free carriers in the waveguide region. For this concept, modulation efficiencies of high-speed devices are limited with typical voltage-length products $U_\pi L$ of the order of 10 Vmm, leading to a high energy consumption of the devices of around 1 pJ/bit. Furthermore the amplitude-phase coupling, inherent to the plasma dispersion effect, hampers highest signal quality for higher order advanced modulation formats where precise and independent control of amplitude and phase is necessary.

Silicon-organic hybrid (SOH) integration can overcome these limitations by combining silicon-on-insulator (SOI) slot waveguides with electro-optic cladding materials. This approach leads to remarkably small voltage-length products of down to 0.5 Vmm measured at DC and avoids unwanted amplitude-phase coupling. We demonstrate 16QAM signaling at symbol rates of 28 GBd and 40 GBd leading to line rates (net data rates) of up to 160 Gbit/s (133 Gbit/s) for a single polarization. This is the highest value achieved by a silicon-based modulator up to now. Limiting the symbol rate to 28 GBd enables low drive voltages of only 0.6 Vpp and record-low energy consumptions of only 19 fJ/bit. This is the lowest energy consumption that has so far been reported for a 16QAM modulator at 28 GBd.

9516-7, Session 2

A numerical investigation of silicon-based optical sampling

Mahmoud Jazayerifar, Daniel Bross, Technische Univ. Berlin (Germany); Kambiz Jamshidi, Technische Univ. Dresden (Germany)

Since the jitter of optical oscillators are much less than their electronic counterparts, optical sampling has inherent advantages in this regard which can be used for high resolution, high bandwidth sampling of both electrical and optical signals. Optical parametric process can be used for optical sampling as it was already shown with highly nonlinear fibers (HNLF) [1] and silicon waveguides [2, 3]. However, the previous works on silicon waveguides were mostly focused on the characterization, and to the best of our knowledge, the optimum waveguide design for this purpose has not yet been comprehensively studied which is the main focus of our investigation in this paper. In order to do so, we first develop a numerical model for the nonlinear propagation in silicon waveguides. It should be mentioned that unlike in HNLFs, the efficiency of the nonlinear Kerr effect in silicon is limited by the effects such as two photon absorption (TPA) and free carrier absorption (FCA) which are also included in our model. Using the model as well as using a mode solver software namely FIMMWAVE, we discuss the optimum waveguide structures leading to the maximum conversion efficiency (output idler/input signal) and on-off extinction ratio. We identify two different cases namely high repetition rate sampling and low repetition rate sampling and discuss how the optimum waveguide differs in these two cases. We will show that up to 10 dB of conversion efficiency is achievable in the low repetition case with 30 dBm of peak pump power.

References

[1] S. Radic, et. al., “Parametric signal processing,” IEEE Journal of Selected Topics in Quantum Electronics, vol. 18, no. 2, pp. 670-679, 2012.

[2] L. K. Oxelowe, et. al., “Silicon Photonics for Signal Processing of Tbit/s serial data signals,” IEEE Journal of Selected Topics in Quantum Electronics, vol 18, no. 2, pp. 996-1005, 2012.

[3] H. Ji, et al., “Optical waveform sampling and error-free demultiplexing of 1.28 Tb/s serial data in a nanoengineered silicon waveguide,” Journal of Lightwave Technology, vol. 29, no. 4, pp. 426-431, 2011.

9516-8, Session 3

Silicon nanophotonic integrated devices enabling multiplexed on-chip optical interconnects *(Invited Paper)*

Daoxin Dai, Jian Wang, Sitao Chen, Zhejiang Univ. (China)

Advanced multiplexing technologies are needed to realize ultrahigh capacity for optical interconnects. Wavelength-division-multiplexing (WDM) technology has been developed very successfully not only in long-haul optical communication networks but also in the optical interconnects for data communication. Recently the mode-division-multiplexing technology is becoming very attractive to improve the link capacity for a single wavelength carrier. It is also possible to have a multi-dimensional hybrid multiplexing technology which combining different multiplexing technologies together. It is well known that multiplexers are the key devices for realizing these multiplexing technologies. This paper gives a review for the recent progresses of our on-chip (de)multiplexers based on silicon-on-insulator (SOI) nanowires. First, we present the ultrasmall wavelength-division-multiplexers, including SOI-nanowire arrayed-waveguide grating (AWG) (de)multiplexers with novel layout designs, as well as flat-top microring optical filters. Second, the results for the multi-channel mode (de)multiplexers based on asymmetric directional couplers are presented. Finally the hybrid multiplexers enabling more than two (de)multiplexing technologies simultaneously are presented, including the 8-channel hybrid (de)multiplexer with four modes and double polarizations, and the 64-channel hybrid (de)multiplexer with four modes and 16 wavelengths.

9516-9, Session 3

Optimized, constant-loss taper for mode conversion *(Invited Paper)*

Alexandre Horth, McGill Univ. (Canada); Raman Kashyap, Ecole Polytechnique de Montréal (Canada); Nathaniel Quitoriano, McGill Univ. (Canada)

Silicon photonics (SP) enable high optical mode confinement through the large index of refraction contrast between silicon and silicon dioxide (nSi~3.5/nSiO2~1.5) as well as excellent transmission properties at telecom wavelengths. This tight optical confinement allows SP waveguides to minimize both the amount of cross talk between densely packed waveguides and radiation losses at small bend radii; both of which are required for optical interconnect applications. However, the mode area of SP waveguides is orders or magnitude smaller than that of a typical single-mode fiber optic which makes efficient mode coupling difficult between these two waveguides. One method used for accomplishing mode conversion consists in defining inverse tapers on the SP chip. Proposed in this paper is a novel taper geometry, the constant-loss taper (CLT). This geometry is derived iteratively with 1D slabs of silicon embedded in silicon dioxide using coupled-mode theory (CMT). The efficiency of the CLT is compared to both linear and parabolic tapers using CMT and via 2D finite-difference time-domain simulations. It is shown that over a short 4.45 mm taper the CLT’s mode conversion efficiency is ~ 90%, 10% more efficient than a parabolic taper. Using basic arguments from variational theory, the CLT is also shown to be ideal, within the formalism developed, any deviation from its shape results in increased losses.

9516-10, Session 3

Expanding sampling in a SWIFTS-Lippmann spectrometer using an electro-optic Mach-Zehnder modulator

Fabrice Thomas, RESOLUTION Spectra Systems (France) and Institut de Planetologie et d’Astrophysique de Grenoble (France); Mikhaël de Mengin Poirier, Samuel Heidmann, Institut de Planétologie et d’Astrophysique de Grenoble (France); Alain Morand, Pierre Benech, IMEP-LAHC (France); Christophe Bonneville, Thierry Gonthiez, RESOLUTION Spectra Systems (France); Etienne P. Le Coarer, Guillermo Martin, Institut de Planétologie et d’Astrophysique de Grenoble (France)

High resolution spectrometers are nowadays achievable in compact devices using integrated optics. The SWIFTS technology has in particular proved its efficiency for the high-rate high-resolution analysis of laser sources, without any moving parts.

The key point of the SWIFTS technology is the sampling of a standing wave - created in an optical waveguide ended by a mirror (Lippmann configuration) - using diffusing nanodots distributed along the waveguide’s surface. The discrete and regular measurement of the wave’s amplitude by these sampling centers allows obtaining the source spectrum, thanks to an adapted Fourier-like transform. But, since each nanodot must be coupled with one pixel of a linear detector array, the size of the current sensors (typically 20 µm) is a limit for a complete sampling of the wave, according to the Nyquist-Shannon criteria (typically (?/2n)/2 = 150 nm for ? = 1 µm and n = 1.5).

In this work, we propose an alternative to this sub-sampling using the electro-optical properties of Lithium Niobate technology, in a typical Mach-Zehnder intensity modulator configuration, with an initial imbalance between the arms, coupled to a linear SWIFTS-Lippmann spectrometer. This first combination of an active integrated optical device and an integrated high-resolution high-speed SWIFTS spectrometer allows considering the spectral reconstruction of broadband and complex sources.

An unbalanced Mach-Zehnder interferometer is placed between the SWIFTS-Lippmann spectrometer and the light source to be analyzed. This

generates two wave packets : the classical "static" Lippmann wide band fringes, stuck to the waveguide/mirror interface ; and the "dynamic" wide band fringes, at a distance of the mirror according to the initial imbalance of the modulator, which can be moved along the sampling centers under application of a modulation voltage on its arms (changing the optical path difference between the two beams).

With quite reasonable control voltages (<100V), we can move the "dynamic" wave packet under the nanodots to compensate the sub-sampling related to their spacing (typically 50 µm optical delay, to be consistent with the standard detectors arrays). Thus the interferogram can be rebuilt with a good sampling in a very short time, thanks to the electro-optical performances of Lithium Niobate technology (standard modulators up to several GHz).

We will present the measurements of broadband sources' interferograms sampled by this setup, and the spectral reconstructions for SLED sources at 850 nm and 1050 nm, white sources and complex sources such as Bragg gratings in the visible and near infrared domain.

This work opens the way to electro-optic devices where external optical path delay scan could be replaced by internal phase-modulation using electro-optic effect.

REFERENCES

[1] E. Le Coarer, S. Blaize, P. Benech, I. Stefanon, A. Morand, G. Lerondel, G. Leblond, P. Kern, J.-M. Fedeli and P. Royer "Wavelength-scale stationary-wave integrated Fourier-transform spectrometry", Nature Photonics, 1 (8), pp.473-478, 2007.

[2] T. Katchalski, G. Levy-Yurista, A.A Friesem, G. Martin, R. Hierle and J. Zyss (2005) "Light modulation with electro-optic polymer-based resonant grating waveguide structures", Opt. Express, 13 (12), 4645-4650.

[3] «Concept of a miniature optical spectrometer using integrated optical and micro-optical components » I. Avrutsky, K. Chaganti, I. Salakhutdinov and G. Auner. Applied Optics 45 (30), pp. 7811-7817, 2006.

[4] "A simple miniature optical spectrometer with a planar waveguide grating coupler in combination with a plano-convex lens". K. Chaganti, I. Salakhutdinov, I Avrutsky and G. W. Auner.Optics Express, 14 (9), pp. 4064-4072, 2006.

9516-11, Session 3

High-resolution TE&TM near-infrared compact spectrometer based on waveguide grating structures

Guillermo Martin, Institut de Planétologie et d'Astrophysique de Grenoble (France); Fabrice Thomas, Samuel Heidmann, Institut de Planetologie et d'Astrophysique de Grenoble (France); Mikhaël de Mengin Poirier, Institut de Planétologie et d'Astrophysique de Grenoble (France); Nadège Courjal, Gwenn Ulliac, FEMTO-ST (France); Alain Morand, Pierre Benech, IMEP-LAHC (France); Pierre Kern, Etienne P. Le Coarer, Institut de Planétologie et d'Astrophysique de Grenoble (France)

Integrated optics spectrometers can be essentially classified into two main families: based on Fourier transform [1] or dispersed modes [3,4]. In the first case, an interferogram generated inside an optical waveguide is sampled using nanodetectors, these scatter light into the detector that is in contact with the waveguide. A dedicated FFT processing is needed in order to recover the spectrum with high resolution but limited spectral range [1]. Another way is to extract the optical signal confined in a waveguide using a surface grating [2] and directly obtain the spectrum by means of a relay optics that generates the spectrum on the Fourier plane of the lens [3,4], where the detector is placed.

Following this second approach, we present a high-resolution compact dispersive spectrometer (??=1.5nm at ?=1050nm) based on guided optics technology. The propagating signal is dispersed out of a waveguide thanks to a surface grating that lays along it. A simple relay optics images the generated spectrum on the focal plane array, with limited optical aberrations. This simple optical setup does not need any moving part, leading to a robust instrument easy to align.

Focused Ion Beam technique is used to etch the nano-grooves that act as individual scattering centers and constitute the surface grating along the waveguide. The waveguide is realized using X-cut, Y-propagating Lithium Niobate substrate, where the effective index for TE and TM guided modes is different. This results in a strong angular separation of TE and TM diffracted modes. Using a single cylindrical lens to collect the wide-angle spread flux, we are able to easily measure both polarizations separately in the focal plane array.

