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Challenges towards the simulation of GaN-based LEDs beyond the semiclassical framework (Invited Paper)

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The elusive nature of the loss mechanisms occurring in GaN-based light-emitting diodes (LEDs) has turned the debate over droop, the non-thermal decline of the internal quantum efficiency at high current densities, into a lively controversy that divides the optoelectronic community. Several different mechanisms have been invoked to explain droop (among them are Auger recombination, carrier delocalization from composition fluctuations, and carrier (leakage from the active region), but no droop theory formulated so far has been unambiguously “proven” yet in the general case, and LED designers still have to rely upon empirical models ridden of fitting parameters. An accurate treatment of vertical carrier transport across the active region would imply to replace the semiclassical Boltzmann picture with quantum mechanical approaches, e.g., on the density-matrix formalism, the Green’s function theory, or the Wigner function picture. On the other hand, the modeling of realistic state-of-the-art LEDs requires the description of 3D device-related effects (e.g., current crowding), which are currently beyond the reach of quantum atomistic approaches. LED modelers taking up the challenge have to face the staggering computational cost and complexity of first-principles models in order to attempt a self-consistent description of carrier recombination and transport, or to address the appropriateness of quantum-corrected models complementing current semiclassical simulation approaches. Starting from microscopic many-body models of carrier recombination and transport in nanodevices, we will discuss key issues arising in both choices and suggest possible pathways for predictive, yet manageable, LED modeling.

AlGaN digital alloys for deep-ultraviolet application

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The development of AlGaN based semiconductor have been primarily driven by the demand of large bandgap material in deep-ultraviolet (UV) applications. However, the transverse-magnetic (TM) dominant transition in high Al-content AlGaN alloy active region resulting from the higher crystal-field split-off valence sub-band leads to significantly lower efficiency in deep-UV light-emitting diodes (LEDs) applications. Previous works suggested that the AlN/GaN short-period superlattice yielded transverse-electric (TE) dominant emissions leading to high efficiency deep-UV emitter. Thus, a systematically understanding on how to utilize superlattice-based AlGaN material to achieve tunable optoelectronic properties is critical for high efficiency deep-UV applications with various spectral regimes.

In this work, we proposed the AlGaN digital alloys to investigate the tunable optoelectronic properties for high efficiency deep-UV applications. The AlGaN digital alloy is the short-period superlattice formed by growing thin film AlN and GaN layers alternately, where the thickness of each layer can be engineered with step of monolayer (ML). By tuning the thickness of AlN layer (m ML) and GaN layer (n ML), the Al-content and bandgap of AlGaN digital alloy could be engineered correspondingly. Our findings show that AlGaN digital alloy with the optimum design can result in heavy-hole sub-band as the dominant transition for achieving TE-dominant emission. In addition, the large resonant coupling and suppression in charge separation for digital alloy also increase the carrier wavefunction overlap remarkably. Moreover, the absorption spectra of AlGaN digital alloys were shown to have broadband coverage properties. Our findings demonstrated the potential of the AlGaN digital alloy as an alternative nano-engineered material in achieving tunable optoelectronic properties for high efficiency deep-UV applications.
9742-4, Session 1

**Numerical analysis on the influence of quantum barriers in UV-A AlGaN light-emitting diodes**

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The ultraviolet-A (UV-A) AlGaN-based light-emitting diodes (LEDs) are of great interest for UV curing, sensing, biochemistry, and water or air sterilization applications and, hence, various researches for improving the device performance of UV-A LED have been attempted. However, in nitride-based LEDs grown on c-plane orientation, the surface charges at hetero-interfaces arising from the discontinuity in built-in polarization of adjacent epi-layers have strong effect upon the electrical and optical performance. Specifically, the polarization-induced electrostatic field in the multiple-quantum well (MQW) active region causes the energy band to form triangular wells and barriers, which thus results in the spatial separation of electron and hole wavefunctions in the quantum wells (QWs). This phenomenon, known as the quantum-confined Stark effect (QCSE), will severely degrade the radiative efficiency of LEDs. To overcome this detrimental effect, several methods regarding the active region design, such as the usage of polarization-reduced barriers, non-polar or semi-polar substrates, staggered QWs, etc., have been proposed. In this study, the influence of quantum barriers on the characteristics of UV-A LEDs are investigated systematically by finite element analysis method. Particularly, various doping profiles of the barriers are explored in an attempt to enhance the LED performance. The UV-A LED structure used as a reference was grown on c-plane sapphire substrate by MOCVD, which had 14-nm-thick QWs and an emission peak-wavelength of 365 nm at 500 mA. Important characteristics, such as the energy band profiles, carrier transportation, carrier distribution, inter-band transition, and built-in electrostatic field, are studied in detail.

9742-5, Session 1

**Rare-earth-doped GaN-based light-emitting diode: a model of current injection efficiency**

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Rare-earth doped GaN, specifically GaN:Eu, devices have attracted considerable attention due to the red light emission owing to the intra 4f transition of the Eu dopants. It is known that electrically driven GaN:Eu red light emitting diodes (LED) exhibit low efficiency compared to those which are optically excited. The main reason for this difference is the dependency of internal quantum efficiency on current injection efficiency and radiative efficiency -for electrically driven devices- rather than in the interplay ratio of radiative and non-radiative processes as in the optically excited devices. Thus, a development of a current injection efficiency model is crucial for the understanding and design optimization of heterostructure with the prospect of realization of high efficiency GaN based LEDs. In this work we develop a current injection efficiency model for GaN:Eu based heterostructure LED. The current injection efficiency model takes into consideration the defect assisted energy transfer from trap-complexes into the Eu+3 site by utilizing the Shockley-Read-Hall recombination theory, the carrier lifetime in the barrier and well, as well as the de-excitation time of Eu+3 sites. A group of rate equations regarding the carriers, traps and Eu+3 sites is addressed and analyzed in order to describe the current injection efficiency in GaN:Eu heterostructure LED. Our findings allowed the optimized carrier injection and confinement in the GaN:Eu structure to achieve higher internal quantum efficiency compared to rudimentary GaN based p-n junctions with an active region of Eu-doped GaN. Further analysis of the proposed model for the GaN:Eu LED will be discussed.

9742-6, Session 2

**A Monte Carlo simulator for noise analysis of avalanche photodiode pixels in low-light image sensing**

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Noise performance of avalanche photodiodes in light detection is typically described by the excessive noise factor, taking into account only the increase of the variance of the output electron count distribution with respect to the input. This approach is attractive since the excessive noise factor, together with the avalanche gain, can easily be included into the signal-to-noise ratio expression of the complete detection chain. For low-light applications down to single-photon counting, that description is typically not sufficient since one is also interested in the higher moments of the output distribution. Analytical derivation of the output electron count distributions of avalanche photodiodes is typically possible only for very simple electric field profile approximations, which is often not a sufficient description of reality. This work presents a Monte Carlo simulator for numerical prediction of the output distribution that can be applied to any arbitrary electric field profile as well as any light absorption profile and therefore serve as a useful tool for device design and optimization. Comparison with the standard McIntyre theory is provided for a constant field profile showing good agreement. Furthermore, the presented method is used to predict the avalanche noise performance of recently presented pinned avalanche photodiode pixel (4-T PAPD) with the electric field profile extracted from a finite-element simulation. The pixel is aiming for improvements in high-speed and low-light level image detection in minimally-modified CMOS image sensor technology.

9742-7, Session 2

**Modeling and simulation of a 3D-CMOS silicon photodetector for low-intensity light detection**

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This paper presents a design and simulation of a novel high performance 3D-silicon photodetector for implementing in the low intensity light detection. The photodetector is modeled by inspiration of general MEMS fabrication to make a 3D- structure in the silicon substrate (1015/cm3), p-type using a bulk micromachining process, and based on a complementary metal-oxide semiconductor (CMOS) technology. The design includes a lateral NIP detector with the electrodes on the top surface and a vertical n+/p junction as an optical window that is perpendicular to the cathode for lateral illumination. This structure can greatly enhance the carrier collection and efficiency. The optimization of the doping profile in the optical window independent from the doping profile to create Ohmic contacts on the top surface is realized in this approach. The finite-element(FEM) simulation is carried out using COMSOL Multiphysics relies on the theoretical and the physical concepts, and then the assessment of the results is done by the numerical analysis with SILVACO (Atlas) device simulator. The results, which are verified by two simulators, are in a good agreement and obtain a reliable estimation for the performance of the 3D-photodetector. Light is regarded as a monochromatic beam with a wavelength of 633nm. The simulation is conducted under the reverse bias dc voltage in the steady-state. We present photocurrent-voltage (I-V) characteristic under the different light intensities (2.10^-3/mW/cm2), and dark-current-voltage (I-V) characteristic. The results show the realization of low dark current (1420^-3[A] at V=2V), and high sensitivity (Ip=2710^-9[A] for intensity=2(mW/cm2)) in the 3D-photodetector.
Graphene-based heterojunction photodetectors with ultra-broadband and high responsivity at room temperature
Che-Hung Liu, You-Chia Chang, Theodore Norris, Zhaozhu Zhong, Univ. of Michigan (United States)

The ability to efficiently detect light over a broad spectral range is central to various technology applications such as imaging, sensing, spectroscopy and communication etc. Graphene is among one of the most promising candidate materials for ultra-broadband photodetectors, as its absorption spectrum covers the entire ultraviolet to far-infrared range due to its unique gapless linear band structure. However, the photoresponsivity of graphene-based photodetectors has so far been limited due to the small optical absorption coming from its monolayer structure nature. People prove the integration of colloidal quantum dots in the light absorption layer can greatly improve the photoresponsivity of graphene photodetectors, but the spectral range of photodetection is reduced because light absorption occurs in the quantum dots. Here, we report an ultra-broadband photodetector design based on graphene heterostructures. The detector is a phototransistor utilizing the thin tunnel barrier formed by the heterojunction interface. Under optical illumination, photo-excited hot carriers generated in the absorption layer tunnel into channel layer, leading to a charge build-up in absorption layer and a strong photo-gating effect on the channel conductance. The devices demonstrated room temperature photodetection from visible to the near-infrared range, with near-infrared responsivity higher than 1 A/W, as required for most applications. These results address the key challenges for broadband infrared detectors and truly open up promising future development of graphene-based optoelectronic applications.

Toward designing back-illuminated CMOS image sensor based on 3D modeling
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The complementary metal oxide semiconductor (CMOS) active pixel sensor (APS) has attracted increasing interest due to demand for miniaturized system-on-chip capability, low-power, and cost-effective imaging systems during the past two decades. Back-illuminated image sensor has attracted attention due to enhanced sensitivity and its commercialization in recent years. Because of the complexity of the 3D integration of photodiode and the optimization of metal layer distribution to maximize the sensitive area, 3D modeling together with effective optical modeling method is indispensable. In this work, based on Crosslight CSuprem and APSYS, we present 3D modeling of an APS unit designed for comparing the opto-electronic effect between front- and back-illumination. The opto-electronic responses are presented versus various power intensity and illumination wavelength. The optical efficiency and quantum efficiency from FDTD modeling are also presented. For appropriately designed sensor structure, it is shown that back-illumination could achieve improved sensitivity within certain wavelength range. The presented results demonstrate a methodological and technical capability for 3D modeling optimization of complex CMOS image sensor.

Dynamics of nanolasers subject to optical injection and optical feedback (Invited Paper)
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In recent years interest in nanolasers has grown due to their potential applications in photonic integrated circuits, optical information processing and system-on-a-chip technologies. Several nano-scale lasers have been explored [1-3]: micro-post nano-pillar and bowtie, nanowire and nano-patch lasers.

Such nano-lasers are anticipated to exhibit enhanced dynamical performance which may arise from a combination of physical factors including the Purcell spontaneous emission enhancement factor F, and enhanced spontaneous emission coupling expressed in the factor, ?. The impact of Purcell enhanced spontaneous emission on the modulation performance of nano-LEDs and nano-lasers [4] has been examined. It was shown by means of a simple analysis that the direct-current modulation bandwidth of such lasers may suffer deleterious effects due to increased F and ?. A number of recent investigations of the dynamical performance of nano-lasers have been made. Ding et. al. explored the dynamics of electrically pumped nano-lasers where the effects of F and ? on nano-laser performance were studied [6]. Recent work has explored the dynamical response of nano-lasers subject to direct current modulation in both small-signal and large-signal regimes [7].

The present paper will delineate a range of nonlinear dynamical behaviours which arise in nanolasers subject to external optical influences. Firstly attention will be given to the impact of external optical feedback on nanolasers [8]. Secondly the dynamical behaviour of semiconductor nanolasers under external optical injection will be treated. Finally consideration will be given to effects arising in nano-lasers subject to multiple optical injections.

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References
9742-11, Session 3

Randomness extraction from a chaotic laser diode with dispersive self-injection (Invited Paper)

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High-speed generation of random bits has attracted much attention recently by utilizing chaotic dynamics in lasers subject to different perturbations. In this work, extraction of randomness is investigated from a chaotic semiconductor laser using self-injection via a dispersive element. The optical feedback invokes the chaotic dynamics, while the dispersion induces different delays to different frequency components. The dispersion effectively conceals the information of the feedback delay time, thereby improving the emission intensity waveforms for extracting random bits. Numerically, the concealment of the time-delay information is verified using a rate-equation model as the dispersion is varied independently. Experimentally, randomness is extracted using a single-mode laser diode under feedback from a fiber grating, which provides the dispersion tunable through adjusting the detuning frequency. The results show that the undesirable time-delay signature is reduced by about 10 times, so the sampling rate for random bit generation becomes continuously tunable without sacrificing the randomness quality. The overall output rate in random bit generation (RBG) can be tuned across 3 orders of magnitude up to 100 Gbps. The results are promising for applications of the high-speed random bits in digital systems with tunable rates.

9742-13, Session 3

Gain compression effect on the modulation dynamics of an optically injection-locked semiconductor laser using gain lever

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Directly-modulated lasers are the best candidates for efficient, low-cost fibre optic communication networks [1]. While the bandwidth of such lasers is limited by their relaxation oscillations, two well-known techniques allow increasing their modulation bandwidths: the gain lever effect [2] and optical injection-locking (OIL) [3]. Gain lever consists in using a laser with two separate electrical regions: firstly, a long section DC-biased far above threshold and secondly a much shorter section modulated and biased close to transparency, thus having a much higher differential gain than the long section where carriers are clamped. While a moderate increase of the modulation bandwidth can be observed, the very large modulation efficiency obtained may not be suitable for practical applications. On the other hand, when a semiconductor laser is locked to an external master laser, a resonance can be found in its modulation response at a frequency corresponding to the detuning between the two lasers. OIL thus allows pushing the resonance peak to very high frequencies without affecting modulation efficiency but at the expense of a frequency dip occurring in the modulation response. Very recently, we studied theoretically the simultaneous use of both effects and observed that gain lever allows lifting the modulation response at the frequencies where the dip appears under OIL [4]. This paper goes a step beyond by investigating the effect of gain compression on the modulation dynamic of such lasers. Calculations show that the gain-lever laser operating under OIL does remain a unique configuration for the development of 40 Gbps broadband transmitters.

References


9742-12, Session 3

Optically induced lasing state hysteresis in a two-state quantum dot laser

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Quantum dot lasers based on InAs can lase from multiple distinct energy states. As with conventional semiconductor lasers these devices can emit from the ground state (GS). However, single state lasing from the first excited state (ES) and the second excited state can also be obtained as well as simultaneous two-state lasing from the GS and first ES. The behavior of these devices under optical injection into the GS when the free-running operation is GS lasing only has been well studied in recent years. However, their behavior when undergoing optical injection into the GS when the free-running operation is single-state lasing from the first ES has only recently been examined. Optical injection into the GS can suppress the ES emission and cause the device to lase from the GS only, even with relatively weak injection strengths. We demonstrate the existence of an injection-induced bistability between the GS emission and ES emission and a consequent hysteresis loop in the output lasing state, revealed by sweeping the power of the master laser up and down close to the lasing wavelength of the GS. We investigate the size of the loop as the operating point of the laser is varied. We also investigate the influence of the wavelength of the master laser and identify several new dynamic two-state pulsing regimes. We investigate the system using a detailed model tailored specifically for quantum dot lasers and show excellent agreement with the experimental results.

9742-14, Session 3

Influence of master linewidth on the relaxation regime of a laser submitted to optical injection

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Surprisingly, the coherency of the master laser has been neglected in simulations of the slave-laser dynamics due to optical injection while it has a major impact. We show experimentally and theoretically that this important parameter affects the response of a slave laser submitted to optical injection for the relaxation regime, when a large discrepancy in laser line of the master is considered.
Dynamics of optically-injected semiconductor nanolasers

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Semiconductor nanolasers are attractive candidates for use as directly-modulated sources in next-generation optical communication networks [1, 2]. Their attractiveness relies in the dimensions of the optical cavity, well below the diffraction limit. First, this offers promises for a tighter integration of optoelectronic devices on a microchip. Then, optical cavities of subwavelength dimensions exhibit an enhanced spontaneous emission, quantified by the Purcell factor. This factor is proportional to the ratio between the cubed lasing wavelength and the cavity volume [3] and becomes significant with cavity dimensions below the emission wavelength. The increased spontaneous emission of nanolasers allows reaching lower threshold currents, and these enhanced carrier dynamics offer the possibility to achieve large modulation bandwidth using direct modulation of the device. While the technology has not yet reached maturity, modulation bandwidths up to 60 GHz have already been predicted theoretically for directly-modulated semiconductor nanolasers [4]. While such values are large compared to the bandwidths achievable using edge-emitting semiconductor lasers, they are still lower than what could be achieved with external light modulators. As for edge-emitters, optical injection can however be used to enhance the modulation bandwidth of directly-modulated nanolasers [5]. In this case, the light from an external master laser is injected into the slave nanolaser, which can lock to the master wavelength under specific injection conditions. The direct-modulation response of the injection-locked laser then exhibits a resonance at the frequency detuning between the master and slave lasers, which allows reaching 3-dB bandwidths much larger than the free-running bandwidth of the slave laser.

References

Modeling of ultrashort pulse generation in mode-locked VECSELs (Invited Paper)

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In mode locking of Vertical External Cavity Surface Emitting Laser's (VECSEL's) with a saturable absorber, experiments have been able to generate light pulses on the order of 100fs. These ultrashort pulses are now on the same order as the characteristic timescale of the intraband scattering in the Quantum Well's (QW's), and for modeling the mode locking behavior it is essential to understand the interaction of the light field with the QW's on a microscopic level. The challenge of using the microscopic theory is that there are significant computational requirements for mode locking simulations. The time scale of the light field propagating inside the cavity is on the order of nanoseconds while the interaction with the QW's is on the order of the length of the pulse.

We will present results on modeling and numerical simulations of mode locking in VECSEL's with a saturable absorbers inside a linear- and a V-cavity. The light field is propagated using Maxwell's equations and the QW's are modeled microscopically using the semiconductor Bloch equations. Studying the computationally intensive 2nd Born theory we can extract effective rates that are used to model the higher order correlation effects such as polarization dephasing. By investigating mode locking in this model we can extract useful information about how the microscopic carrier behavior influences the generation of mode locked pulses and what features of the system could be constraining the generation of ultrashort pulses.

Dynamic model of pulsed laser generators based on multi-junction N-p-N-i-P heterostructures


Generation of high-power laser pulses is a topical task for a wide variety of practical applications: optical communications in free space, optical activation of high-voltage switches, nonlinear frequency conversion, and range-finding systems. This communication considers a dynamic model of a multi-junction heterostructure integrating the functions of a fast current switch and a high-efficiency laser emitter. The functions of the current switch are provided by the formation of two stable electrical states with high and low conductance. In our case, the formation of two stable states is provided by the electrical bistability in the integrated optoelectronic coupler constituted by a heterophototransistor (N-p-N) and a laser diode (N-i-P). Significant specific features of the operation of the given optoelectronic coupler are the one-side injection of carriers of only a single type from the transistor into the laser part and the suppression of the control injection current from the laser part into the base of the transistor. As a result, the heterophototransistor is controlled via the optical activation by light generated in the active region of the laser part. Specific features of the feedback beyond the lasing threshold (saturation of the spontaneous emission flux and deformation of the spontaneous-emission and absorption spectra) are analyzed. Approaches to designing a multi-junction heterostructure with faster switching (rise and decay times of about 1 ns) and higher peak current (>10 A) are considered. It is shown that an important part is played in the dynamics of the injection drive currents of the laser part by the modulation by excess carriers of the charge of the lightly doped base and collector regions of the transistor part. As a result, a field domain is formed, which serves as a virtual emitter of electrons and holes via impact ionization. A satisfactory agreement between the simulation results and experimental data is obtained.