The realized grating has 100 grooves with a period of 10um. The measurement of the resolution of the setup was performed using a tunable source, between 1030-1077nm, by 1nm steps. The results are presented in the figure below. Our experimental setup presents a spectral resolution Rexp=lambda/?lambda=1050/1.5=700 for a diffracting structure 1mm long, using a f=150mm lens. Discussion on the parameters that can be tuned to increase resolution, and their impact in compacity of the spectrometer, will also be presented.

9516-12, Session 3

Photovoltaic maximum power point search method using a light sensor

Mariusz Ostrowski, Wroclaw Univ. of Technology (Poland)

Photovoltaic solutions are gaining engineers attention due to the growing demand for renewable energy. Nevertheless, the main disadvantage of PV panels is their low efficiency and non-linear current-voltage characteristic. Both of the above depend on the insolation and the temperature. That is why, it is necessary to use the maximum power point search systems. Commonly used solutions vary not only in complexity and accuracy but also in the speed of searching the maximum power point. Usually, the measurement of current and voltage is used to determine the maximum power point. The most common in literature are the perturb and observe and incremental conductance methods. The disadvantage of these solutions is the need to search across the whole current-voltage curve, which results in a significant power loss. In order to prevent it, the techniques mentioned above are combined with other methods, for instance the open circuit voltage or the short circuit current. This procedure determines the starting point of one of the above methods and results in shortening the search time. However, these methods require disconnecting the photovoltaic panel from the load. Modern solutions use the temperature measurement to determine the open circuit voltage. The voltage in the maximum power point depends mainly on the temperature of the photovoltaic panel, and the current depends mainly on the lighting conditions. The proposed method uses the measurement of illuminance and calculates the current at the maximum power point, which is used as a reference signal in power conversion system. Due to the non-linearity of the light sensor and of the photovoltaic panel, the relation between them cannot be determined directly. Therefore, the proposed method is divided into two sub-programs. The first one uses the correlation curve between the light sensor and the current at the maximum power point to determine the starting point of perturb and observe search algorithm. When the first sub-program reaches the maximum power then the second one calculates the difference between the starting point and the actual point of maximum power, the error values. Afterwards, on its basis, it modifies the value of the correlation curve coefficients.

The conducted simulations present high effectiveness of the proposed method. As comparing to a similar method that uses the temperature measurement, the search time decreased by 15% and the accuracy of tracking remained unchanged. When the method starts its speed is no less than the perturb and observe method speed. The speed increases as getting next errors values and calculating new values of correlation functions. During the simulation, the error of maximum power point tracking did not exceed 1% whereas in the method using the temperature measurement the error was 6%.

The procedure of using the light sensor in the maximum power point search algorithm greatly increases the capability of tracking. The conducted simulations prove not only the correctness of proposed method but also its high efficiency. By using the adaptive modification algorithm of correlation coefficients, the proposed method does not depend on the used photovoltaic panel or light sensor.

9516-13, Session 4

High-speed and compact photonic crystal modulators *(Invited Paper)*

Toshihiko Baba, Yosuke Terada, Yokohama National Univ. (Japan)

Mach-Zehnder optical modulators based on carrier plasma dispersion are the key devices in Si photonics transmitters. For the applications of optical interconnects, wide working spectrum and temperature tolerance are the important advantages of Mach-Zehnder modulators, while their large size is a drawback. This constrain is solved by wideband and low-dispersion slow light in photonic crystal waveguides. Silica-cladded photonic crystal waveguides produces approximately constant group index of 20 - 25 in the wavelength bandwidth of 10 - 15 nm at telecom wavelengths when well-designed lattice shifts are introduced. This index is 5 - 6 times larger than that of rib waveguides, which are usually employed in Si conventional modulators. We can expect a comparably large enhancement in modulation efficiency if the slow light mode spatially overlaps with the carrier plasma dispersion area at the p-n junction embedded in the waveguide similarly to that in rib waveguides. When we use a straight p-n junction, the overlap is degraded to half due to the larger penetration of the slow light mode into the photonic crystal cladding. When we use an interleaved p-n junction, this degradation is recovered and almost the same overlap is achieved. The 5 - 6 times larger modulation efficiency allows sufficient performance with a phase shifter length of 200 microns. The modulator including Si photonic crystal slabs, which consist of 200 nm diameter holes, can be fabricated by standard CMOS-compatible process. The on-chip insertion loss is typically 5 dB. The clear open eye is observed at 25 Gbps with a push-pull drive voltage of 1.75 V, an extinction ratio of 3 dB, and a modulation loss of less than 1 dB. The QPSK modulation is also obtained with a phase shifter length of 250 micron; clear constellation pattern is observed at 10 Gbaud for a drive voltage of less than 5 V with an error vector magnitude of less than 20%.

9516-14, Session 4

All optical memories on a photonic crystal chip *(Invited Paper)*

Masaya Notomi, NTT Basic Research Labs. (Japan)

No Abstract Available

9516-15, Session 4

Controlling silicon photonic devices all optically based on photothermal effects in plasmonics *(Invited Paper)*

Min Qiu, Xi Chen, KTH Royal Institute of Technology (Sweden); Yuechun Shi, KTH Royal Institute of Technology (Denmark); Fei Lou, Yiting Chen, Lech Wosinski, Min Yan, KTH Royal Institute of Technology (Sweden)

Silicon (Si) photonics is the rising technology in integrated photonic circuits, for realizing high speed data interconnect with minimized size and low power consumption. Using the thermo-optical (TO) effects to switch silicon photonic devices is widely chosen as an efficient method for on-chip control of optical signals. Recently, we show that efficient narrow-band light absorption by metal-insulator-metal (MIM) structure can lead to high-speed light-to-heat conversion at a micro- or even nano-scale. Such a MIM structure can serve as a heater for achieving all-optical light control based on the TO effect. More importantly, the MIM absorber design introduces less thermal capacity to the device, compared to conventional electrically driven TO devices. In this talk, we review our recent experimental works on all-optical switching based on a silicon micro-disk and a silicon ring resonator integrated with MIM light absorbers. Direct integration of the absorber facilitates efficient heat conduction from light-induced heat source towards the devices, leading to a high-speed TO switching of the micro-disk resonance.
The photothermally tunable silicon photonic devices may provide new perspectives for all-optical routing and switching in integrated Si photonic circuits.

9516-16, Session 4

Plasmonic nanoantenna switches *(Invited Paper)*

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

No Abstract Available

9516-17, Session 5

High-efficiency fully etched fiber-chip grating couplers with subwavelength structures for datacom and telecom applications

Daniel Benedikovic, Univ. of Zilina (Slovakia); Pavel Cheben, Jens H. Schmid, Dan-Xia Xu, Jean Lapointe, Siegfried Janz, National Research Council Canada (Canada); Robert Halir, Alejandro Ortega-Moñux, Univ. de Málaga (Spain); Milan Dado, Univ. of Zilina (Slovakia)

Surface grating couplers are key components to couple light between planar waveguide circuits implemented in silicon-on-insulator (SOI) platform and single-mode optical fibers. Here, we demonstrate using simulations and experiments that a high coupling efficiency can be achieved for an arbitrary buried oxide thickness by judicious adjustment of the grating radiation angle. The coupler strength is engineered by subwavelength structures, which have pitch and feature sizes smaller than the wavelength of light propagating through it, thereby frustrating diffraction effects and behaving as a homogeneous media with an adjustable equivalent refractive index. This makes it possible to apodize the grating coupler, with a preferred single etch fabrication process. The coupling efficiency of the grating coupler is optimized for operating with the transverse electric (TE) polarization state at the wavelengths near 1.3 ?m and 1.55 ?m, which are wavelength bands particularly attractive for datacom and telecom interconnects applications. The design and analysis of surface grating couplers is carried out using two-dimensional (2-D) Fourier-eigenmode expansion method (F-EEM) and finite difference time domain (FDTD) method. The simulations shows a peak fiber-chip coupling efficiency of -1.61 dB and -1.97 dB at datacom and telecom wavelengths, respectively, with a minimum feature size of 100 nm, compatible with 193 nm deep-ultraviolet (DUV) lithography. The measurements of our fabricated continuously apodized grating coupler demonstrate fiber-chip coupling efficiency of -2.16 dB at a wavelength near 1.55 ?m with a 3 dB bandwidth of 64 nm. These results open promising prospects for low-cost and high volume fabrication of surface grating couplers in SOI using 193 nm DUV lithography, which is now in several silicon photonics foundries. It is also predicted that a coupling efficiency as high as -0.42 dB can be achieved for the coupler structure with a bottom dielectric mirror.

9516-18, Session 5

High efficiency blazed fiber-chip grating coupler based on interleaved trenches

Carlos A Alonso Ramos, Univ. de Málaga (Spain) and Univ. Paris-Sud 11 (France); Daniel Benedikovic, Univ. of Zilina (Slovakia); Pavel Cheben, Shurui Wang, National Research Council Canada (Canada); Robert Halir, Univ. de Málaga (Spain); Jean-Marc Fédéli, CEA-LETI (France); Alejandro Ortega-Moñux, Univ. de Málaga (Spain); Jens H. Schmid, Dan-Xia Xu, National Research Council

Canada (Canada); Milan Dado, Univ. of Zilina (Slovakia); Iñigo Molina-Fernández, Univ. de Málaga (Spain)

The silicon-on-insulator platform allows a large photonic integration density with substantially increased number of functionalities per chip and high-performance devices that can be fabricated at mass scale. The ability to test devices at a wafer level is an important prerequisite for a cost-effective implementation in a mass production platform. Surface grating couplers allow the wafer-scale testing, obviating the need of dicing and facet preparation prior to device testing. However, efficiency of grating couplers is limited by several factors, including power leakage to the substrate, back reflections, and mismatch between the radiated near field and the optical fiber mode.

Here we propose a fiber-chip surface grating coupler that interleaves standard full and shallow trenches to maximize directionality in the upward direction. The coupler operation principle exploits the blazing effect to control the interference condition between the deep and shallow trenches. This results in constructive interference in the superstrate (air) and destructive interference in the substrate (silicon), therefore maximizing grating directionality. We set the silicon thickness to 220 nm and the etch depths to 220 nm (full) and 70 nm (shallow), as typically used in silicon photonic foundries. The blazing effect is controlled by the separation (and the resulting optical path difference) between the two sets of trenches. By adjusting this separation, a grating directionality exceeding 95% can be achieved independently of the bottom oxide (BOX) thickness. We also show that the blazing effect is remarkably robust to typical fabrication tolerances. Line width variations of ±30 nm and misalignment between the deep and shallow trenches of ±40 nm still yield a directionality exceeding 90%.

Blazed grating couplers have been fabricated by LETI using 193 nm DUV lithography, on a 220 nm thick silicon layer, with a 3 ?m bottom oxide with interleaved standard full (220 nm) and shallow (70 nm) etch trenches. We experimentally demonstrate a coupling efficiency of -2.2 dB. Different coupler realizations (with different exposition dose or with intentionally introduced misalignment between the deep and shallow etch trenches) results in a coupling penalty of less than 0.5 dB, confirming device robustness. However, back-reflections are found to be ~15% in this first set of fabricated devices. To reduce grating reflectivity, we propose to implement an index-matching transverse sub-wavelength structure in the first two grating periods. This helps minimize back-reflections and further improves coupling efficiency, with calculated back-reflections of less than 2% and an excellent efficiency of -1.05 dB. The minimum feature size is 100 nm, i.e. compatible with deep-UV lithography.

In conclusion, we have reported a surface grating coupler in an SOI wafer with 220 nm thick silicon layer that interleaves standard full (220 nm) and shallow (70 nm) etch trenches to achieve a grating directionality exceeding 95%. The coupler exploits the blazing effect and obviates the need for overlays, bottom reflectors, or custom etch depths. An important advantage of our coupler is that its high directionality is almost independent of the BOX thickness. We have experimentally demonstrated blazed grating couplers with -2.2 dB efficiency and robust to line width variations and misalignment errors.