Investigation on electro-optic optical comb generation with higher spectral resolution and bandwidth

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With the use of electro-optic modulator based comb generator, ultra-wideband optical comb is stably and flexibly synthesized from a continuous-wave light. Larger modulation depth at a higher repetition rate would proportionally enhance bandwidth of the generated comb. Practically, however, achievable modulation depth is limited by available output power of microwave amplifiers. In addition, the repetition rate, i.e. comb spacing, is determined by system-side requirements. For example, frequency
spacing of the generated comb should fit to the wavelength grid of optical fiber networks. Narrower frequency spacing is requested for photonic measurements assisted by advanced electrical signal processing based on low-speed electronics.

In this paper, through analytical and numerical investigations, we propose and discuss a variety of configurations, parallel/serial configurations, for electro-optic comb generation with higher bandwidth and/or narrower frequency spacing.

9742-19, Session 4

Coherence properties of fast frequency swept lasers revealed via full electric field reconstruction

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This work describes a novel interferometric technique capable of resolving both the phase and intensity dynamics in semiconductor lasers. The technique allows for the complete reconstruction of the electric field of the device in a real-time, single-shot measurement. To demonstrate the power of the technique, a time-delayed self-referencing variation of the technique is used to characterise the intensity and phase dynamics of a compact fast frequency swept laser utilising a tunable Fabry–Perot filter (15 GHz filter width, ~10cm cavity length, 50 kHz sweep rate, 20 THz sweep), typically used in optical coherence tomography applications. Complete knowledge of the electric field of the source allows a direct time-resolved analysis of the dynamic coherence properties of the swept-source to be completed in a single-shot measurement.

During a single sweep, the swept-source laser exhibits mode-locking, mode-hopping and chaotic behaviour dependent on both the sweep direction and speed. The interferometric technique described and developed in this work allows for an in-depth experimental investigation of the evolution of the laser output, revealing in detail the modal structure and its evolution as the laser transitions between different operational regimes. The experimental method prescribed is therefore capable of providing an unique insight into the underlying physics of operation of a fast frequency swept source. The experimental results are shown to be in excellent agreement with numerical simulations, based on a reduced form of a classical model for a ring cavity laser. The experimental results replicate both the phase and intensity dynamics, in addition to the modal evolution.

9742-20, Session 4

Spectral filtering effects in synchronized semiconductor laser networks

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Bidirectional coupling of semiconductor lasers (SLs) through optical injection is a well established method to generate chaotic signals which, through their dynamics, may give rise to several applications from sensing to monitoring and from communication to security. Recent works have shown the capability of joint behavior or complete synchrony of mutually coupled networks of SLs. In these works, the coupling architecture, the operational conditions and the properties of the active elements determine the types of dynamics of the emitted optical signals, through which the network can potentially be synchronized. In this experimental work, a network of mutually coupled semiconductor lasers has been synchronized through chaotic optical signals that spectrally extend over 10GHz. The synchronization among the lasers that participate in the coupled network is affected, besides the structural and operational conditions, by the signals’ bandwidth that circulates optically. Here we show that the synchronization performance of the detected signals when monitoring the network nodes through optoelectronic conversion is in direct dependence on the signal bandwidth. Smaller signal bandwidth at the GHz range may result in synchronization with cross-correlation values over 0.97 in most of the SL nodes, rejecting higher frequencies that are not optimally synchronized. Another source of improving the synchronization of the network that has been recorded in this experimental setup is by harnessing the de-synchronization events that are almost always apparent, especially when emitted signals include power dropouts.

9742-21, Session 5

Model order reduction for the time-harmonic Maxwell equation applied to complex nanostructures

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Fast and efficient methods for solving the time-harmonic Maxwell’s equations are indispensable in optimization of optical properties or reconstruction of unknown parameters. These problems are common in fields such as optical metrology and computational lithography. Highly accurate geometrical modelling and numerical accuracy at low computational costs are a prerequisite for any simulation study of complex nano-structured photonic devices. We present a reduced basis method (RBM) for the time-harmonic electromagnetic scattering problem capable of handling geometric and non-geometric parameter dependencies allowing for online evaluations in milliseconds. It is based on our finite element Maxwell solver JCMsuite which offers adaptive hp-refinements on unstructured 3D meshes. The method allows to split the computation in a computationally expensive construction phase in which the reduced basis is built self-adaptively from snapshot solutions with a control of approximation errors. In the online phase only the reduced, very low dimensional system has to be solved which is orders of magnitude faster. We apply the RBM to compute light-scattering at optical wavelengths off periodic arrays of fin field-effect transistors (FinFETs). These have a complex device geometry with feature sizes in the range of nanometers, where the width and height of specific parts or more complex properties as the rounding of edges can vary in a large range with scaling factors up to 15.

In order to analyze these features with the RBM the finite element mesh has to be parameterized in a way that preserves its topological structure.

9742-22, Session 5

Criteria of backscattering in chiral one-way photonic crystals

Pi-Ju Cheng, Shu-Wei Chang, Academia Sinica (Taiwan)

Optical isolators are important devices in photonic circuits. To reduce the unwanted reflection in a robust manner, several setups have been realized using nonreciprocal schemes. In this study, we show that the propagating
modes in a strongly-guided chiral photonic crystal (no breaking of the reciprocity) are not backscattering-immune even though they are indeed insensitive to many types of scatterers. Without the protection from the nonreciprocity, the backscattering occurs under certain circumstances. We present a perturbative method to calculate the backscattering of chiral photonic crystals in the presence of chiral/achiral scatterers. The model is, essentially, a simplified analogy to the first-order Born approximation. Under reasonable assumptions based on the behaviors of chiral photonic modes, we obtained the expression of reflection coefficients which provides criteria for the prominent backscattering in such chiral structures. Numerical examinations using the finite-element method were also performed and the results agree well with the theoretical prediction. From both our theory and numerical calculations, we find that the amount of backscattering critically depends on the symmetry of scatter cross sections. Strong reflection takes place when the azimuthal Fourier components of scatter cross sections have an order l of 72. Chiral scatterers without these Fourier components would not efficiently reflect the chiral photonic modes. In addition, for these chiral propagating modes, disturbances at the most significant parts of field profiles do not necessarily result in the most effective backscattering. The observation also reveals what types of scatterers or defects should be avoided in one-way applications of chiral structures in order to minimize the backscattering.

9742-23, Session 5

Short pulse generation based on ultrafast transient Bragg gratings
Yonatan Sivan, Aviran Halstuch, Shai Rozenberg, Shlomo Pinhas, Amiel Ishaaya, Ben-Gurion Univ. of the Negev (Israel)

Pulsed electromagnetic waves have a fundamental importance in wave physics and have both a fundamental and applicative importance. In general, short pulses are limited to central wavelengths of 800nm or around 1080 nm. Pulses at all other central wavelengths require complicated and relatively inefficient wave-mixing interactions. In this work, we propose a novel, flexible alternative to short pulse generation by employing a transient Bragg grating to extract a short pulse from a long one. We denote this process as spectral inheritance – a spectrally-narrow signal pulse inherits the wide spectrum of a switching pump pulse. This can be done via Cross-phase modulation in Kerr media, or more efficiently using free-carrier or even thermal nonlinearities. This enables the generation of short pulses at any wavelength and almost any duration, and provides a new route for spatio-temporal pulse shaping.

We demonstrate the concept theoretically via exact numerical solution of the Maxwell equations. We also derive a simplified model based on an extension of standard coupled mode theory for short pulses and solve the mode equations analytically for low efficiencies. We show excellent agreement between all these approaches. Finally, we demonstrate the effect experimentally in standard silica fibers illuminated by an intense pump propagating through a phase mask, showing sub nanosecond pulses extracted from a much longer signal wave.

9742-68, Session 5

Diffraction patterns from multiple tilted laser apertures: numerical analysis
Anton V. Kovalev, Vadim M. Polyakov, ITMO Univ. (Russian Federation)

A smooth and good quality near field output laser radiation is desirable for applications in plasma diagnosis, thermonuclear synthesis and high order harmonics generation. A multiple apertures diffraction problem frequently arises in optical systems design, particularly, for master oscillator power amplifier laser systems.

In order to ensure and validate spatial noise suppression in laser, we propose an efficient method to calculate diffraction patterns. It is efficient both for near and far fields. The task is hard to address analytically for an arbitrary aperture shape, initial beam intensity and wavefront profiles. Also, incline of active elements facets and retroreflectors forming a laser amplifier assumes that aperture and observation planes are tilted with respect to each other. It complicates the analytical calculation.

Our method for numerical calculation of multiple tilted apertures near and far field diffraction patterns is based on Rayleigh-Sommerfeld diffraction theory and the integral evaluation via fast Fourier transform based circular convolution of the initial field complex amplitudes distribution and the impulse response function. The resulting and initial field angular spectrum coordinates rotation and the impulse response matrix modification is used to consider aperture and observation planes mutual tilt.

The method is computationally efficient and has good accordance with the results of traditional direct numerical computation and experimental diffraction patterns from the Phobos-Ground laser amplifier which included 8 consequent tilted apertures. The method can be applied for diffraction problems in various fields of optics including system design and holography.

9742-26, Session 6

All-optical control of quantum-dot single-photon emission
Dominik Breddermann, Dirk Heinz, Artur Zrenner, Stefan Schumacher, Univ. Paderborn (Germany)

In the context of designing single-photon sources, semiconductor quantum dots are widely studied. Here, we propose and study a new emission scheme allowing for all-optical control of the emitted single photon. Our scheme is based on the two-photon transition between the biexciton and the ground state: the first photon is stimulated by an external laser field, the second photon is spontaneously emitted when the quantum dot relaxes to
its electronic ground state. We demonstrate theoretically that the properties of the spontaneously emitted single photon, such as polarization state, frequency, and even the linewidth, can be efficiently controlled with the driving laser field.

In our theoretical model, the quantum dot is coupled to photons of two cavity modes with orthogonal polarizations and to an external classical light field. We compute the system dynamics numerically from the Liouville-von Neumann equation including photon losses and pure dephasing of the electronic coherences. Additionally, the corresponding Heisenberg equation of motion is evaluated to gain some analytic understanding.

9742-27, Session 6

Study of electro-absorption effects in 1300nm In(Ga)As/GaAs quantum dot materials

Soroush Alisobhani, David T. D. Childs, Nasser Babazadeh, The Univ. of Sheffield (United Kingdom); Benjamin Stevens, University of Sheffield (United Kingdom); Kenichi Nishi, Mitsuru Sugawara, QD Laser, Inc. (Japan); Keizo Takemasa, QD Laser Inc. (Japan); Richard A. Hogg, The Univ. of Sheffield (United Kingdom)

Quantum Dot (QD) absorbing media operating at 1300nm on GaAs substrates present a number of technological advantages. Electro-absorption modulator (EAM) integrated distributed feedback laser, may overcome some limitations in direct modulation of QD lasers, and enable realization of negatively chirped pulses. As for avalanche photo-diodes, the InGaAs/InP counterpart exhibits higher dark currents and multiplication noise. Both devices, in addition to QD lasers, are attractive for future incorporation (either monolithic or hybrid) of QD InAs/GaAs structures on a Silicon platform.

Here, we describe a study of electro-absorption effects in high quality 1300nm InAs/GaAs QD materials grown by Molecular Beam Epitaxy. These material exhibit comparatively low inhomogeneous line-width, large state-separation, and limited tunneling breakdown (i.e. low dark current). We analyze the Quantum Confined Stark Effect in the QD states, and compare the permanent dipole moment to other literature reports of QDs at shorter wavelengths. We also compare the QCSE of the QDs to reports for various QW systems (GaAs/AlGaAs, InGaAs/GaAs, InGaAsp/InP). We show that the rate of shift of the QD ground-state absorption peak is slightly smaller than that of most QW systems (~0.1 meV/kVcm-1 c.f. 0.15-0.2 meV/kVcm-1) with a relatively insensitive absorption to applied electric field. Both observations are attributed to the strong localization of the QD states. As a consequence, we observe a strong QD absorption peak at all biases up to avalanche breakdown, which is not inherent in QW systems. We explore possible future uses of 1300 QDs in EAM applications, absorber regions in APDs, and electro-refraction modulators.

9742-29, Session 6

Study of light emission polarisation control in quantum dot laser

Dharmendra Kumar, Indian School of Mines (India); Chandra M. Negi, Banasthali Univ. (India); Jitendra Kumar, Indian School of Mines (India)

In recent years, most of the studies on the polarized light emission have been carried out for semi-polar InGaN/GaN nano structure. However, there has been has been very little work carried out on the polarized light emission and control in non-polar semiconductors.

In this paper, a theoretical analysis of the optical characteristics and polarization properties of quantum dot laser that uses interband transitions in structurally anisotropic InGa-xAs/GaAs QDs is presented. We demonstrate the polarized light emission and control by using a non-polar semiconductor material (InGaAs/GaAs QDs). We examine the steady states as well as the transient polarization of self-assembled QD lasers. We use multi-band effective mass k.p model with the strain effect taken into account to calculate valence sub-band energy levels in anisotropic QDs. The Luttinger Kohn Hamiltonian is numerically solved to calculate the energy eigenvalues, eigenvectors and wave functions of the QDs. The optical gain spectrum is calculated using the density matrix approach. We have solved the 2-mode rate equations numerically using fourth-order Runge Kutta method to analyze the dynamic characteristics of InGaAs/ GaAs quantum dot laser (QDLs). The effect of structural anisotropy, material composition, carrier densities and strain on light emission polarization ratio has been studied in detail. The polarization ratio gradually enhances with the structural anisotropy and carrier density. However, increase in the strain and indium composition worsens the polarization ratio. Furthermore, the effect of injection current on turn on dynamics has been studied. This work can provide useful information for designing polarized light sources using non-polar semiconductor materials.

9742-28, Session 6

Spatial hole burning, comb spectrum robustness, and intensity noise in quantum dot lasers and microlasers

Artem V. Savelyev, Alexey Zhukov, Mikhail V. Maximov, St. Petersburg Academic Univ. (Russian Federation)

Spatial hole burning (SHB) in quantum dot lasers (QDL) and microdisk lasers (MDL) was studied and its significant impact on lasers operation has been shown clearly.

The edge-emitting QDL are known to have broadband emission spectrum containing dozens of Fabry-Perot modes (comb spectrum). It has been experimentally demonstrated that laser spectrum has low relative intensity noise (RIN) of individual modes. This behavior, though rather useful for application, is controversial to previous knowledge: multi-mode semiconductor laser operation typically leads to complicated dynamics or chaos with high RIN of individual modes.

Emission spectrum, RIN of individual modes in QDL have been studied beyond conventional rate-equation approach for photon concentration and QD filling numbers. We also study spectral robustness in the presence of weak wavelength dependence of losses and other perturbations. The conclusion is that SHB is responsible for QD laser beneficial properties such as low RIN noise and stable multi-mode lasing. This SHB role is due to spatial isolation of charge carriers in QDL together with highly non-equilibrium character of carriers’ dynamics. We demonstrate it numerically by modeling of transitional types of QD-QW lasers with variable in-plane diffusion constant.

In the MDL few QD are involved in lasing (~100) what makes their random distribution relatively to mode nodes an important issue. Thus, we study an impact of SHB effect on mode competition and emission spectra in MDL. It has been shown that due to a random nature of QD positions the emission spectrum could significantly vary in nominally identical devices.

9742-30, Session 7

Superradiance in quantum-dot nanolasers (Invited Paper)

Christopher Gies, Frank Jahnke, Univ. Bremen (Germany); Heinrich A. M. Leymann, Alexander Foerster, Jan Wiersig, Otto-von-Guericke Univ. Magdeburg (Germany); Christian Schneider, Martin Kamp, Sven Höfling, Julius-Maximilians- Univ. Würzburg (Germany); Marc Assmann, Manfred Bayer, Technische Univ. Dortmund (Germany)

New nanoscale light emitting devices often operate in regimes where cavity-
Quantum feedback stabilized solid-state emitters

Julia Kabuss, Alexander Carmele, Technische Univ. Berlin (Germany); Dmitry O. Krimer, Stefan Rotter, Technische Univ. Wien (Austria); Andreas Knorr, Technische Univ. Berlin (Germany)

Device operating point stabilization of semiconductor lasers via a classical self-feedback setup is adequately described with the well known Lang-Kobayashi model. However, this model is no longer valid in the regime of few photons and few emitter excitations, i.e. in the quantum limit. The regime of coherent quantum feedback is of fundamental interest for ongoing research and applications involving single qubit manipulations, the stabilization and creation of non-classical states or the shaping of traveling single photon pulses. To realize this, it becomes necessary to develop analytical and numerical schemes to properly address photon feedback in the true quantum limit, but with the possibility of reproducing the Lang-Kobayashi limit.

In this contribution, we present a feedback scheme involving recurring feedback cycles, that can be used to stabilize Rabi-oscillations in a cavity quantum electrodynamics. From analytic formulas valid for a JCM with single photon feedback, we can extract specific conditions for the feedback parameter in order to realize an efficient interference of in- and outgoing photon population. Further, the analysis serves as a benchmark for an operator based description of quantum feedback in the Heisenberg picture. Here, we derive time-delayed differential operator equations, that are used to expand a hierarchy of time correlated expectation values. Based on this method, factorization techniques become possible and allow for a microscopic as well as semi-classical description of quantum self-feedback. Supported by our first results, the field of coherent quantum self-feedback offers a wide range of relevant applications and enables a new way to study fundamental quantum optical phenomena, e.g. state selective quantum network protocols via feedback control.

Creation and control of entanglement by time-delayed quantum-coherent feedback

Sven M. Hein, Alexander Carmele, Andreas Knorr, Technische Univ. Berlin (Germany)

Quantum information science relies on the feature of distant quantum entities (mostly qubits) to form non-local states. A main challenge consists of generating such non-local entangled states between qubits. We exploit the fact that for coupled qubits, the true eigenstates of the coupled system are usually highly entangled, and also of slightly different excitation energy. This allows to address the different entangled eigenstates by highly frequency-dependent control schemes.

In our proposal, we present such a control mechanism, and demonstrate how it can be used to create entanglement from a fully separable initial state. The mechanism of our choice is time-delayed quantum-coherent feedback. If a qubit occupation decays via the emission of a photon, one can store this photon for a certain “delay time” and couple the radiation back into the qubit afterwards. Through the choice of the delay time, one can set the phase of the feedback, which will then lead to either an increased or decreased qubit decay. The feedback phase, and therefore this increase or decrease, strongly depends on the qubit frequency. In particular, it can be used to separate different entangled states in a quantum network by enhancing the decay of all entangled eigenstates except one.

We discuss this protocol on the example of two coupled qubits, and analyze its effectiveness depending on the feedback delay time. We then generalize the analysis to networks of more than two qubits. We also discuss different approaches for experimental implementation.
Towards an edge-emitting strained-Ge laser fabricated by means of a CMOS process (Invited Paper)

Giovanni Capellini, IHP GmbH (Germany); Michele Virgilio, Univ. di Pisa (Italy); Yuji Yamamoto, Stefan Lischke, Jochen Kreissl, IHP GmbH (Germany); Lars Zimmermann, Bernd Tillack, IHP GmbH (Germany) and Technische Univ. Berlin (Germany); D. Peschka, M. Thomas, Annegret Glitzky, R. Nürnberg, Weierstrass-Institut für Angewandte Analysis und Stochastik (Germany); Klaus Gärtner, Univ. della Svizzera italiana (Switzerland); Thomas Koprucki, Weierstrass-Institut für Angewandte Analysis und Stochastik (Germany); Thomas Schroeder, IHP GmbH (Germany)

Tensile strained germanium microstructures are a candidate as gaining material in Si-based light emitting devices due to the beneficial effect of the strain field on the radiative recombination rate.

We have recently proposed a fabrication method, based on Si complementary-metal-oxide-semiconductor (Si-CMOS) standard processes, enabling the realization of Ge microstrips in which a biaxial tensile strain of \(?\delta b\text{?}0.8\%\) is achieved by means of a SiN stressor layer. The strips geometry and their fabrication process are compatible with electrical injection through standard contact modules and with the formation of a Fabry-Perot cavity for an edge-emitting laser. A great advantage of the discussed approach, in which the active material features a quasi-direct band gap, is an expected radiative recombination enhancement at moderately increased temperatures (\(?700\text{°C}\), compatible with on-chip lasing operation.