9516-19, Session 5

Highly efficient fiber-chip edge coupler with large mode size for silicon photonic wire waveguides

Martin Papes, VŠB-Technical Univ. of Ostrava (Czech Republic); Pavel Cheben, National Research Council Canada (Canada); Winnie N. Ye, Carleton Univ. (Canada); Jens H. Schmid, Dan-Xia Xu, Siegfried Janz, National Research Council Canada (Canada); Daniel Benedikovic, Univ. of Zilina (Slovakia); Carlos A. Ramos, Robert Halir, Alejandro Ortega-Moñux, Univ. de Málaga (Spain); André Delâge, National Research Council Canada (Canada); Vladimír Va?inek, VŠB-Technical Univ. of Ostrava (Czech Republic)

Fibre-chip edge couplers are extensively used in integrated optics as one of the key structures for coupling of light between planar waveguide circuits and optical fibers. In this work, fiber-chip couplers with high coupling efficiency and large mode size are presented for coupling to submicron silicon photonic wire waveguides. The main goal is to substantially increase the mode size for direct coupling to optical fibres with large mode sizes and circumvent the need for lensed fibres. We demonstrate by simulations a 95% mode overlap between silicon wire waveguides in a 220 nm silicon-on-insulator (SOI) platform and a high numerical aperture single mode optical fiber with 6 μm mode field diameter. We also demonstrate 89% mode overlap between a silicon wire and standard SMF-28 fiber (10.4 μm mode field diameter). An important advantage of the proposed concept is that both high coupling efficiency and large mode size can be achieved at the same time without the need to increase bottom oxide thickness, which in our design is limited to 3 micrometers. This remarkable performance is achieved by implementing in SiO2 upper cladding two thin high-index Si3N4 layers. The silicon nitride layers effectively increase the effective refractive index of the upper SiO2 cladding layer near the facet and are gradually tapered out along the coupler to provide mode transformation and coupling to silicon wire waveguide. The optical property of Si3N4 layers is controlled by subwavelength refractive index engineering. Simultaneously, the Si-wire waveguide is inversely tapered along the coupler. The mode coupling at the chip facet is studied using vectorial 2D mode solver (FIMMWAVE) and the mode transformation along the coupler is studied by 3D Finite Difference Time Domain (FDTD) simulations. The couplers are optimized for operating with transverse electric (TE) polarization and the operational wavelength is centered at 1.55 μm.

9516-20, Session 5

A subwavelength structured multimode interference coupler for the 3-4 micrometers mid-infrared band

Alejandro Sánchez-Postigo, Juan Gonzalo Wangüemert-Pérez, Robert Halir, Alejandro Ortega-Moñux, Carlos A. Alonso Ramos, Íñigo Molina-Fernández, Univ. de Málaga (Spain); Jordi Soler Penadés, Univ. of Southampton (United Kingdom); Milos Nedeljkovic, Optoelectronics Research Ctr. (United Kingdom); Goran Z. Mashanovich, Univ. of Southampton (United Kingdom); Pavel Cheben, National Research Council Canada (Canada)

The mid-infrared is attracting increasing attention since many molecules, including potentially hazardous gases such as methane and carbon dioxide, exhibit very specific absorption spectra in this wavelength region. Integrated optical devices are envisioned to enable compact and low-cost measurement solutions for such molecules. Silicon and germanium are particularly well suited for integrated mid-infrared photonics as they are transparent in a wide wavelength range and can benefit from the fabrication technology developed for near-infrared applications [1]. In fact, a variety of silicon devices have recently been demonstrated in the mid-infrared, including fiber-to-chip grating couplers, ring-resonators and simple multimode interference couplers (MMIs) [2,3]. MMIs can provide different functionalities ranging from simple power 1x2 splitters to 2x4 hybrids for coherent detection. In any of these configurations a broad bandwidth is key if flexible operation is to be achieved, e.g. to detect different gases. However, the MMIs proposed so far are based on classical design approaches and as such their bandwidth is limited. Here we present a proof-of-concept design of a sub-wavelength patterned MMI that has a virtually flat wavelength response in the complete 3μm – 4μm band, providing a more than fourfold bandwidth enhancement over classical designs.

Our design is based on a conventional silicon-on-insulator stack, since the excess losses of the silicon guided mode due to the silicon-dioxide BOX are rather small (below 1.1 dB/cm) in the considered wavelength range. A 500nm thick Si layer with a single, full etch is used. The cladding material is air. MMIs operate by launching light into a wide, multi-mode waveguide, where several higher order modes are excited and interfere as they propagate, forming images of the input field at specific distances. These imaging distances are controlled by the beat-length (L_ϖ) of the two lowest order modes. A reference design of a classical 2x2 MMI with a 6.8μm wide multimode region results in a beat length that varies between 55μm and 40μm in the 3μm – 4μm wavelength range. Since the physical device length is fixed this results of a detuning of the MMI with wavelength, limiting its bandwidth [4]. Our approach consists in segmenting the multimode region at a sub-wavelength pitch, thereby engineering its refractive index and dispersion [5]. Specifically, using a segmented multimode region with at 50% duty-cycle and a pitch of ~475nm we achieve a virtually constant beat length of L_ϖ ~ 13μm in the complete 3μm – 4μm wavelength range. The sub-wavelength MMI thus not only exhibits an improved performance, but is also about three times shorter than the conventional device.

[1] R. Soref, "Mid-infrared photonics in silicon and germanium", Nature Photonics, 4, 495-497, 2010

[2] G. Mashanovich et al., "Low loss silicon waveguides for the mid-infrared," Optics Express 19, 7112-7119, 2011

[3] G. Roelkens et al., "Silicon-based heterogeneous photonic integrated circuits for the mid-infrared," Optics Express 3, 1523-1536, 2013

[4] A. Maese-Novo et al., "Wavelength-Independent Multimode Interference Coupler" Optics Express, 21, 7033-7040, 2013

[5] R. Halir et al., "Waveguide sub-wavelength structures: a review of principles and applications," Laser and Photonics Reviews, 2014

9516-21, Session 5

Simulations of quasiperiodic subwavelength grating structures for filtering and other applications

Pavel Kwiecien, Czech Technical Univ. in Prague (Czech Republic); Junjia Wang, McGill Univ. (Canada); Ivan Richter, Czech Technical Univ. in Prague (Czech Republic); Jirí Ctyroky, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Ivan Glesk, Univ. of Strathclyde (United Kingdom); Lawrence R. Chen, McGill Univ. (Canada)

Recently, as a flexible and perspective alternative to standard silicon-on-insulator (SOI) nanophotonic platform, subwavelength grating structured (SWG) waveguides and more advanced nanophotonic structures based on this novel concept have attracted increasing attention within the community. Such structures rely on Bloch wave propagating concept, in contrast to standard index guiding mechanism. In this way, they can indeed provide a promising alternative to standard nanophotonic platform, due to a variety of signal processing functions provided with tunability of SWG structure parameters. This additional variability in the (effective) refractive index functionalities, applied in designs of novel integrated-optical nanophotonic components and devices, provides welcomed flexibility of present and potential for new concepts and components, without significantly increasing fabrication complexity. A SWG structure is based on a (quasi)-periodic arrangement between two different materials, i.e. rectangular blocks of silicon of different dimensions embedded into a lower-index superstrate, with a period much smaller than the wavelength of the light. Clearly, by changing the filling factor, i.e., the duty-cycle of the SWG structure, its effective refractive index can be varied essentially between that of the superstrate and that of substrate (silicon). Applying this idea, several types of SWG based structures and devices have been proposed in last couple of years, such as straight guides, crossings, mode transformers and convertors, polarization converters, ring resonators, MMI couplers, and specially designed tapered couplers for efficient light in/out coupling into SWG structures. However, it was not until recently when several of us have realized and theoretically demonstrated, with the help of properly tuned quasiperiodic modulation in grating structuring, that the SWG concept can also be used for designing SWG filtering devices such as Bragg optical filters.

This contribution is thus devoted to a detailed numerical analysis of various novel designs of nanophotonic structures based on SWG with additional quasiperiodic modulation. For the numerical analysis, we effectively used and combined two approaches, either 3D Fourier modal methods, based on our two recently developed in-house and independent algorithms, aperiodic rigorous coupled wave analysis (aRCWA) and bidirectional expansion and propagation method based on Fourier series (BEX) with the Lumerical's 2.5D FDTD commercially available propagation method. This comparison have not only enabled to ensure the reliability of the results, but also determined the advantages as well as limitations of the individual approaches. Based on that, we propose, simulate, and possibly optimize, the behavior of several filters and other structures based on SWG and quasiperiodicity modulation concept, with the discussion of their potential applicability.

9516-22, Session 6

Circuit modeling based optimization of high speed carrier depletion silicon modulators

Seyedreza Hosseini, Kambiz Jamshidi, Technische Univ. Dresden (Germany)

Various high bandwidth optical modulators have been proposed to address the demand for ever-increasing bandwidth hungry electro optic convertors for short range optical interconnects [1]. Precise modeling of these modulators are important to design effective devices for various applications. Circuit modelling is an analytical approach, which is based on physical modeling of optical modulators that helps us to get a better understanding of its performance. Finding model parameters from physics of the problem, helps us to seek a solution which is closer to reality and the predictions from this model are also more reliable. Intrinsic (carrier depletion area) and extrinsic (the electrical pads and pre-metal dielectric layers) parameters limit the speed of an optical modulator [2].

In this paper, we study a circuit model, which its elements have been extracted based on the cross section of carrier depletion optical modulators in BiCMOS compatible silicon on insulator (SOI) platform. Circuit model elements, i.e. capacitors and resistors are calculated [3]. Fringing capacitances of pn junction based on conformal mapping theory in electrostatics applications are also included in our modeling [4]. Return loss is usually used as an output data of circuit model [5] but in this paper, the return loss and frequency response of modulator are calculated. Through this model, the effects of doping level, modulator length and bias voltage on device bandwidth and modulation efficiency are investigated. Based on that, several optimizations on the speed of modulators (with and without drivers) are carried on to find the best performance of these modulators with different limitations. Tradeoff limits of optical modulators parameters are discussed and possible solutions to enhance the performance limits are presented and an analytical relation is also calculated for 3dB bandwidth using presented circuit model.

References

[1] Ansheng Liu, Ling Liao, Doron Rubin, Juthika Basak, Yoe Chetrit, Hat Nguyen, Rami Cohen, Nahum Izhaky and Mario Paniccia, "Recent development in a high-speed silicon optical modulator based on reverse-biased pn diode in a silicon waveguide" Semicond. Sci. Technol. (2008)

[2] Frédérique Deshours, Catherine Algani, Fabrice Blache, Georges Alquié, Christophe Kazmierski, and Christophe Jany, "New Nonlinear Electrical Modeling of High-Speed Electroabsorption Modulators for 40 Gb/s Optical Networks", Journal of lightwave technology, (2011)

[3] Hui Yu and Wim Bogaerts "An Equivalent Circuit Model of the Traveling Wave Electrode for Carrier Depletion-Based Silicon Optical Modulators" Journal of lightwave technology, (2012)

[4] Hasitha Jayatilleka, Wesley D. Sacher, and Joyce K. S. Poon, "Analytical Model and Fringing-Field Parasitics of Carrier-Depletion Silicon-on-Insulator Optical Modulation Diodes" IEEE photonic journal, (2013)

[5] Hui Yu, Marianna Pantouvaki, Joris Van Campenhout, Dietmar Korn, Katarzyna Komorowska, Pieter Dumon, Yanlu Li, Peter Verheyen, Philippe Absil, Luca Alloatti, David Hillerkuss, Juerg Leuthold, Roel Baets, and Wim Bogaerts, "Performance tradeoff between lateral and interdigitated doping patterns for high speed carrier-depletion based silicon modulators" Opt Exp, (2012).

9516-23, Session 6

Modeling of anisotropic grating structures with active dipole layers

Kamil Postava, VŠB-Technical Univ. of Ostrava (Czech Republic); Tibor Fordos, Ecole Polytechnique (France) and Univ. Paris-Sud 11 (France) and VŠB-Technical Univ. of Ostrava (Czech Republic); Henri Jaffres, Unité Mixte de Physique CNRS/Thales (France) and Univ. Paris-Sud 11 (France); Lukas Halagacka, VŠB-Technical Univ. of Ostrava (Czech Republic); Henri-Jean Drouhin, Ecole Polytechnique (France); Jaromir Pistora, VŠB-Technical Univ. of Ostrava (Czech Republic)

In our previous paper [1] we have proposed a new approach for modeling of polarized light emission from anisotropic multilayers with active dipole layers. The method is suitable to model spin-polarized light emitting diodes (spin-LED) and spin-lasers. This paper deals with generalization of the approach to scattering matrix (S-matrix) formalism and to laterally periodic structures in the frame of rigorous coupled wave algorithm (RCWA). We use expansion of the permittivity tensor in a grating layer into Fourier series and the periodic electromagnetic field in the structure is expressed using a matrix method including appropriate boundary conditions. The new approach based on S-matrix formalism is also suitable for modeling of emission from MQW laser structures with multiple source layers.