In this talk we present the results of fully-coupled 2D optoelectronic simulations of the emission properties of an edge-emitting Ge laser device relying on a material-gain model accounting for the influence of the tensile strain distribution, doping, and operating temperature which has been validated and calibrated using temperature-dependent microphotoluminescence measurements performed on Ge microstrips.

On the way of pushing silicon transistors beyond their limits

Dzianis Saladukha, Tomasz J. Ochalski, Tyndall National Institute (Ireland) and Cork Institute of Technology (Ireland); Felipe Murphy-Armando, Tyndall National Institute (Ireland); Michael Clavel, Mantu Hudait, Virginia Polytechnic Institute and State Univ. (United States)

Fast electronics, based on silicon manufacturing processes, could bypass silicon limits with thin film deposition techniques. Germanium is an interesting candidate as both a transistor channel and photonic material, due to its high hole mobility and close direct-indirect band structure. Introducing additional strain in the Ge layer is one possible way to tailor the band structure and significantly increase the hole mobility, improving its quality as a transistor channel material. We studied Ge under biaxial tensile strain induced by lattice mismatch with an InGaAs buffer layer grown on Si substrates. To study the band structure and optical properties of the material, we used a low temperature photoluminescence technique. Spectra taken at He temperature showed emission up to 2.1 um, which is lower than previously reported energies. We used a 32-band k•p model of the Ge electronic band structure to theoretically confirm that the band minimum is at the L-valley and corresponds to recombination with a heavy hole. From the model, we determined that recombination from the L-heavy hole (L-hh) and L-light hole (L-lh) emit with different light polarisations along different crystallographic directions. Thus, we collected the optical emission propagated along different crystallographic directions to measure the relative contribution from L-hh and L-lh transitions, and so determined the energy of the band gap.

Reciprocity principle and nonequivalence of counterpropagating modes in whistlegoemtry ring lasers

Fei-Hung Chu, Hemashilpa Kalagara, Gennady A. Smolyakov, Marek Osi?ski, The Univ. of New Mexico (United States)

A key feature of the whistlegoemtry semiconductor ring lasers (WRLs) is the asymmetry between the two counterpropagating modes, with the device structure strongly favoring unidirectional operation. The asymmetry between modal losses results in different lifetimes for the two counterpropagating modes, which might be misconstrued as a violation of the Helmholtz reciprocity principle and the time-reversal symmetry of Maxwell’s equations. According to the Helmholtz reciprocity principle, a ray of light and its reverse ray encounter matched optical events, such as reflections, refractions, and absorption in a passive medium, or at an interface. While this principle does not apply to moving, non-linear, or magnetic media, it is expected to apply to the WRL structure when properly interpreted.

The important realization is that the reciprocity principle applies to the complete solution of the Maxwell’s equations when a mode conversion takes place, but not to each mode separately. In the WRL structure, the mode conversion occurs due to bending losses (which are symmetric and
non-equilibrium state evolution, as well as the much longer time durations cluster expansion is truncated at a level allowing parametric studies using the Bose-Hubbard Hamiltonian and Heisenberg picture. The resulting solving equations of motion for atomic populations and coherences, derived temperature Bose-condensed gases. The approach involves numerically lessons learned when modeling semiconductor lasers. Microscopic details have to be included. This is done by borrowing from coherence can be long lived without coupling to any thermal reservoir. Because atomtronic devices operate in the ultracold regime, where quantum states (QWs), the light-emitting transistor (LET) which operates in the regime of spontaneous emissions has achieved up to 4.3 GHz modulation bandwidth. A 40 Gbit/s transmission rate can be even achieved using transistor laser (TL). The transistor laser provides not only the current modulation but also direct voltage-controlled modulation scheme of optical signals via Franz-Keldysh (FK) photon-assisted tunneling effect. In this work, the effect of FK absorption on the voltage modulation of TLs is investigated. In order to analyze the dynamics and optical responses of voltage modulation in TLs, the conventional rate equations relevant to diode lasers are first modified to include the FK effect intuitively. The theoretical results of direct-current (DC) and small-signal alternating-current (AC) characteristics of optical responses are both investigated. While the DC characteristics look physical, the intrinsic optical response of TLs under the FK voltage modulation shows a giant AC enhancement with a 40 dB peak, which however is not observed in experiment. A complete model composed of the intrinsic optical transfer function and an electrical transfer function fed back by optical responses is proposed to explain the behaviors of voltage modulation in TLs. The abnormal AC peak disappears through this optoelectronic feedback. With the electrical response along with FK-included photon-carrier rate equations taken into account, the complete voltage-controlled optical modulation response of TLs is demonstrated.

The role of optoelectronic feedback on Franz-Keldysh voltage modulation of transistor lasers
Chi-Hsiang Chang, National Taiwan Univ. (Taiwan); Shu-Wei Chang, Academia Sinica (Taiwan); Chao-Hsin Wu, National Taiwan Univ. (Taiwan)
Possessing both the high-speed characteristics of heterojunction bipolar transistors (HBTs) and enhanced radiative recombination of quantum wells (QWs), the light-emitting transistor (LET) which operates in the regime of spontaneous emissions has achieved up to 4.3 GHz modulation bandwidth. A 40 Gbit/s transmission rate can be even achieved using transistor laser (TL). The transistor laser provides not only the current modulation but also direct voltage-controlled modulation scheme of optical signals via Franz-Keldysh (FK) photon-assisted tunneling effect. In this work, the effect of FK absorption on the voltage modulation of TLs is investigated. In order to analyze the dynamics and optical responses of voltage modulation in TLs, the conventional rate equations relevant to diode lasers are first modified to include the FK effect intuitively. The theoretical results of direct-current (DC) and small-signal alternating-current (AC) characteristics of optical responses are both investigated. While the DC characteristics look physical, the intrinsic optical response of TLs under the FK voltage modulation shows a giant AC enhancement with a 40 dB peak, which however is not observed in experiment. A complete model composed of the intrinsic optical transfer function and an electrical transfer function fed back by optical responses is proposed to explain the behaviors of voltage modulation in TLs. The abnormal AC peak disappears through this optoelectronic feedback. With the electrical response along with FK-included photon-carrier rate equations taken into account, the complete voltage-controlled optical modulation response of TLs is demonstrated.

Modeling atomtronic circuits (Invited Paper)
Weng W. Chow, Sandia National Labs. (United States); Cameron J. Straatsma, Univ. of Colorado (United States); Dana Z. Anderson, Univ. of Colorado at Boulder (United States)
It is widely believed that atomtronic circuits can be studied using the same modeling framework as their electronic counterparts. This is false because atomtronic devices operate in the ultracold regime, where quantum coherence can be long lived without coupling to any thermal reservoir. Microscopic details have to be included. This is done by borrowing from lessons learned when modeling semiconductor lasers.
This talk describes a model for atomtronic circuits based on finite temperature Bose-condensed gases. The approach involves numerically solving equations of motion for atomic populations and coherences, derived using the Bose-Hubbard Hamiltonian and Heisenberg picture. The resulting cluster expansion is truncated at a level allowing parametric studies involving time scales that cover the rapid population dynamics relevant to non-equilibrium state evolution, as well as the much longer time durations typical for device operation.
The model is demonstrated by studying the system dynamics in the presence of atom injection and extraction in a double-well potential. The talk summarizes the results on the manifestation of phase locking between finite-temperature Bose-Einstein condensates.

Feedback control of optomechanical systems
Nicolas L. Naumann, Leon Droenner, Technische Univ. Berlin (Germany); Sven M Hein, Berlin University of Technology (Germany); Alexander Carmele, Andreas Knorr, Julia Kabuss, Technische Univ. Berlin (Germany)
Optomechanics (OM) has evolved into an influential field of research due to the direct coupling of mechanical motion to the light field inside a cavity by radiation pressure.
Due to similarities in the underlying Hamiltonian formulation, we explore a semiconductor (SC) system as an analogue of optomechanics.
Here, the optical cavity mode is replaced by the resonance of a SC quantum dot (QD) and a single phonon mode replaces the mechanical oscillator.
Advanced fabrication techniques allow to integrate this setup very compactly either by confining a QD inside an acoustic single phonon mode cavity or by exploiting a natural effective single mode coupling to optical phonons.
We are interested in the regimes, where the analogue is valid and where it fails.
In order to clarify this, we explore three exemplary effects in the semiclassical limit.
Bistable behavior can be considered to illustrate the similarities quantitatively: In the limit of many QDs the SC system is in full analogy to approaches the OM system.
Furthermore, we consider the enhancement of the damping of the phonon number and the generation of a high number of coherent phonons, which are closely related and can be achieved for both systems.
While the optical cavity confines bosons, which may sustain an arbitrary number of excitations, the QD exhibits fermionic nature, allowing only limited excitation.
This most important differences between the OM and the SC systems also can be traced back to this difference in excitation statistics.

Photon momentum and optical forces in cavities
Mikko Partanen, Teppo Häyrynen, Jani Oksanen, Jukka Tulkki, Aalto Univ. School of Science and Technology (Finland)
In this work, we study optical forces in cavity structures by using our recently developed quantized fluctuational electrodynamics (QFED) formalism. Our approach for formulating the field operators is based on defining position-dependent photon ladder operators that obey canonical commutation relations. The introduced ladder and number operators have a very clear physical interpretation and they give new insight, e.g., to the local photon number balance, the formation of the local thermal equilibrium, and the optical energy transfer.
Investigations of radiation pressure and the momentum of light in dielectrics have frequently involved arguments about the correct form of the electromagnetic field momentum in material media. The Abraham and Minkowski forms for the single photon momentum are given by $\hbar k_0/
n and $\bar{\kappa}$ on $n_0$, which naturally depend on the vacuum wavenumber $k_0$, but also introduce contradicting and confusing dependencies on refractive index $n$. During the past century, powerful arguments have been advanced in favor of both momenta and various experimental setups measuring the forces due to light also seem to support both momenta. Our results show that the Minkowski momentum is the total momentum of the photon and the associated polarization wave whereas the Abraham momentum neglects the momentum of the polarization wave.

While allowing detailed studies of quantum field fluctuations in interfering structures, our methods also provide practical tools for modeling optical energy transfer and the formation of thermal balance in nanodevices as well as studying electromagnetic forces in optomechanical devices.