[1] T. Fördös, K. Postava, H. Jaffrès, and J. Pi?tora, Matrix approach for modeling of emission from multilayer spin-polarized light-emitting diodes and lasers, J. Opt. 16 (2014) 065008.

9516-24, Session 6

Nonlinear aperiodic rigorous coupled wave analysis: algorithm and applications

Pavel Kwiecien, Ivan Richter, Czech Technical Univ. in Prague (Czech Republic); Jirí Petrácek, Brno Univ. of Technology (Czech Republic)

Based on our previous extended experience with linear Fourier modal methods, applied to various nanophotonic computational tasks (ranging from subwavelength grating waveguide based devices, nanoplasmonic based devices, magnetophotonic nonreciprocal waveguides, to nanostructures with surface plasmon resonance response), we present here a novel implementation of the aperiodic Rigorous Coupled Wave Analysis (aRCWA) method extended for modeling Kerr-nonlinear photonic structures, labeled as NL-aRCWA. The implementation of the Kerr-nonlinear medium is done through the iteration process. Firstly, the Kerr medium structure is divided into a finite rectangular grid, then electric field intensity is calculated in each grid cell and subsequently, the refractive index of each cell is modified according to Kerr nonlinearity. The iteration process runs until a corresponding change of refractive index is smaller than given small value. This algorithm has been tested and appears stable, even for high Kerr-nonlinearity coefficients. Our new extension of the aRCWA method will be demonstrated on several nonlinear-based photonic structure examples, e.g. a nonlinear Bragg resonator grating. Next, the attention will be given to the analysis of nonlinear plasmonic couplers based on slot waveguides. As for the plasmonic couplers, due to strong enhancement of local electromagnetic fields, nonlinear optical phenomena can be boosted in such devices. Also, nonlinear effects enable active control of optical propagating signals. The results from this method will be compared with an alternative approach, named nonlinear eigenmode expansion (NL-EME) technique, introduced by one of us recently. A comparison between the methods shows a good agreement, and the advantages of our NL-aRCWA implementation will be discussed.

9516-25, Session 6

Enhanced radiation amplitude by current-driven diffusing-growing mechanism of electromagnetic field near cutoff in a waveguide

Min Sup Hur, Ulsan National Institute of Science and Technology (Korea, Republic of)

The cut-off condition in the waveguide is usually avoided in general waveguide circuits since the power transmission is significantly deteriorated by radiation reflection near the boundary. However it is possible to get an alternative, non-stationary mode of power transmission near cut-off: the diffusion-growing of the locally-energy-fed electromagnetic field. Such a temporally evolving mode can be modeled by a driven-diffusion equation of the electromagnetic field with complex diffusion coefficient. The diffusion equation of the field can be obtained starting from the general wave equation of the field, where the field is decomposed into a temporally slow amplitude and fast oscillating eikonal parts. Some interesting solutions of the diffusion equation indicate that the electromagnetic field grows as a function of time by sqrt(t), and the growing field slowly diffuses outward from the current source. As the diffusing-growing field comes across the tapered section of the waveguide, it can be effectively converted into a free space radiation with significantly higher amplitude than in the case of direct coupling between radiating antenna and free space or coupling via a waveguide but high above the cut-off. In terms of circuit, the enhanced radiation amplitude can be interpreted as an increased radiation impedance for the current source, or reduced one for a voltage-driven source, where in any case the power transmission from the radiation source to the free space increases.

9516-27, Session 7

Femtosecond laser 3D writing: from smart catheters to distributed lab-in-fibre sensing *(Invited Paper)*

Peter R. Herman, Kevin A. J. Joseph, Moez Haque, Jason R. Grenier, Kenneth Kuei-Ching Lee, Univ. of Toronto (Canada)

Miniaturization and integration of chemical and biological devices with optical components has been a key driving force behind the development of multifunctional lab-on-a-chip microsystems. Optical sensors have also found many advantages in optical fibers that have been deployed over a billion kilometres worldwide in recent decades as our telecommunication networks. The concept of developing ubiquitous sensing networks relies on similar development of novel miniaturized and integrated in-fiber microsystems. To this end, advanced laser processing is enabling the development of a new optofluidic lab-in-fiber (LIF) platform [1] in which very small samples (nL) of analyte may be detected over widely distributed fiber communication networks or inside challenging environments like the human body. In this way, an all-fiber based platform offers seamless integration into existing communication networks or biomedical probes that is otherwise not possible with more traditional lab-on-a-chip based technologies.

Femtosecond laser direct-writing is a well-established technology in which nonlinear optical interactions result in highly precise and customizable refractive index or structural changes of controlled three-dimensional (3D) shapes. However, writing in the cladding of fiber is heavily distorted by astigmatism in the cylinder fiber shape. Such distortion was compensated here by focusing the laser beam with a high NA (1.25) oil-immersion lens matched to the refractive index of the fiber cladding. Optical fibers were exposed with a Yb-fiber chirp pulsed amplified femtosecond laser (IMRA, FCPA ?Jewel, ? = 1044 nm/522 nm (SHG)) optimized for writing waveguides, microfluidic channels, reservoirs, FBGs, and couplers in the core and cladding of buffer-stripped Corning SMF-28 optical fiber.

In this paper, we examine the formation of optical circuits in fiber cladding on three levels: (1) internal modification of the pre-existing core waveguide to implant in-line fiber devices such as Bragg grating

filters, (2) structuring of the near-waveguide region to control waveguide birefringence or mode, and (3) the generation of optical circuits in the fiber cladding that optically connects with the fiber core waveguide.[2] Each of these approaches dramatically enhance the optical functionality of optical fiber, facilitating new approaches in optical interrogation by interferometric and differential analysis [2]. The laser further enables fluid reservoirs, microfluidic channels, micro-optics, and open cavities to be selectively etched in the fiber for the seamless integration of fiber Bragg gratings (FBGs), Mach-Zender interferometers, and Fabry-Perot cavities with microfluidic sensing components [1], defining a multifunctional optofluidic analysis platform centered entirely in-fiber. Examples of torsion, shape, thermal, and refractive index sensing are presented together with new directions for development of in-fiber polarizers and smart biomedical catheters.

REFERENCES

[1] M. Haque, K. K. C. Lee, S. Ho, L. A. Fernandes, P. R. Herman, Lab Chip, 14, 3817 – 3829 (2014)

[2] J. R. Grenier, M. Haque, L. A. Fernandes, K. K. C. Lee, P. R. Herman. "Femtosecond Laser Inscription of Photonic and Optofluidic Devices in Fiber Cladding" in Planar Waveguides and other Confined Geometries Springer Series in Optical Sciences, 1st ed., vol. 189, G. Marowsky, Ed., Springer, 2015, pp. 67 – 110.

9516-28, Session 7

Diamond nanophotonics *(Invited Paper)*

Marko Loncar, Harvard School of Engineering and Applied Sciences (United States)

No Abstract Available

9516-29, Session 7

Epitaxially grown vertical junction phase shifters for improved modulation efficiency in Silicon depletion-type Mach-Zehnder modulators

Saeed Sharif Azadeh, Sebastian Romero-García, Florian Merget, Alvaro Moscoso-Mártir, Jeremy Witzens, RWTH Aachen Univ. (Germany)

High-speed Silicon modulators based on the plasma effect have been extensively investigated mainly by means of introducing reverse-biased p(i)n junctions as phase shifters. The main challenge for such modulators is to maximize their modulation efficiency without compromising high-speed performance and insertion losses. Here, we propose a highly efficient Silicon modulator based on a Mach-Zehnder Interferometer in which the doping profile of a vertical pin junction is precisely controlled by means of successive implantation and Silicon overgrowth steps. The precise level of control afforded by this fabrication procedure allows separately optimizing doping concentrations in the immediate vicinity of the junction and in surrounding electrical transport layers at the nanometric scale, enabling record performance levels. Free carrier absorption losses are minimized by implementing high carrier densities only in the waveguide regions where they benefit the most, i.e., in the immediate vicinity of the junction. Moreover, reliance on epitaxial steps allows extremely precise location of the junction and maximization of the field overlap, while substantially relaxing alignment tolerances for the implantation steps with minimal performance penalties. Since these devices entirely rely on single crystal Silicon, performance degradation caused by poor transport and high optical losses in poly- or amorphous Silicon (as seen in semiconductor-insulator-semiconductor phase shifters) is avoided. Furthermore, unlike conventional plasma effect Silicon phase shifters, the bandwidth of the proposed phase shifters is independent of the applied reverse voltage and thus offers a better eye opening for large signal modulation, and the phase shift versus applied voltage is linearized making them more suitable for the generation of complex constellation diagrams. Device geometries are based on careful simulation of the fabrication process with Synopsys' TCAD software package and are iteratively optimized to maximize the optical modulation amplitude, the drive voltage and the insertion losses of several modulator topologies. The efficiency of the single ended phase shifters is expected to reach a $V_\varpi.L$ of 0.72 V.cm with 4 dB/mm of absorption losses, a significant improvement for depletion type modulators. Lumped element Mach-Zehnder Modulators with folded waveguides as well as travelling-wave modulators with phase matching based on meandered waveguides or discrete recovery loops have been designed. Their RF characteristics have been simulated and optimized with Ansoft HFSS. Optimized device metrics for different applications will be reported. These devices are currently being fabricated.

9516-30, Session 7

Wavelength dependence of Pockels effect in strained silicon

Pedro A. Damas, Xavier Le Roux, Eric Cassan, Delphine Marris-Morini, Laurent Vivien, Institut d'Électronique Fondamentale (France)

Silicon photonics is being considered as the future photonics platform, mainly for the reduction of photonics system costs and the increase of the number of functionalities on the same integrated chip by combining photonics and electronics. Moreover, silicon is also a promising platform for a wide range of nonlinear optical processes due to its strong optical confinement and high optical susceptibilities.

However, silicon is a centrosymmetric crystal which inhibits all second-order nonlinear optical effects. Nevertheless, this limitation can be overcome by straining the crystal lattice and break its symmetry, which is achieved by depositing a stress overlayer (typically SiN) on silicon. These structures can accommodate Pockels effect, which allows light modulation in silicon at speeds that are not limited by carriers and driven at much lower power consumption than those based on the variation of carrier concentration.

In the present work we experimentally demonstrate Pockels effect in silicon waveguides strained by a SiN overlayer deposited by PECVD, with ~1GPa stress. We analyse the second order nonlinear effects for three different waveguide widths and for a wide range of the NIR spectra wavelengths, from 1.3um to 1.64um. This information is relevant to understand the effects of wavelength in the efficiency of Pockels phenomena inside the waveguide.

From that study, we were able to show that the studied nonlinearities are stronger for higher wavelengths and narrower waveguides.

The highest measured second order nonlinear susceptibility was 336 pm/V, obtained for the longest wavelength (1.64um) and lowest width (385 nm), which is, for our knowledge, the highest reported value in the literature for such kind of structures. We also provide a justification of the presented results based on the changes of mode confinement with the wavelength and the interaction of the optical mode with the strain inside the silicon waveguide. These results prove to be a relevant step towards not only a better understanding of the origin of Pockels effect in strained silicon but also for efficient optical modulation in this promising type of devices.

9516-31, Session 7

Photoluminescence of graphene oxide integrated with silicon substrates

Maurizio Casalino, Consiglio Nazionale delle Ricerche (Italy); Ilaria Rea, Istituto per la Microelettronica e Microsistemi (Italy); Lucia Sansone, Consiglio Nazionale delle Ricerche (Italy); Monica Terracciano, Luca De Stefano, Principia Dardano, Istituto per la Microelettronica e Microsistemi (Italy); Michele Giordano, Anna Borriello, Consiglio Nazionale delle Ricerche (Italy); Giuseppe Coppola, Univ. of Cambridge (Italy); Ivo Rendina, Istituto per la Microelettronica e Microsistemi (Italy)

In this work we have investigated both the photoluminescence signal emitted by graphene oxide (GO) nanosheets infiltrated in silanized porous silicon (PSi) matrix and the detection of near-infrared (NIR) signals by graphene/Silicon Schotky junctions.