9742-45, Session 10
Theoretical investigations of optical properties of Ga(In)AsBi quantum well systems using 8-band and 14-band models
Marta Gladysiewicz, Wroclaw Univ. of Technology (Poland); Igor Ivashev, Marek S. Wartak, Wilfrid Laurier Univ. (Canada)

Novel approach to bandgap engineering of semiconductor materials aimed at obtaining lasers emitting at ultra-long wavelengths, is the alloying of GaAs with another binary compound of bandgap smaller than InAs. Alloying GaAs with GaBi or InBi are obvious possibilities. To model the resulting systems requires the formulation of VBAC (valence band anticrossing) model as an extension of 8-band model to 14-band kp model. We conducted theoretical investigations of a Ga(In)AsBi systems using 8-bands and 14-bands Hamiltonians. We present results of electronic band structure and the material gain evaluated for a single quantum well composed of Ga(In)AsBi grown along (001) direction on GaAs and InP substrates. The VBAC model which accounts for the interactions in the valence band is used. This approach is difficult to use as the VBAC parameters in those systems are not accurately known at present. As an alternative, we made comparison with 8-band model. Our results indicate that for GaAsBi/GaAs quantum wells and carrier concentrations below (typical for semiconductor lasers) similar gain spectra are obtained with 8-band and 14-band kp models. We also show that using GainAsBi quantum wells with 5% of Bi grown on InP substrates with the compressive strain of 2% it might be possible to achieve emission wavelengths above $\mu$m.

We also analyzed the effect of arbitrary substrate orientation on the band structure and optical gain calculated with 14-band model.

9742-46, Session 10
Influence of p-doping on the gain and refractive index dynamics in quantum dash based semiconductor optical amplifiers
Katarzyna Komolibus, Cork Institute of Technology (Ireland); Tomasz Piwonski, Tyndall National Institute (Ireland); Siddharth Joshi, Nicolas Chimot, III-V Lab. (France); John Houlihan, Waterford Institute of Technology (Ireland); François Lelarge, III-V Lab. (France); Guillaume Huyet, Cork Institute of Technology (Ireland)

In this work, ultrafast carrier dynamics in a p-doped dash-in-a-well (DWELL) structure emitting at 1.5 $\mu$m is investigated. Recently, InAs quantum dash (QDash) lasers are of great interest as they operate in the telecom C-band window demonstrating high modal gain and low, temperature-insensitive threshold current. In addition, intentional p-doping of the active region is expected to increase their differential gain and reduce the phase-amplitude coupling factor resulting in low chirp. It is particularly important to understand the effect of p-doping on the carrier dynamics and its direct influence on the dynamic characteristics of QDash lasers, in particular the modulation bandwidth and chirp. A DWELL semiconductor optical amplifier, consisting of 6 layers of InAs QDashes embedded in a 7 nm thick quantum well, is examined using heterodyne pump-probe spectroscopy. This enabled the study of the gain and refractive index dynamics in various operational regimes including forward and reverse bias relevant for understanding the physical processes which govern the operation of two-section mode-locked lasers based on this material system. A comprehensive analysis of the timescales related to carrier relaxation and escape processes will be presented and compared with results obtained from similar undoped materials. Access to simultaneous measurement of the gain and refractive index recovery provide an opportunity to determine the ‘dynamical’ ?-factor which influences the bandwidth of directly modulated lasers. Moreover, carrier dynamics of 1.55 $\mu$m QDashes will be compared to quantum dots emitting at 1.3 $\mu$m demonstrating the effect of different quantum confinement on the relaxation and escape processes.

9742-47, Session 11
Theoretical insights into hybrid perovskites for photovoltaic applications (Invited Paper)
Jacky Even, soline boyer-richard, Institut National des Sciences Appliquées de Rennes (France); marcelo carignano, Hamad Bin Khalifa University (Qatar); laurent pedesseau, jean-marc jancu, Institut National des Sciences Appliquées de Rennes (France); Claudine Katan, Institut des Sciences Chimiques de Rennes (France)

In this review, we examine recent theoretical and experimental investigations on 3D and layered hybrid perovskites (HOP), that combine spectroscopic studies, classical solid-state physics concepts and density functional theory (DFT) simulations to understand their exceptional photovoltaic and optoelectronic properties. It allows defining a new class of semiconductors, where the pseudocubic high temperature perovskite reference structure plays a central role for 3D HOP [1]. A general symmetry analysis of electronic Bloch states, lattice strain, molecular rotations and optical phonons yield new insight into the influence of lattice distortions, including loss of inversion symmetry, as well as spin-orbit coupling. Electronic band folding and degeneracy, phase transitions, effective masses, carrier collision processes and optical absorption are analyzed. Thermally activated molecular rotations and disorder, are important for room temperature screened excitonic properties of 3D HOP. Quantum and dielectric confinement in layered HOP are quantitatively determined, using a new DFT method [2]. The theoretical concepts are compared to recent experimental investigations on the excitonic properties of HOP [3].


9742-48, Session 11
Theoretical studies of Rashba and Dresselhaus effects in hybrid organic-inorganic perovskites for optoelectronic applications
Laurent Pedesseau, Institut National des Sciences Appliquées de Rennes (France); Mikaël Kepenekian, Univ.
Absorption enhancement by textured InP in solar cells

Seokhun Yun, Taeksoo Ji, Chonnam National Univ. (Korea, Republic of)

InP seems to be the ideal material for solar cells because it exhibits fast carrier velocity. InP, however, is unwilling to commercialize on a large scale photovoltaic device because of its high material cost. Previously, InP solar cells using hetero junctions with ITO were examined to overcome the aforementioned disadvantage in past. However, ITO also suffers from high material cost and difficult control of tin diffusion. In this research, Aluminum doped ZnO is sputtered onto a ?-type InP. Using adjusting dot array patterns of InP substrate, we achieved a solar cell efficiency up to 10%.

REFERENCES


Industrial robot’s vision systems

Radda Iureva, Evgenii O. Raskin, Igor I. Komarov, Nadezhda K. Maltseva, ITMO Univ. (Russian Federation); Michael E Fedosovsky, AO “Diakont” (Russian Federation)

Unlike traditional survey methods, internal diagnostics does not require opening the underground part of the pipeline construction and dismantling. Video inspection of the pipeline relates to methods for non-destructive testing and allows us to solve the following problem diagnosis:

- Detection of surface defects (cracks, lack of fusion, dents, sink marks, scores, shells);
- Identify foreign objects (metal bars, stones, welded into the electrodes);
- Assessment of the internal surface of pipes (corrosion, pollution and so on.).

While monitoring the pipeline the robotic crawler moves through the pipe, transmits television picture tube on the inner surface of the monitor screen of the operator. Communication with the robot control station and its power is supplied via a cable length up to 20 meters. The robotic system uses the method of structural illumination 3d-view. Robotic systems need to get from the start point to the finish point, given the fact that the situation in
the working space that is necessary to investigate, is not fully known and, in
addition, changes in motion. Vision Systems are used to identify obstacles
to the process of movement on a trajectory to determine their origin,
dimensions and character. The object is illuminated in a structured light, TV
camera records projected structure.

Distortions of the structure uniquely determine the shape of the object in
view of the camera. The reference illumination is synchronized with the
camera. The main parameters of the system are the basic distance between
the generator and the lights and the camera parallax angle (the angle
between the optical axes of the projection unit and camera).

The control system for complex robotic in-line inspection includes
information and a control part (robot control equipment, sensors, vision
system and the microprocessors pre-processing) on the mobile
robot; post operator of the mobile robot (remote control; computer for
information processing) and a set of receiving and transmitting equipment,
ensuring the transfer of information from the robot to the position of
the operator and the control commands from the operator’s station to the
mobile robot. Vision system not only provides the planning movement in
non-deterministic environment, but also leave only strategic level for
videographer man: a system of communication with the operator is reduced
to issuing assignments and adoption of the report on its implementation.
The payment for facilitating life of the operator is rather expensive: technical
vision is to be flexible and have breadth of features of natural intelligen

9742-64, Poster Session
Design and simulation of photonic crystal
structure based channel drop filter for
optical communication system

Mayur K. Chhipa, Engineering College Ajmer (India); Ekta Rewar, Manipal Univ. (India); Lalit Kumar Dusad, Engineering College Ajmer (India)

In this paper channel drop filter (CDF) is designed by a dual curved circular
photonic crystal ring resonator. The ring resonator works as an energy
coupler via capturing the electromagnetic energy propagated in the input
waveguide and sends it to the output waveguide at its resonant frequencies.
The PhC designs have been optimized for telecommunication wavelength
(?1= 1.571 µm, ?2= 1.591 µm and ?3= 1.611 µm) by varying the whole structure
refractive indices. In eight-channel ITU-T G. 694.2 CWDM systems, the eight
wavelengths (? are used to add/drop the channels over the range from 1471
nm to 1611 nm with 20 nm channel spacing, in this paper we have designed
the structure for L band CWDM systems. The photonic crystal (PhC) based
on two dimensional (2D) square lattice periodic arrays of Silicon (Si) rods
in air structure have been simulated using Finite Difference Time Domain
(FDTD) method and photonic band gap is being calculated using plane
wave expansion (PWE) method. The designed filter gives very good
dropping efficiency whose corresponding refractive indices are 3.47, 3.533,
and 3.778 respectively. Both point and line defects are utilized to design
this channel drop filter. In between both waveguides dual curved photonic
crystal ring resonator is designed. Four scatter rods are placed at all the four
corners of PCRR. Two observation points are placed at the two output ports
to measure transmission spectrum. All the simulation work is performed on
OptiFDTD software (Licensed Version) at GEC, Ajmer, Rajasthan, INDIA.

9742-65, Poster Session
The simulation and experimental research on the sensing characteristics of few-
mode-fiber based LPFG

Guanghui Chen, Mei Sang, Chenhao Zhong, Tianjin Univ. (China); Biao Wang, Weigang Zhang, Nankai Univ. (China)

Compared with FBG, long period fiber gratings (LPFGs) have higher sensitivity
in many aspects. With the development of few-mode fiber (FMF),
few mode long period fiber gratings (FM-LPFGs) has grasped a lot of
research focus in recent years. The copropagating coupling between a core
mode and a cladding mode, or two different core modes, will bring different
effects on the sensing characteristics of temperature, strain and refractive
index. However, the coupling characteristics between core modes and
cladding modes have been rarely reported in theory before. In this paper,
based on the coupled-mode theory, we simulate the transmission spectrum
of the FM-LPFGs by use of MATLAB and COMSOL software. Assuming
that all the power is launched in a certain mode, we calculate the coupling
coefficients and the transmission spectrums between the core modes (LP01,
LP11, LP21, and LP02) and the cladding modes LPm (m=1) at 1550nm.
In addition, we change some fiber parameters like grating period, refractive
index modulation depth and cladding diameter to analyze their effect on
the transmission spectrum. Based on the simulation, we fabricate some FM-
LPFGs by the CO2 laser, and use them in temperature sensing experiments.
With the certain strain, we measured the temperature sensing sensitivity of
the FM-LPFGs. The measured sensitivities of temperature is -43.98pm/˚C.