Concerning photoluminescence, the formation of GO-PSi hybrid structure has been confirmed by several spectroscopic techniques, such as FTIR spectroscopic reflectometry and steady-state photoluminescence, while FFT analysis has revealed a refractive index increase, due to the infiltration of GO inside the PSi layer, of 0.05. In addition a strong enhancement of the PL emitted from GO by a factor of almost 2.5 with respect to GO on crystalline silicon has been experimentally measured. This enhancement has been attributed to the high PSi specific area. Finally we have observed a weak wavelength modulation of GO photoluminescence emission, this characteristic is very attractive and opens new perspectives for GO exploitation in innovative optoelectronic devices and high sensible fluorescent sensors.

Concerning detection, we have fabricated and characterized a graphene/Si Schottky photodetector (PD) able to detect the wavelength of 1550 nm taking advantage of the internal photoemission effect (IPE). IPE is the optical excitation of electrons into the metal to energy above the Schottky barrier and then transport of these electrons to the conduction band of the semiconductor. We have investigated IPE through a Schottky junction obtained by replacing metal with graphene incorporated into a simple Fabry-Perot micorcavity. Devices exhibit a spectral responsivity following the typical behaviour described by the Airy's formula proving that optical cavity plays a key role in the absorption mechanism. Moreover we showed that a further increase in responsivity could be obtained by taking advantage of the Schottky barrier lowering whose analytical formulation has been extracted in a semi-empirical way. A maximum responsivity of about 0.08 mA/W at –5 V around 1550 nm, has been experimentally reported and these devices result attractive for power monitoring, imaging and reflectography NIR applications. These results open the path to the investigation of graphene PD integrated into more complex optical microcavity like disk or ring resonator.

9516-32, Session 7

Pixel isolation in Type-II InAs/GaSb superlattice photodiodes by femtosecond laser annealing

Sona Das, Utpal Das, Indian Institute of Technology Kanpur (India); Nutan Gautam, Sanjay Krishna, The Univ. of New Mexico (United States)

Type-II InAs/GaSb superlattice (SL) based photodetectors are of increasing interest for the fabrication of midwave infrared range (MWIR) and longwave infrared range (LWIR) focal plane arrays (FPAs). Conventional FPA processing includes mesa etching for pixel isolation. One of the limiting factors of mesa etched SL detector is the occurrence of high surface leakage currents [1]. As the pixel sizes decrease, surface leakage becomes the dominant dark current mechanism, due to incorporation of impurities on the dangling bonds of the etched mesa sidewalls.

In this work, we present a pixel isolation technique in the SL detector array, by forming a more resistive higher band gap material from the SL, in the inter-pixel region. The isolation behavior has been characterized by measuring inter-pixel resistance. A femto-second laser anneal of the SL structure of the inter-pixel SL regions, has been used to increase the band gap. A barrier between the pixels is expected to increase the inter-pixel resistance. The p-i-n detector structure, used in this work, has a Type-II SL of 10 monolayers of InAs/ 10 monolayers of GaSb superlattice grown on an n-type GaSb substrate, designed to work in the MWIR (3-5 ?m). Using standard optical lithography and liftoff process, Ti (500 Å)/ Au (3500 Å) p+ ohmic contacts on 200 μm x 200 μm pixels have been made. 9 ?m ? 9 ?m pixel arrays have also been used, although 10 K measurements have not yet been possible with these devices. Subsequently, to isolate the pixels, the top p+ and p-type graded doping layers between the pixels have been chemically etched using 1H3PO4: 2H2O2: 20H2O through the top metal contacts as etch masks. A 775 nm mode-locked 150 fs pulses at a repletion rate of 1 kHz has been used to irradiate these p+ etched SL structures, from the top surface. The laser energy density has been varied between 0.002 - 0.005 J/cm2 for exposure times of 100 - 150 s.

During laser exposure, the top metal contacts act as photomasks in the pixel area and hence the SL structure between the pixels regions only have been laser annealed. The laser annealed and un-annealed devices were then gold wire bonded to measure the 10 K current-voltage (I-V) characteristics between two adjacent pixels. The back-to-back diode reverse resistance between two adjacent pixels shows a greater than two fold increase, after laser anneal, as compared to un-annealed SLs. The improved isolation between the pixels can be attributed to interdiffusion of the laser annealed InAs/GaSb superlattice structure. As a result, the annealed SL region looses its type-II low bandgap property and forms a bulk In¬¬ξGa1-xAsySb1-y barrier material between the pixels. Using a thermionic emission model, the increase in barrier height is estimated to be ≥ 5 meV in the laser annealed superlattice, which explains the observed increase in inter-pixel resistance.

[1] Elena A. Plis, Maya Narayanan Kutty, and Sanjay Krishna, “Passivation techniques for InAs/GaSb strained layer superlattice detectors,” Laser Photonics Rev. 7, No.1, pp .45–59, 2013.

9516-26, Session PS

Algorithm applying a modified BRDF function in Λ-ridge concentrator solar radiation

Kamil Plachta, Wroclaw Univ. of Technology (Poland)

This paper presents an algorithm based on a modified BRDF function, which determines the surface properties of anisotropic materials. The simulation results enable the selection of a suitable material for the construction of mirrors ?-ridge concentrator system.

?-ridge concentrator system consists of two mirrors arranged in the shape of ?-ridge and constitutes integral part of the photovoltaic system. The solar radiation reflected from the mirrors is directed at the surface of the photovoltaic panels. The corresponding angle of incidence of sunlight provides dual-axis tracking system. The efficiency of the system of photovoltaic results from the following parameters: inclination of the angle mirrors, reflective and absorptive properties of material of the mirrors and frequency step of tracking system.

The parameters describing the properties of surface are roughness, density of the material, temperature, factor of scattering, reflection, absorption, or transmission. Due to variety of parameters, analysis of the reflected light is difficult to obtain using numerical methods therefore algorithm applying a modified BRDF function. This function has 4 degrees of freedom, which allows the spatial distribution of the reflected light description.

The algorithm is divided into two stages in order to increase the speed of the calculation. The first stage calculates the global lighting, sets out the parameters of the incident radiation, which illuminates the point, and determines the amount of light reaching that point. The second, simulates local lighting and calculates transformation of the incident light to the light reflected from the surface at given point. This solution of algorithm distinctively imitates reflective properties of the anisotropic surface.

Simulation presents the dependence (wavelength ?=680nm) of the scattering angle (?s=45°) from the value of BRDF function for silicon surface polished electrochemically, and steel surface polished mechanically. The results showed (BRDF dependence [sr^(-1)] from ?s [degree]) that the first surface of the radiation is directionally reflected in 97.4%. Inequalities described by spatial waves within all of the measured range of spatial waves make scarce contributions to the scattering diffusion. In the case of the second surface, the results confirm the appearance of directional scattering near specular reflection and reduction in intensity of the reflectance value, confirming a higher surface roughness of the steel polished mechanically.

Next simulation determines the parameters of various surfaces, including aluminum, copper, steel, chrome and silver. Simulations were performed for different values of angle of incidence and wavelength in range 350-750nm. The simulation results showed that aluminum is the best material for construction of ?-ridge concentrator, for which the value of spectral reflectance is 0.93, remaining at this level throughout the entire measured wavelength range. Mirrors made of silver reach similar spectral reflectance. Nonetheless, within the range of wavelength 350-400nm, the value decreases by 74%. The worst material for construction of the mirror is steel, with 0.58 as the average value of monochromatic reflectance.

The obtained results allow to determine roughness and other statistical parameters of the surface. Application of this concentrator will increase the efficiency of photovoltaic panels by 7-11%, compared to the same solution without the concentrator.

9516-34, Session PS

Design of a compact spectrophoto-goniometer based on a Cardan joint

Karolina Macúchová, Zdenek Novák, Josef Zicha, Czech Technical Univ. in Prague (Czech Republic)

Spectrodirectional measurement combined with measurement of radiation distribution function enable to study illumination characteristics of different light sources. The experiments are realized with a goniometer. In this paper we present design of such an optical instrument for measurement of radiation and spectral characteristics of various visible light sources. The instrument enables to measure various tasks from the field of technical radiometry to photobiology. The measurement technique combines simultaneous measurement of spectral data with overall radiation characteristics of different light sources. Design of the instrument is compact, robust and its kinematics is based on Cardan joint. The device was designed for laboratory measurement and educational purposes. The measurement process is fully automated or enables semi-automated control. For research purposes, the adjustment of proper position of the light source within the optical axis of the device is manually controlled. This instrument finds its use in research projects focusing on study of bioluminescence and surface textures and is utilized for measurement of radiation and spectral distribution functions.

9516-35, Session PS

Efficient ultrafast optical parametric amplification and wavelength conversion in silicon waveguides

Hongjun Liu, Qibing Sun, Nan Huang, Xi'an Institute of Optics and Precision Mechanics (China)

Silicon waveguides with micro-nano structures offers a variety of nonlinear effects that can be used to process optical signals at speeds of 100 Gbit s-1 and beyond, detect signals at unprecedented sensitivities for novel sensing applications and enable broadband electro-optic modulation. Compared with fibers, the silicon waveguides with micro-nano structures have inherent advantages due to the large values of Kerr parameter, Raman gain coefficient and the tight confinement of optical mode. In this topic, efficient ultrafast optical parametric amplification and wavelength conversion via four-wave mixing (FWM) in silicon waveguides are demonstrated. In the ultrafast FWM process, the spectra are greatly broadened, and it is difficult to achieve efficient wavelength conversion and parametric amplification when the pump and signal pulse widths are close to or less than 100 fs because of the spectral overlap. The spectral overlap can be suppressed by tailoring the dispersion profiles of the silicon waveguides, and separable spectra are obtained for parametric amplification with 200 fs pulses. As a result, on-chip parametric gain as high as 26.8 dB and idler conversion gain of 25.6 dB is achieved with a low pump peak power over a flat bandwidth of 400 nm in a 10-mm-long dispersion engineered silicon waveguide. In addition, the impact of initial chirp on the wavelength conversion is also investigated, and relative narrower FWM spectra with most of the energy remain in the central peak can be obtained using appropriate initial chirp. The conversion bandwidth greater than 500 nm with peak conversion efficiency of -1.6 dB can be obtained.

9516-36, Session PS

Optimization Design of pulse compression multilayer dielectric gratings

Shuwei Fan, Shenli Jia, Liang Bai, Xi'an Jiaotong Univ. (China)

As a milestone in the development of laser technique,chirp pulse amplification(CPA) technique is widely applid to produce ultra high power laser.Pulse compression gratings (PCG),one of CPA core components, is becoming hot topic. Mixed metal dielectric gratings(MMDG) with wider spectrum and higher DE are gradually used as compression gratings. Paper's main work about MMDG is as follows:

Thin-film structure with high reflectance, which would be applied to MDG and MMDG, was designed by combining characteristic matrix method and global optimization algorithm. The reflectance of the thin-film was closed to 100% after being optimized, and the bandwidth was over 200nm. Meanwhile the influence of metal thickness to reflectance was also analyzed.

Grating design software based on vector rigorous coupled-wave theory was developed to analyze diffraction characteristics of MDG and MMDG. The parameters which affected diffraction efficiency, such as groove depth, incident angle, duty cycle and top residual thickness, were studied with the aid of the software.Studies showed that parameters of MMDG had a larger process tolerance. Combining generic algorithm and simulated annealing , the optimization design of MDG and MMDG was studied, which demonstrated that the highest diffraction efficiency was over 99% and bandwidth of MMDG was to over 200nm, 50nm wider than that of MDG.

In the paper,preliminary study on laser damage threshold of thin-film structure was done by discussing the internal electric field distribution of the thin-film.

9516-37, Session PS

Ultralong photonic nanojet formed by dielectric cubes

Cheng-Yang Liu, Li-Jen Chang, Tamkang Univ. (Taiwan)

The direct observation of nano-scale targets with conventional microscope is difficult because of the diffraction limit. The evanescent waves store subwavelength information of targets and are missed before reaching the focal plane. The photonic nanojet is a highly focused electromagnetic field with a subwavelength waist and low divergence. The capability of generating photonic nanojets using dielectric cubes working in the visible light region is introduced and investigated numerically. The simulation of electric intensity distributions for a dielectric cube is performed using the finite-difference time-domain method. The focusing characteristic of the photonic nanojets is evaluated in terms of both focal length and transversal full width at half maximum along both transversal directions. The utilization of photonic nanojet is limited by the short length of nanojet. Because short length only allows nanojet to detect the near surface targets, we are interested in photonic nanojet modulation for far-field system. For this reason, the ultra-long photonic nanojet is studied by theoretical calculations for a dielectric cube.

We construct three-dimensional finite-difference time-domain computational model for a dielectric cube. The refractive indices of the dielectric cube and surrounding medium are 1.46 and 1. Light source of wavelength 532 nm propagates from left to right. By changing the dimension of the dielectric cube, it has been demonstrated that the focus point is moved from inside to outside the cube with a high intensity nanojet. The results show that the length of photonic nanojet is elongated greatly. The location and size of the photonic nanojet depend on the dimension of the dielectric cube. The focal length increases as dimension increases. The super resolution imaging of the dielectric cube can be expected from the focal length and the maximum intensity. The photonic nanojet enhancement and super resolution technique could be functional for the imaging of nano-scale targets on substrates and films.

9516-38, Session PS

Numerical calculation of DOS in nanograting layers using method of auxiliary sources

Vitali Ghoghoberidze, SoftMaster Co. Ltd. (Georgia); Sergey Petrosyan, Mikheil Mebonia, Ilia State Univ. (Georgia); D. Kakulia, Iv. Javakhishvili Tbilisi State Univ. (Georgia); Avto Tavkhelidze, Ilia State Univ. (Georgia)

New materials are required for a new generation of energy converters and coolers. Nanostructuring allows changing material properties so that they satisfy the requirements of a particular energy conversion device. Modern solar cells comprised of semiconductor layers. Photons absorbed in these layers generate an electron hole pair. The p ? n junction which is formed by the thin layers separates electrons and holes and forces electrons to run through the load to perform useful work. Conversion efficiency and other parameters strongly depend on charge carrier (electron and hole) mobility in thin layers [1]. Nanograting fabricated on the surface of thin layer increases carrier mobility and improves the characteristics of solar cells [2]. Nanograting changes material properties. These changes are fully determined by the density of quantum states P(E) Changes in itself can be described by introducing geometry factor G such that P(E)=P_0(E)/G where, P_0 (E) is density of states in plain layer[3]. To calculate G Schrodinger time-independent equation should be solved in Nanograting geometry. It was one of the goals of the work to solve this problem using numerical methods. There is a full mathematical analogy between quantum billiards and electromagnetic resonators .Therefore, it is reasonable to use the Method of Auxiliary Sources (MAS) for quantum billiard calculation, as it is most efficient numerical approach for solving eigen value problems. It was one of the goals of the project to solve this problem using digital methods. Method of Auxiliary Sources (MAS) has been propoused by Georgian mathematician V. Kupradze [4]. In the MAS for EM boundary value problems are solved numerically by representing the electromagnetic fields in each domain of the structure by a finite linear combination of fundamental solutions of the relevant field equations, corresponding to sources situated at some distance from the boundaries of each domain. The “auxiliary sources” producing these solutions are chosen to be elementary currents/charges located on fictitious auxiliary surface, usually conforming

to the actual surface of the structure. The method only requires points on the auxiliary and actual surfaces, without resorting to the detailed mesh structures as required by other methods. Finally the problem is reduced to linear system of algebraic equations. Solution of which are coefficients of the decomposition.Coefficients should be obtained. by solving of the mentioned linear system where one of the coefficients is fixed. It means that the field inside area of interest becomes non-trivial only when the main parameter of the problem is near to eigenvalues and we can easily observe the forming of eigenfunctions. Intensity of the field reaches maximum on eigenvalues.We wrote our program in Fortran code. it contains two files. First part generated digital array analogous to the boundary conditions of quantum billiard and creates 100 auxiliary sources on its basis. The second part of the program sums radiation from the sources and finds wave vector value. In the case of project success, we will be able to change Si properties in such a way that high efficiency solar cells can be prepared from

Si material Using interference lithography we fabricate (NG) on the surface of thin layers to change their electronic properties. Using these techniques, gratings with 10-nm and even sub-10 nm pitch were fabricated.

[1] N. Peranio, M. Winkler, D. Bessas, Z. Aabdin, J. König, H. Böttner, R.P. Hermann, O. Eibl, Journal of Alloys and Compounds,

521, pp. 163–173, 25, (2012).

[2] A. Tavkhelidze, V. Svanidze , International Journal of Nanoscience, Vol. 7, No. 6, pp. 333-338, (2008). [3] A. Tavkhelidze, J. Appl. Phys. 108, 044313 (2010).

[4] V. Kupradze, in Success of Mathematical Sciences, vol. 22, Moscow, 1967, pp. 59-

9516-39, Session PS

Development of hybrid polymer/silicon-on-insulator electro-optical intensity modulator

Edgars Nitiss, Martins A. Rutkis, Univ. of Latvia (Latvia)

Electro-optic (EO) modulators are one of the most important and widely used elements in the devices for measurement and information technology. Currently, much effort is devoted towards the development of new nanoscale EO modulator designs operating over a wide wavelength range with very low switching voltages. Organic nonlinear-optical (NLO) materials are one of the most promising candidates for the implementation in high performance and low cost waveguide photonics devices due to their multiple advantageous properties such as low cost, low dielectric constants, high nonlinearity (up to 300 pm/V) and others.

In this work we present a new type of hybrid polymer/silicon-on-insulator (SOI) EO intensity modulator. One of the great strengths of the proposed design would be the simplicity of preparation. The EO modulator comprises NLO active polymer waveguides embedded into oxidized Si trenches on SOI wafer. The performed numerical simulations of the device suggest that 0.5 GHz operation with 1.5 V half-wave voltage at 780 nm could be achievable if EO polymer with EO coefficients of 100 pm/V is used as waveguide core. We also demonstrate the results of experimental development of the hybrid polymer/SOI EO modulator prototype.

9516-40, Session PS

Electrooptic 1*2 switch based on proton-exchanged channel waveguides in LiNbO3

Sergey M. Kostritskii, Yuri N. Korkishko, Vyacheslav A. Fedorov, Optolink RPC (Russian Federation)

Integrated-optic 1?2 switch utilizing electrooptically controllable directional coupler has been developed in LiNbO3 substrates with proton exchange technology. Such an integrated-optic switch has the newly designed Y-branching power divider allowing for high switching contrast at the both optical output ports and low bias voltage. Optimisation of Y-branching power divider allows to find the compromise between smaller ?PTC (?PTC = 0.5 – PTC, where PTC is power transfer coefficient) and higher branching losses (?b) via choice of geometry and fabrication conditions providing appropriate values of both parameters. BPM simulation shows that the cosine junction with average branching angle ? = 1.9? is the optimal geometry, as it allows obtain ?b about 0.6 dB at ?PTC ? 0.01. Our experimental study confirms this theoretical finding.

Switches were fabricated using X-cut LiNbO3 and Y-propagating geometry to operate at the 1520-1580 nm wavelength range. The electrode structure consists of three electrodes coplanar with the waveguides. The necessary electrode pattern was photolithographically delineated in uniform Au-Cr layer that was deposited over substrate. Electrodes length ranged from 7 to 11 mm, yielding various values of the switching voltage for a driving AC-signal. The main parameters of the switches were measured by coupling depolarized light into the waveguides with the aid of an isotropic single mode fiber. A fiber Lyot depolarizer utilizing PM fiber was used to decrease sharply DOP of a superluminescent diode (SLD) radiation (central wavelength is ~1540 nm) and, hence, minimize a polarization-dependent error in measurement results. To determine the insertion losses, we use a fiber-to-fiber coupling set-up. Switching characteristics measurements were made by applying an AC-modulating voltage on electrodes and monitoring the harmonic amplitudes in output optical signal with photodiode, spectrum analyzer and lock-in amplifier. A 23 dB switching contrast (extinction ratio at the bar and cross states) and 2.5 dB insertion losses were obtained for a device with a 9 mm electrodes length.

9516-41, Session PS

Surface photovoltage and field effect on lateral conductivity in structures wth Ge-nanonclusters grown on Si (001) surface

Yurii Hyrka, National Taras Shevchenko Univ. of Kyiv (Ukraine)

The structures with Ge-nanoclusters, grown on SiO2/Si(001) and Si(001) surfaces are promising candidates for optoelectronics as well as for solar cells and optical memory circuits. This is due to their spatial luminescent and transport properties. Crystalline germanium nanoclusters (NCs) are grown by a molecular-beam epitaxy technique on chemically oxidized Si(100) surface at 700ºC. The other type of studied samples was self-assembled Ge nanoclusters grown on Si(100) in the Stranski-Krastanov mode. It was shown that structures with Ge-nanoclusters, grown on silicon surface characterized by fluctuations of the electrostatic field induced by positive charges which are trapped by quantum levels of Ge nanoclusters and/or Ge-nanoclusters/Si interface states. Field effect on lateral conductivity with different gate voltage and surface photovoltage spectra were studied in the temperature range from 80 to 290 K. The transport mechanisms were discussed.

9516-42, Session PS

Estimation of the sinusoidal oscillation parameters in the adaptive optics system based on the example of the photovoltaic system

Dariusz Kania, Wroclaw Univ. of Technology (Poland)

In modern adaptive optics systems, there is a problem of a sinusoidal oscillations rejection resulting from telescope structural vibrations. These oscillations are undesirable and reduce the system performance. One of the methods of the rejection is an appropriate damping signal generation using estimated oscillation parameters. The estimation problem occurs also in the photovoltaic system. In such a system solar cells are combined together to form photovoltaic panels to generate the DC signal converted by the inverter to the AC (sinusoidal) signal with specified parameters. This paper focuses on the fast and accurate estimation of these parameters taking into account the presence of harmonics in the signal. The estimation method is based on using maximum decay sidelobes windows and the Fast Fourier Transform procedure.

In reality, the AC signal is not a pure sinusoid and it is often distorted in a deterministic manner by harmonics and in a random manner by white, "colored" or quantization noise. The signal spectrum is blurred due to the presence of harmonics. In the practical case the analog signal is converted to the digital form by the A/D converter. Therefore, the estimation error depends on the systematic error (with the ideal sampling and pure sinusoidal signal), the error caused by the quantization noise by using the A/D converter with finite number of bits and the error caused by harmonic components (spectrum leakage). Several parameters determine which error component is dominant in the estimation results. The systematic error value depends on the number of samples N in a measurement window, number of signal periods in a measurement window (CiR – Cycles in Range), the time window order H. The level of the relative systematic error is approximately 10^-10 for estimation conditions N=512, CiR=1.5, H=2. The value of the error caused by the quantization noise depends mainly on the number of the A/D converter bits b but also on the value of N, H and CiR. The level of this relative error is approximately 10^-6 for estimation conditions N=512, H=2, CiR=1.5, b=16. The value of the error caused by the presence of harmonic components depends on the distance between the harmonic component and the fundamental component in a frequency domain, the THD (Total Harmonic Distortion) ratio of the signal, values of N, CiR and H. The level of this relative error is approximately 10^-3 for the tested signal with THD=10%, CiR=1.5, N=512, H=2. An increase in the value of H increases the estimation error caused by harmonic components close to the fundamental component but also reduces the estimation error in other cases. It is important to use a filter that reduces unwanted harmonics before the data processing.

The information provided in this paper can be used to determine the approximate level of estimation error before starting the estimation process. The estimation method can be used in the photovoltaic system as well as in the adaptive optics system.

9516-43, Session PS

Integrated optical design for dynamic laser beam shaping with membrane deformable mirrors

Oliver Pütsch, Andreas Olk, RWTH Aachen Univ. (Germany); Peter Loosen, RWTH Aachen Univ. (Germany) and Fraunhofer-Institut für Lasertechnik (Germany)

Laser beam shaping can be identified as key technology for applications ranging from laser materials processing to lithography or medical treatments. The integration of active optics like deformable mirrors exhibits significant innovative capacity for the development of actively controlled and adaptive optical systems for highly flexible laser materials processing. To take full advantage of the capability for the active modulation of a high bandwidth of spatial frequencies that is in line with dynamic temporal and spatial beam shaping, the huge amount of degrees of freedom has to be considered already within the early stage of development. Since the functionality of commercial available ray-tracing software has been mainly specialized on geometric dependencies and their optimization within constraints, the complex system technology of deformable mirrors cannot be sufficiently taken into account yet. The complex multidisciplinary electro-mechanic-optical characteristics of electrostatic driven membrane deformable mirrors comprise inter-actuator coupling and saturation that results in nonlinear deformation whose consideration is actually not covered by the standard functionality of the current commercial available ray-tracing software.