9742-66, Poster Session
Laser-assisted photoprocesses in
nanostructured silicon films

Dmitry E. Milovzorov, Fluens Technology Group Ltd. (Russian Federation)

The optical quantum generation was experimentally observed by using silicon
nanocrystalline film which was irradiated by second-harmonic of
YAG:Nd3+ laser Matrix Hamiltonian for a model of Si-Si-Si-bridge with small
external field perturbation was proposed. The coherent solution for a system
with master equations which described photo-assistant electron transport
in one dimensional chain of coupled quantum wells with two energy levels
was obtained. The decoherence of electronic processes of excitation and
tunneling causes the destruction of laser generation. Such behavior of
upper-level population by its rising up to saturation value can be explained
strictly by decoherent conditions, the time of coherence decay was
estimated, and the conditions by which the photoluminescence in polarized
nanostructured silicon film was appeared are considered. There are coherent
and decoherent modes in electron transport realizing optical quantum
generation. Both of them are possible in nanogstructured media that has
its geometrical parameters which are comparable with Gauss laser beam
pumped nanocrystals. Because, the strong local fields inside the stressed
polarized nanocrystalline silicon film play a great role in tuning or detuning
by variation of levels’ energetic positions and, therefore, result in optical
photon emission.

9742-67, Poster Session
Characterization of the non-collinear
acousto-optical cell based on calomel
(Hg2Cl2) crystal and operating within the
two-phonon light scattering

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Performances of any system for data processing based on acousto-optical
technique are mainly determined by parameters of the acousto-optical
cell (AOC) exploited within the schematic arrangement. Here, basic
properties of the AOC, involved into a novel processor for precise optical
spectrum analysis dedicated to modern astrophysical applications, are
considered. Because potential applications of this processor will be focused
on investigations in extra-galactic astronomy as well as studies of extra-
solar planets, an advanced regime of the non-collinear two-photon light
scattering has been elaborated for spectrum analysis with significantly
improved spectral resolution. Under similar uprated requirements, the
AOC, based on that specific regime in the calomel (Hg2Cl2) crystal,
had been chosen, and its parameters were analyzed theoretically and
Long Period Fiber Gratings (LPFGs) are periodic structures on a fiber with longer periodicity than the wavelength, which couple light from low order modes into higher-order modes. In the past two decades LPFGs were broadly investigated, and exploit for temperature, strain and index of refraction sensors [1].

LPFGs on tapered fiber were demonstrated with side-contacted metal grating [2], CO2 laser writing [3], or with photosensitive fiber [4]. However, these methods are hard to tune, asymmetric, have high losses or requires coupling to unique fibers.

We present a method for fabricating stable, cheap and simple LPFGs on single mode fibers (SMF) with tunable parameters. We taper a SMF using CO2 laser and combined again. The wavelength shifts of two polarized lights with variations in temperature can be maximized by controlling the relative angle of a polarizer resulting in the improvement of temperature sensitivity. By exploiting the wavelength swept laser, we can monitor the temperature variation faster than previous studies using broadband source and spectrometer.

9742-70, Poster Session

Long-period fiber grating induced by mechanical oscillations

Shir Shahal, Hamootal Duadi, Moti Fridman, Bar-Ilan Univ. (Israel)

Long Period Fiber Gratings (LPFGs) are periodic structures on a fiber with longer periodicity than the wavelength, which couple light from low order modes into higher-order modes. In the past two decades LPFGs were broadly investigated, and exploit for temperature, strain and index of refraction sensors [1].

LPFGs on tapered fiber were demonstrated with side-contacted metal grating [2], CO2 laser writing [3], or with photosensitive fiber [4]. However, these methods are hard to tune, asymmetric, have high losses or requires coupling to unique fibers.

We present a method for fabricating stable, cheap and simple LPFGs on single mode fibers (SMF) with tunable parameters. We taper a SMF using CO2 laser tapering machine, and at one point we excessively increase the laser power and cause the fiber to loose. The loose fiber vibrates in the laser beam which results in fluctuations of the tapered fiber diameter, namely the LPFG. All the parameters of the LPFG, such as periodicity, efficiency and diameter are accurately controlled in real time by tuning the width and length of the tapered fiber and the speed of the moving motors. We also demonstrated two combined LPFG with different parameters on a single fiber. Our method will open a rout toward novel LPFG devices which are low cost, highly tunable and have low coupling losses. The full experimental details and results will be presented.

References:

9742-72, Poster Session

Dielectric elastomer-based laser beam pointing method with broadband wavelength

Tomohiko Hayakawa, Lihui Wang, Masatoshi Ishikawa, The Univ. of Tokyo (Japan)

We will report a novel method to manipulate the direction of a laser beam by controlling the deflection of the dielectric elastomer (DEA). When a voltage is applied on the DEA, the electrostatic pressure will arise from the Coulomb forces and squeeze the elastomer, so the thickness of the DEA elastomer can be dynamically controlled. If a laser beam passes through a layer of transparent material with a certain angle, there will be a parallel shifted displacement between the entrance and exit direction. The degree of the shifted displacement is determined by the thickness and the refractive index of the material. If we apply different voltages on a DEA, the laser’s shifted displacement will become possible to control. Because the system is activated by adjusting different voltages on the elastomer, there is no mechanical movement.

Because the deflection of a single DEA elastomer was small, we employed multi-layers of the DEA elastomers so that the total range of the shifted displacement could be amplified. We had employed different wavelengths of laser beams to test our system, and the experimental result showed that it was well transmittance in ultraviolet and visible wavelength bands and had achieved high-precision controlled in micro-millimeter. It is a new method to manipulate laser beam with high-precision control but without mechanical movement, and it is possible to be used in the partial of the laser application field, such as a laser cutting or drilling machine or 3D printing.

9742-74, Poster Session

Photo-induced dynamics in the Reststrahlen band of SiC using transient infrared spectroscopy

Bryan T. Spann, Ryan Compton, Daniel Ratchford, Adam D. Dunkelberger, James P. Long, U.S. Naval Research Lab. (United States); Paul Klein, Sotera Defense Solutions, Inc. (United States); Joshua D. Caldwell, Jeff C. Owratzky, U.S. Naval Research Lab. (United States)

Realizing actively tunable nanophotonics would have wide-ranging implications for sensing, lasers, and metamaterials. By photo-exciting free-carriers in 4H-SiC, we induce significant changes in reflectance around the “Reststrahlen band” where the permittivity is negative due to charge oscillations of the optical phonons in the mid-infrared. To do this, we use a 355 nm pulsed pump laser for excitation then probe the resulting dynamics in a reflectance geometry with a line-tunable CO2 laser near the 10 um range. This spectral region gives rise to surface phonon polaritons resonances which have modal lifetimes significantly longer than that of plasmonics systems, providing less loss and higher resonant quality factors. We use a model of permittivity that accounts for both phononic and free-carrier contributions that accounts for the observed physics very well. The observed carrier-induced changes in the permittivity which modify the reflectance suggest useful tunability in nanoscale resonators, providing an avenue towards actively tunable nanophotonic devices.

References:
9742-75, Poster Session

Development of new maskless manufacturing method for anti-reflection structure and application to large-area lens with curved surface

Kazuya Yamamoto, Nalux Co., Ltd. (Japan); Toshimitsu Takaoka, Hidetoshi Fukui, Yasuyuki Haruta, Nalux Co. Ltd. (Japan); Tomoya Yamashita, Seiichiro Kitagawa, Nalux Co., Ltd. (Japan)

In general, thin-film coating process is widely applied on optical lens surface as anti-reflection function. In normal production process, at first lens is manufactured by molding, then anti-reflection is added by thin-film coating. In recent years, instead of thin-film coating, sub-wavelength structures adding on surface of molding die are widely studied and development to keep anti-reflection performance. As merits, applying sub-wavelength structure, coating process becomes unnecessary and it is possible to reduce man-hour and cost. In addition to cost merit, there are some technical advantages on this study. Adhesion of coating depends on material of plastic, and it is impossible to apply anti-reflection function on arbitrary surface. Sub-wavelength structure can solve both problems. Manufacturing method of anti-reflection structure can be divided into two types mainly. One method is with the resist patterning, and the other is mask-less method that does not require patterning.

What we have developed is new mask-less method which is no need for resist patterning and possible to impart an anti-reflection structure to large area and curved lens surface, and can be expected to apply to various market segments.

We report developed technique and characteristics of production lens.

9742-77, Poster Session

III-nitride monolithic LED covering full RGB color gamut

Hussein S. El-Ghoroury, Chih-Li Chuang, Mikhail V. Kisin, Ostendo Technologies, Inc. (United States)

We present numerical simulation results for the first successful implementation of III-nitride monolithic multi-color LED covering full sRGB color gamut. As an experimental benchmark, we employ three-color red-green-blue (RGB) monolithic LEDI grown at Ostendo Technologies and utilized in Ostendo proprietary Quantum Photonic Imager (QPI) device2. For simulation we use COMSOL-based programs developed at Ostendo Technologies Inc.

Active region of our multi-QW three-color RGB LED incorporates specially designed intermediate carrier blocking layers (ICBL) controlling carrier transport across the active region and carrier redistribution among the QWs with different emission wavelengths. ICBLs are proved to be essential elements of multi-color LED active region requiring optimization both in material composition and doping. Strong inter-dependence between ICBL parameters and active QW characteristics presents additional challenge to multi-color LED design.

Combination of several effects was crucial for adequate simulation of experimentally observed RGB color control features. Standard drift-diffusion transport model was completed with rate equations for dynamic QW populations which appeared severely off-balanced from corresponding mobile carrier subsystems. QW kinetic model has been also completed with Auger-assisted QW depopulation which enhances the nonequilibrium character of QW populations and supports the mobile carrier transport across the ICBLs.