This motivates the development of an integrative development method for the realization of active beam shaping systems with deformable mirrors. The functionality of the ray-tracing program ZEMAX® is coupled with the model of a membrane mirror to provide the internal optimization routines with the available control voltages. The mirrors modelling data is gathered experimentally by measuring the influence functions of the membrane using white light interferometry. Together with additionally derived optimization criteria for the solution of beam shaping problems the optimal control voltage set is determined by taking into account the mirror characteristics with high precision. Thereby the considered intensity distributions do not only cover the generation of fundamental radial and rectangular symmetrical beam shapes (tophat, square, donut) out of an TEM00 input distribution but also nearly arbitrary intensity distributions like triangles and gradient profiles are taken into account. The integrative method enables reliable predictions on the performance of active optical systems comprising membrane deformable mirrors in an early stage of development. Additionally, the determination of optimal control voltage sets enables the open loop control of the system and allows for switching between different beam shapes within far less than a second. Comparatively long convergence times of heuristical algorithms such as simulated annealing or generic algorithms in line with closed loop control approaches are completely avoided.

The simulation environment has been verified with a laboratory setup that is designed for 975nm and that enables intensity distributions with extensions in the order of 300µm. The investigations currently being conducted within cooperative projects at RWTH Aachen University and Fraunhofer ILT already show significant innovative capacity for the development of actively controlled and adaptive optical systems for laser materials processing.

9516-44, Session PS

Terahertz material characterization for nonreciprocal integrated optics

Martin Micica, VŠB-Technical Univ. of Ostrava (Czech Republic); Mathias Vanwolleghem, Institut d'Electronique de Microélectronique et de Nanotechnologie (France) and Univ. des Sciences et Technologies de Lille (France); Jamal Ben-Youssef, Univ. de Bretagne Occidentale (France); Tomás Horák, Institut d'Electronique de Microélectronique et de Nanotechnologie (France) and Univ. des Sciences et Technologies de Lille (France); Jean-François Lampin, Univ. des Sciences et Technologies de Lille (France) and Institut d'Electronique de Microélectronique et de Nanotechnologie (France); Kamil Postava, Jaromír Pistora, VŠB-Technical Univ. of Ostrava (Czech Republic)

Interest in nonreciprocal terahertz (THz) integrated optics makes it necessary to look for new materials active in this region and precisely characterize their electromagnetic properties. In this paper we present important aspects of the methods for determination of the permittivity functions in the far infrared (FIR) and THz spectral range. The techniques are applied to cyclic olefin copolymer (Topas) and hexaferrites ($BaFe_{12}O_{19}$, $SrFe_{12}O_{19}$). Topas is a promising material in integrated THz devices, thanks to its low absorption in this region. On the other hand, hexaferrites have been recently demonstrated to have ferromagnetic resonances up to millimeter wave frequencies. They are therefore promising candidates for the realization of gyrotropic (isolation and circulation) functionalities. All samples were studied by Fourier transform infrared spectroscopy (80 – 8000 cm-1) on a Bruker VERTEX 70v and THz time domain spectrometer TPS spectra 3000 (5 – 100 cm-1), both in transmission and reflection. The advantage of the presented THz time domain spectroscopy is the measurement of electric field wavefunction, which allows to obtain both amplitude and phase spectra. In this work we present the measured spectra and reveal by data processing and extraction of the electromagnetic properties (complex permitivity and complex index of refraction) interesting behavior of the studied materials in the FIR and THz spectral range.

9516-45, Session PS

Magnetoplasmonic waveguiding structure with nonreciprocal dispersion of guided TM modes

Lukas Halagacka, Kamil Postava, VŠB-Technical Univ. of Ostrava (Czech Republic); Mathias Vanwolleghem, Beatrice Dagens, Institut d'Électronique Fondamentale (France); Jaromír Pistora, VŠB-Technical Univ. of Ostrava (Czech Republic)

In this paper we numerically analyze via a rigorous anisotropic RCWA the electromagnetic response of a waveguiding structure with nonreciprocal dispersion of guided modes. The considered structure which is based on the high-refractive index waveguide and the plasmonic (gold) 1D periodic grating. The waveguide and the grating are separated by low refractive index layer. The structure operates as follows. The evanescent field of the guided mode in the is used for the excitation of the surface plasmon polaritons (SPPs) at the top side of the grating.

To achieve non-reciprocity the magneto-optical dielectric garnet is assumed to be on the top of the grating. The presence of the transversal magnetization in the garnet leads to the nonreciprocal shift of the SPP.1, 2 Together with the evanescent coupling of guided modes this leads to the nonreciprocal dispersion of guided modes. The structure is studied over various geometry. The thickness of the separation layer is optimized in order to balance between coupling efficiency and optical losses. The grating geometry is varied to achieve coupling of grating's resonances and therefore possible enhancement of the nonreciprocal response. Moreover, by the grating geometry variation, namely the period, the opening, and the grating thickness, we demonstrate how it is possible to switch a preferred propagation direction of the guided mode from forward to backward by the tuning of the coupling between grating's resonances.3, 4

ACKNOWLEDGMENT

Partial support from the projects CZ.1.05/1.1.00/02.0070 (IT4Innovations), IRP 167/2014, and Czech Science Foundation 13-30397S is acknowledged.

REFERENCES

1. G. Armelles, A. Cebollada, A. Garc´ıa-Mart´ın, and M. U. Gonz´alez, "Magnetoplasmonics: Combining Magnetic and Plasmonic Functionalities," Advanced Optical Materials 1, pp. 10–35, Jan. 2013.

2. V. Belotelov, I. Akimov, M. Pohl, V. Kotov, S. Kasture, A. Vengurlekar, A. Gopal, D. Yakovlev, A. Zvezdin, and M. Bayer, "Enhanced magneto-optical effect in magnetoplasmonic crystal," Nat. Nanotechnol. 6, pp. 370–376, April 2011.

3. L. Halagaˇcka, M. Vanwolleghem, F. Vaurette, J. Ben-Youssef, P. Gogol, N. Yam, K. Postava, B. Dagens, and J. Piˇstora, "Experimental demonstration of anomalous nonreciprocal optical response of 1D periodic magnetoplasmonic nanostructures," Proc. SPIE 8988, pp. 89880E–89880E–6, 2014.

4. L. Halagaˇcka, M. Vanwolleghem, K. Postava, B. Dagens, and J. Piˇstora, "Coupled mode enhanced giant magnetoplasmonics transverse kerr effect," Opt. Express 21, pp. 21741–21755, Sep 2013.

Further author information: (Send correspondence to L.Halagaˇcka)
E-mail: lukas.halagacka@{gmail.com, vsb.cz, ief.u-psud.fr}

9516-46, Session PS

Light trap with reactive sun tracking for high-efficiency spectrum-splitting photovoltaic conversion

Harry N. Apostoleris, Masdar Institute of Science & Technology (United Arab Emirates); Marco Stefancich, Consiglio Nazionale delle Ricerche (Italy); Matteo Chiesa, Masdar Institute of Science & Technology (United Arab Emirates)

We present a novel design for a light-trapping system, previously demonstrated as an effective design for spectrum splitting in parallel-junction photovoltaic configurations, with reactive sun-tracking capabilities. The system is based on the design of Goetzberger et al. (Solar Energy Materials and Solar Cells 92 (2008)) in which concentrated light is admitted into the trap through small apertures and randomized by reflection within the trap. By incorporating solar cells of different band gap with dichroic coatings into the interior of the trap, the design can be used to accomplish spectral splitting, assuming the trapping efficiency is sufficiently high. Efficiency is maximized by minimizing the aperture area, which due to the concentration limit imposed by the conservation of etandue, imposes a strong limit on the acceptance angle of the system. The presented design relaxes this constraint by incorporating an optically active material as the receiving surface, to enable reactive sun tracking. Such tracking is achieved by the material undergoing a localized switch between a transparent and reflective state to form an aperture that moved to track the position of a focused light spot (created by a primary optical array, e.g. an array of lenses). We present as a candidate material a composite of paraffin wax and polydimethylsiloxane (PDMS), in which we have acheived localized, light-activated switching between transparent and reflective states. The theoretical limits on efficiency and acceptance angle are demonstrated, and the impact of material selection on the system performance is discussed.

9516-47, Session PS

Transparent-reflective switching for sun-tracking applications

Harry N. Apostoleris, Masdar Institute of Science & Technology (United Arab Emirates); Marco Stefancich, Consiglio Nazionale delle Ricerche (Italy); Samuele Lilliu, Matteo Chiesa, Masdar Institute of Science & Technology (United Arab Emirates)

We present our ongoing work on the development of transparency-switching alkane-elastomer composites, specifically composites of paraffin wax and polydimethylsiloxane (PDMS), with particular emphasis on their application as dynamic apertures in light-trapping solar

energy systems. We review the theoretical mechanism responsible for transparent-reflective switching in the materials, which we have identified as a structural transformation caused by the paraffin phase transition and resulting in the formation of a turbid, light scattering structure composed of dispersed wax crystals that can be reversibly destroyed and recreated by crossing the transition temperature of the paraffin. We describe our progress in two main areas: enhancing the contrast between the transparent and reflective states by systematic variation of fabrication parameters, including composition ratios and choices of materials, and the activation of localized, light-induced switching, which we have demonstrated in principle using a broad-spectrum absorbing pigment, by incorporation of selectively absorbing pigments.

9516-48, Session PS

Side Band Suppression for Wide Band Optical RoF Systems

Hraghi Abir, SUP'COM (Tunisia); Samir Ben Abid, Ecole Nationale d'Ingénieurs de Tunis (Tunisia); Mourad Menif, SUP'COM (Tunisia)

Wide-band communication is currently considered the norm for a plethora of applications including high speed (over 1Gbits/s) wireless short range communications, wireless ad-hoc networks and sensor networks. Its low energy consumption requirements and the potential for high speed communications make Ultra-Wide-Band (UWB) one of the most recently adopted wireless communication systems.

UWB is based on the transmission of a series of high bandwidth pulses to encode information. The most common modulation techniques used for UWB are OOK (On Off Keying), PAM (Pulse Amplitude Modulation) and PPM (Pulse Position Modulation). The spectral response of the pulse, also called monocycle, is instrumental in the shaping of the spectrum of the communication system. UWB over Fiber (UWBoF) systems are mainly faced with two obstacles, the generation of the monocycle, and dispersion due to large spectral width. Chromatic dispersion (CD), especially, is a detrimental phenomena for the transmission of UWB signals over fiber.

In this work, we propose a flexible UWB monocycle generator that is based on multi-tonal excitation of a dual-arm MZM. The proposed generator permits the generation of SSB moncycle that reduce the effects of CD. The proposed generator is easily tunable to accomodate the different constraints imposed by the transmission system including bandwidth and spectral mask.

9516-49, Session PS

Femtosecond writing of depressed cladding waveguides in strongly cumulative regime

Mikhail A. Bukharin, Moscow Institute of Physics and Technology (Russian Federation) and Physics Instrumentation Ctr. of the General Physics Institute (Russian Federation) and Optosystems Ltd. (Russian Federation); Dmitriy V. Khudyakov, Sergey K. Vartapetov, Physics Instrumentation Ctr. (Russian Federation) and Optosystems Ltd. (Russian Federation)

Direct writing with femtosecond laser has become an advanced and widespread technology for waveguides inscription inside optical materials. This technique allows reliable single-step process of production photonic devices and optical integrated elements without additional fabrication of mask, in contrast to standard fabrication techniques. To design, inscribe and investigate properties of such delicate femtosecond laser written elements as microstructured waveguides and directional couplers based on them it is necessary to know actual spatial profile of refracted index and its dependence on the writing conditions, for instance, to vary the magnitude of refracted index during the fabrication process. The actuality of the investigation arises from opportunity to write three-dimensional structures into transparent materials for the purposes of integral and nonlinear optics, which cannot be produced with usual lithography and ion diffusion techniques.

In the study we investigate modification of refracted index into fused silica sample under the influence of tightly focused (NA=0.5) femtosecond laser pulses with duration of 360 fs at wavelength 1040 nm. In strongly cumulative regime of femtosecond writing (10^4-10^7 pulses per focal spot) we achieved the change of refracted index with peak values of 0.005 in the irradiated area and its decreasing down to -0.002 in the surrounding area into fused silica. The actuality of the investigation also consists in the range of used characteristics of laser pulses: the obtained results could be achieved with emission from master oscillator without additional amplification (60-150 nJ per pulse, 0.1-10 MHz).

As a part of the study, the magnitude and spatial profile of induced refractive index were investigated in the presence of thermal effects. It was shown that due to shot time interval between femtosecond laser pulses and relatively slow thermal diffusion, the exposed focal region of induced refractive index surrounds by significantly wide cladding with inversely changed refracted index. Based on accurate investigation of the edge effects appear in strongly cumulative regime of femtosecond writing the advanced geometry of depressed cladding waveguides was proposed.

To form waveguide into fused silica it`s proposed, for what is believed to be the first time, to write cladding consisted of interleaved layers of decreased and increased refractive index. The guiding of the light then supports by wide regions of depressed refractive index, which surround huge central region of unexposed core of the waveguide. To verify our suggestion by experiment we have designed and inscribed depressed cladding waveguides in fused silica based on the developed geometry. The waveguiding structures possessed high polarization selectivity, which have been investigated both experimentally and numerically on the base of finite-difference time-domain analysis. Novelty of the obtained findings consists in technique of writing depressed cladding waveguides even in the materials with increasing of refracted index under the influence of femtosecond laser pulses. Depressed cladding waveguides in fused silica are of the great importance for highly irradiation stable optical elements, which maintain their original thermoconductive and spectral properties of core region after femtosecond writing process.

Conference WS100: Laser Energy Workshop

Wednesday - Thursday 15–16 April 2015

Part of Proceedings of SPIE Vol. WS100 Laser Energy Workshop

WS100-1, Session 1

Status of HiPER

Chris Edwards, Science and Technology Facilities Council (United Kingdom)

No Abstract Available

WS100-2, Session 1

Beamtime opportunities at LMJ/PETAL *(Invited Paper)*

Thierry Massard, Commissariat à l'Énergie Atomique (France)

No Abstract Available

WS100-3, Session 1

Latest results from the National Ignition Facility *(Invited Paper)*

John Edwards, Lawrence Livermore National Lab. (United States)

No Abstract Available

WS100-4, Session 2

Towards predictive inertial fusion fluid simulations with application to shock ignition

Stefano Atzeni, Sapienza Univ. di Roma (Italy)

No Abstract Available

WS100-5, Session 2

Collisionless shock acceleration of ions for fast ignition

Robert Bingham, STFC Rutherford Appleton Lab. (United Kingdom)

No Abstract Available

WS100-6, Session 2

Influence of lattice structure on fast electron transport in layered solid targets

Rachel J. Dance, Ross J. Gray, David A. MacLellan, Nicholas M. H. Butler, Univ. of Strathclyde (United Kingdom); Dean R. Rusby, Graeme G. Scott, David Neely, Alex P. L. Robinson, Central Laser Facility (United Kingdom); Bernhard Zielbauer, Vincent Bagnoud, GSI Helmholtzzentrum für Schwerionenforschung GmbH (Germany); Paul McKenna, Univ. of Strathclyde (United Kingdom)

The transport of relativistic electrons driven by intense laser pulses in solid materials remains a key aspect of laser solid interactions that is of fundamental importance, and continues to attract much interest. For applications such as the acceleration of ions or the creation of intense radiation sources, a highly energetic and collimated beam of electrons is advantageous. This is particularly pertinent for fast ignition fusion, within which a beam of fast electrons provides ignition of compressed hydrogenic fuel. The efficiency by which energy is transported is dramatically decreased if the beam becomes broken up and filamented, and as such the onset and cause of beam filamentation is of great importance.

Previous work has shown that the target material lattice structure has a strong effect on the transport of picosecond duration electron bunches [1-3]. In this work, we investigate the influence of lattice structure on fast electron transport in layered solid targets irradiated by relativistic intensity laser pulses. Experimental results and supporting simulations are presented that demonstrate that the fast electron propagation is defined by the transport physics in the layer close to the interaction.

[1] McKenna et al., PRL 106 185004 (2011)

[2] Maclellan et al., PRL 111 095001 (2013)]

[3] Maclellan et al., PRL (at press)

WS100-7, Session 2

Integrated simulation approach for laser-driven fast ignition and its application

Wei-Min Wang, Paul Gibbon, Forschungszentrum Jülich GmbH (Germany)

An integrated simulation approach fully based upon particle-in-cell (PIC) model is proposed, which involves both fast particle generation via laser solid-density plasma interaction and transport and energy deposition of the particles in extremely high density plasma. It is realized by introducing two independent systems in a simulation, where the fast particle generation is simulated by a full PIC system and the transport and energy deposition computed by a second PIC system with a reduced field solver. Data of the fast particles generated in the full PIC system are copied to the reduced PIC system in real time as the fast particle source. Unlike a two-region approach, which takes a single PIC system and two field solvers in two plasma density regions, respectively, the present one need not match the field-solvers since the reduced field solver and the full solver adopted respectively in the two systems are independent. A simulation case is presented, which demonstrates that this approach can be applied to integrated simulation of fast ignition with real target densities.

FI physics including generation of fast electrons via laser plasma interaction, transport of the electrons in coronal plasma with steep density gradient, and heating of the target core. Most studies have mainly focused upon one or two of these processes. Integrated investigations of these processes are essential to fully assess the FI scheme. To include all the three processes within an integrated model, a two-region PIC, was proposed by Cohen et al. in 2010, in which the high plasma density is not clamped artificially. In this model, the simulation box is separated into a low plasma density region and a high density region, where the density at the boundary between the two regions is taken as ~100nc. In the low density region a full PIC algorithm with collisions is taken and in the other region the Maxwell's equations are reduced by use of the Ohm's law to solve the electric fields while the Ampere's law is used to calculate currents of background electrons. This reduced field solver is similar to the one used in the hybrid PIC model, whereas the background plasma comprises macroparticles as in a traditional PIC model. In this case the EM fields are consistent with the plasma density in the whole simulation region. However, a potential challenge for this model arises in that the continuity of EM fields near the boundary of the two regions can be violated due to the noise of the full field solver. This noise is usually several orders of magnitude higher than the one of the reduced field solver, which may mask the real value given by the reduced field

solver after a long period of simulation. Therefore, matching the EM fields around the boundary becomes challenging, although it may be partially solved by increasing the spatial resolution and using a large number of macroparticles per cell.

Here, we propose an approach to release the constraint of the EM field matching around the boundary of the two regions. Our approach involves two independent simulation systems: one using the full PIC model and another applying the reduced model as adopted before in the high density region of the two-region PIC approach. Moreover both the full and reduced Maxwell's equations are solved in the whole simulation box, and the two solutions are independent in our approach. The full PIC system is used to simulate the generation of fast particles via laser plasma interactions. Data of the generated fast particles are copied to the reduced-field-solver PIC system in real time but retained in the full PIC system. The transport of the particles and energy deposition are calculated in the reduced-field-solver PIC system. In this way there is no longer any need to match the two field solutions as usually required in a single PIC system with a boundary to separate two field solvers. The resolution in both PIC systems in our approach can be taken as an usual one to satisfy the full field solver for certain maximum plasma density (e.g. 100 nc), since the reduced field solver need not a high resolution. We call this approach two-system PIC.

WS100-8, Session 2

Laser plasma interactions and shock wave generation

Leonida A. Gizzi, Consiglio Nazionale delle Ricerche (Italy)

No Abstract Available

WS100-9, Session 2

Studying the initial stages of plasma generation using ns pulses

Vasilis Dimitriou, Technological Educational Institute of Crete (Greece)

No Abstract Available

WS100-10, Session 3

Laser technology overview and progress with the Lucia system

Jean-Christophe Francis Chanteloup, Ecole Polytechnique (France)

No Abstract Available

WS100-11, Session 3

Progress with DPSSL laser technology at the Central Laser Facility

Chris Edwards, Science and Technology Facilities Council (United Kingdom)

No Abstract Available

WS100-12, Session 3

Orion: laser and diagnostic development during the first two years of operations

Colin N. Danson, AWE plc (United Kingdom)

Orion became operational in April 2013. Since that time the facility has been routinely operated for both internal and academic access experiments. During this period the facility has been developed and further commissioned to improve laser performance and to bring ne plasma diagnostics on-line. This talk will highlight these developments.

WS100-13, Session 4

Development of new laser materials for fusion drivers

Jindrich Houzvicka, CRYTUR spol s.r.o. (Czech Republic); Michal Koselja, Institute of Physics of the ASCR vvi (Czech Republic); Bedrich Rus, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

No Abstract Available

WS100-14, Session 4

Thermo-optical performance of kJ-class laser fusion systems for HiLASE

Ondrej Slezák, Antonio Lucianetti, Magdalena Sawicka-Chyla, Martin Divoky, Tomás Mocek, HiLASE Ctr. (Czech Republic)

One of the most serious limiting factors for the scaling of high-average-power lasers is the production of heat in the laser amplifiers and other optical components. This heat deposition is the source of severe wavefront distortions, thermally-induced beam depolarization due to birefringence, and in the worst case, optical component damage caused directly by thermal stress. Detailed thermo-optical modelling can help to reduce these issues significantly. The results of performance modeling of a diode-pumped solid-state HiLASE kJ-class laser designed for use in inertial fusion energy power plants will be presented. The amplifier concept is based on a He-gas-cooled multi-slab architecture employing Yb^{3+}:YAG slabs with properly designed amplified spontaneous emission absorbing clad. The slabs are cryogenically cooled by helium gas flowing at high velocity along the slabs faces. Our model consists of detailed 3D energetics modelling which provides the heat deposition within the slab volume, including very intensive heating in the absorbing clad. Next step is the calculation of spatially resolved heat exchange with the cooling gas followed by finite-element based thermal stress calculation. The final part of the calculation consists of Jones matrix rays propagation analysis through an inhomogeneously heated slab volume which allows evaluation of optical path difference and thermally induced depolarization profile. It has been shown that proper design of the amplifier and especially the absorbing clad can significantly decrease the transversal thermal gradients in the amplifier clear aperture which leads to great reduction of thermally induced wavefront distortions as well as thermally induced depolarization. Our numerical model originally developed for the design of HiLASE 100 J/10 Hz laser system has been used for the estimation of thermo-optical performance issues in kJ-class inertial fusion laser system.

WS100-15, Session 4

PETAL diagnostics and system commissioning

Jean-Luc Miquel, Commissariat à l'Énergie Atomique (France)

No Abstract Available

WS100-16, Session 4

Repetition rate laser technologies in ELI-Beamlines relevant to fusion applications

Pavel Bakule, Bedrich Rus, Daniel Kramer, Jack A. Naylon, Jiri Thoma, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Jonathan T. Green, ELI Beamlines (Czech Republic); Roman Antipenkov, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Martin Fibrich, Czech Technical Univ. in Prague (Czech Republic); Jakub Novák, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Michal Koselja, ELI Beamlines (Czech Republic)

No Abstract Available

WS100-17, Session 4

HiLASE thin disc laser programme

Akira Endo, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

No Abstract Available

WS100-18, Session 5

Laser fusion materials: bottlenecks and solutions

Antonio Rivera, Univ. Politécnica de Madrid (Spain)

No Abstract Available

WS100-19, Session 5

Final focussing components for a laser fusion power plant

Angel Rodríguez-Páramo, Univ. Politécnica de Madrid (Spain)

No Abstract Available

WS100-20, Session 5

Simulation of ion radiation in optical materials

Alejandro Prada, Univ. Politécnica de Madrid (Spain)

No Abstract Available

WS100-21, Session 5

Role of tungsten nanostructure on pulsed helium irradiation-induced defects

Gonzalo Vallés, Univ. Politécnica de Madrid (Spain)

No Abstract Available

WS100-22, Session 5

Hydrogen diffusion in irradiated nanostructured tungsten

Miguel Panizo, Univ. Politécnica de Madrid (Spain)

No Abstract Available

WS100-23, Session 6

Development of target injector and repetition rate fusion chamber systems for HiPER

Bedrich Rus, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

No Abstract Available

WS100-24, Session 6

Microtargetry for inertial fusion energy

Martin Tolley, STFC Rutherford Appleton Lab. (United Kingdom)

No Abstract Available

WS100-25, Session 6

Inertial fusion energy target shell production

David Barrow, Cardiff Univ. (United Kingdom)

No Abstract Available

WS100-26, Session 6

Free-standing target supply system for IFE

Elena R. Koresheva, P.N. Lebedev Physical Institute (Russian Federation)

No Abstract Available