9742-50, Session 12

Complex shaped plasmonic nanoparticles (Invited Paper)

Calin Hrelescu, Johannes Kepler Univ. Linz (Austria)

Complex shaped nanoparticles are of particular interest for many applications, where an optimal interaction between light and nanoscale objects is desirable, since such nanoparticles provide easily accessible hot-spots and exhibit multiple plasmon resonances in the visible-NIR spectral range. Single nanostars have been shown to provide high Raman enhancement factors due to the hot-spots located on the tips. Moreover, the individual tips of a single nanostar can be selectively excited. Furthermore, nanostars are more efficient for random lasing than conventional nanoparticle shapes, such as rods.

Here, I present two different types of complex shaped nanoparticles, which manifest several plasmon resonances with strong polarization dependence, namely nanostars and sponge-like nanoparticles that consist of fully percolated gold and air filaments.

The correlation of the scattering spectra with the corresponding nanosponge morphology reveals that the plasmonic properties depend only weakly on the surface roughness, but are decisively influenced by the for each nanosphere unique 3D percolation.

Further, different strategies to modify the luminescence of gain materials upon addition of spectrally matching plasmonic nanostars are described, such as substantially enhanced electroluminescence and enhanced photoluminescence of OLEDs. Financial support was partially provided by the European Research Council (ERC Starting Grant 257158 ‘Active NP’). by the Austrian Klima- und Energiefonds (SolarTrap, Grant 843929) and by Erasmus GATE.

1 C. Hrelescu et al., APL. 94, 153113 (2009).
3 E.M. Perassi at al., ACS Nano 8, 4395 (2014).

9742-51, Session 12

Simulation of semiconductor plasmonic terahertz antennas

Bernd Witzigmann, Maximilian Bettenhausen, Univ. Kassel (Germany); Subhajit Guha, Marcin Kazmierczak, Thomas Schroeder, IHP GmbH (Germany)

The electromagnetic response of doped semiconductors can exhibit plasma frequencies in the terahertz frequency regime. In this presentation, a study of linear dipole antennas with doped germanium is presented. In classical RF antenna theory the electronic response to an electromagnetic field is governed by a metallic DC conductivity (Hagen-Rubens regime). The skin depth is much smaller than the antenna dimensions. Semiconductor antennas in the THz regime allow tuning of the response from the Hagen-Rubens regime close to the transparent regime, where a large phase offset of the electrons and the electromagnetic field occurs. Here, classical antenna models need to be extended by the effect of the surface wave propagation, which is well known from metallic optics as plasmon polaritons. Based on circuit analysis and a full numerical solution of Maxwell's equations, linear antennas with and without center gap are investigated for their use as THz receiver antennas. We will present antenna impedance, efficiency and gap field enhancement and compare a semiconductor design to a conventional metal design.

3 E.M. Perassi at al., ACS Nano 8, 4395 (2014).
9742-52, Session 12

**Transmittance of long-wavelength infrared surface plasmon by hexagonal periodic metal hole arrays**

Byungwoo Lee, Hoe Min Kwak, Ha Sul Kim, Chonnam National Univ. (Korea, Republic of)

For long wavelength infrared transmission, a surface plasmonic device, having the periodic subwavelength metal hole array on Si substrate, was fabricated using photo-lithography and electron beam evaporation. The maximum transmittance was measured 67.8% at 15.4 µm with a plasmonic device composed of a pitch of 5 µm and hole arrays of 3 µm of the surface normal at a 0 degree incident light. Transmission peak was split into two when the hole size became larger than a half pitch of the lattice constant. At the incident angle of 45 degree, the six degenerated (1D) Au/Si surface plasmon mode was split into five modes. The red and blue wavelength shifts were measured at the same time. We will also present a result of the flexible plasmonic device about the transmission of a long wavelength infrared.

9742-53, Session 12

**3D-FDTD simulations for the design and optimization of nanostructures and the resulting plasmonic enhancement in organic ultraviolet photodetector performance**

Monica Esopi, Qiuming Yu, Univ. of Washington (United States)

Organic thin film optoelectronic devices have varied applications, including ultraviolet photodetection. One of the advantages of organic ultraviolet photodetectors is their potential to be fabricated on flexible substrates that can readily be incorporated into durable and field-ready equipment. However, the current popularity of indium tin oxide (ITO) as an electrode precludes devices from being used in applications where flexibility is required, because of ITO’s brittle nature. In this work, we proposed to utilize a nanopatterned aluminum electrode as an alternative, one that would be both cheaper and more flexible than ITO. Most importantly, nanostructured aluminum electrodes can enhance the performance of ultraviolet photodetectors through tuning the surface plasmons to increase the transmission of specific wavelength ranges and to enhance the electric field present within the device. We conducted 3D finite-difference time-domain (3D-FDTD) simulations to design and optimize nanopatterned aluminum electrodes in ultraviolet photodetectors with the device architecture of fused silica/nanopatterned Al/ZnO/F8T2:PC71BM/MoO3/Ag. The optical properties of active layers with different ratios of F8T2:PC71BM and film thicknesses were investigated using UV-Vis spectroscopy, photoluminescence, and ellipsometry. Their experimentally measured refractive indices and extinction coefficients were used in the 3D-FDTD simulations. The effects of the nanostructures’ geometrical parameters, such as Al film thickness, nanohole diameter and spacing, as well as the thicknesses of the active layer and electron transfer layer, on the plasmonics in the device were investigated. The optimal Al nanostructure and optimal device configuration for ultraviolet photodetection was determined.

9742-54, Session 12

**Nonlinear scattering in gold nanospheres**

Po-Ting Shen, National Taiwan Univ. (Taiwan); Cheng Wei Lin, Hsiang-Lin Liu, National Taiwan Normal Univ. (Taiwan);

Shi-Wei Chu, National Taiwan Univ. (Taiwan)

Nonlinear phenomena provide novel light manipulation capabilities and innovative applications. Recently, we discovered a new nonlinear phenomenon on the scattering of metallic nanoparticles by continuous-wave (CW) lasers and applied to super-resolution microscopy that allowed spatial resolution of plasmonic nanostructures down to 7/8

In this work, we elaborate the mechanism behind the nonlinear scattering of gold nanospheres. Based on literatures, the nonlinear mechanism of gold, in the case of four-wave mixing and optical Kerr effect, can be interband transition or hot electron. Another example is saturable absorption, whose nonlinearity is induced from the “bleaching” of plasmonic band. However, we found those mechanisms inadequate to explain our experimental results. Experimentally, we observed that heating the nanospheres by tens of kelvins caused more than 50% reduction in scattering, similar to the effect of CW lasers. We proposed the dominating factor to be “hot lattice” that was usually underestimated in literatures. To further verify the mechanism, the temperature dependence of permittivity of bulk gold is measured, and the corresponding nanoparticle scattering is calculated by Mie theory. Surprisingly, the contribution to nonlinearity due to the change of bulk permittivity is less than 10%. Therefore, we had to combine the permittivity change due to the hot lattice along with local field enhancement due to the nanoparticle plasmonic effects to obtain a satisfactory model for the experimental results. The innovative concept of hot lattice plasmonics not only opens up a new dimension for nonlinear plasmonics, but also predicts the potential of similar nonlinearity in other materials.

9742-55, Session 13

**Hybrid integration of high-Q nanocavities onto silicon-on-insulator**

Dorian Sanchez, Lab. de Photonique et de Nanostructures (France); Guillaume Crosnier, Lab. de Photonique et de Nanostructures (France) and STMicroelectronics SA (France); Alexandre Bazin, Univ. Gent (Belgium); Paul Monnier, Sophie Bouchoule, Grégoire Beaudoin, Isabelle Sagnes, Rama Raj, Lab. de Photonique et de Nanostructures (France); Fabrice Raineri, Lab. de Photonique et de Nanostructures (France) and Univ. Paris Diderot (France)

Photonic crystal (PhC) based nanocavities are believed to play a crucial in the achievement of ultracompact power efficient optoelectronic devices. In this context, the fabrication and the interfacing of such nanocavities made of active materials like III-V semiconductors is an important issue. One of the promising ways to achieve optical circuits which interface a large number of active nanocavities is to make use of the heterogeneous integration of III-V materials onto CMOS-compatible Silicon-On-Insulator (SOI) technology.

Here, we demonstrate the fabrication of passive high-Q (~10⁵) InP-based PhC nanobeam cavities integrated onto SOI waveguides. These cavities made of a ridge waveguide drilled with a row of equally sized holes are optically coupled to SOI waveguides through evanescent wave coupling. We study in particular the impact of the strength of this coupling on the properties of the nanocavities.

The study is conducted by performing transmission measurements of the structures backed by 3D-FDTD calculations. We show that the intrinsic cavity factor of our nanocavities, i.e. that of cavities uncoupled to the waveguides, is greatly influenced by the strength of the coupling. It means that our hybrid structures cannot be depicted by the coupled mode theory which supposes a non-dependence on the coupling of the intrinsic properties of each element. This indicates that special care has to be paid for the design of high-Q cavities integrated onto SOI in order to obtain optimized devices such as nanolasers or filters.
9742-56, Session 13

**Mid-IR high-index dielectric Huygens metasurfaces**

Jun Ding, Univ. of North Texas (United States); Li Zhang, Massachusetts Institute of Technology (United States) and University of Electronic Science and Technology of China (China); Han Ren, Mi Zhou, YuanKun Lin, Univ. of North Texas (United States); Juejun Hu, Massachusetts Institute of Technology (United States); Hualiang Zhang, Univ. of North Texas (United States)

High-index dielectric resonators (DRs) can support both magnetic and electric resonances in nature. By tailing the aspect ratio of the height and length of the DRs, the magnetic and electric dipole modes of the DRs can be manipulated to overlap spectrally, resulting in a full phase control of 2π and a near-unity transmission, which are essential requirements for a highly efficient metasurface. Thus, the high-index DRs could be deemed as Huygens' sources and can be used as the metaatom of a metasurface. Recently, Huygens' metasurfaces have been explored at the microwave and optical frequencies. However, it is still challenging to realize high performance mid-infrared (mid-IR) dielectric Huygens' metasurfaces. To address this issue, in this paper, highly efficient all-dielectric Huygens' metasurfaces working at mid-IR frequencies are demonstrated, which avoid the conduction loss compared to the plasmonic counterparts. The metaatom of the proposed Huygens' metasurface is a cubic DR or its derivatives by perturbing the shape of the cuboid in order to shift the DR's overlapping resonances at identical aspect ratios. PbTe is employed to construct the proposed metasurfaces, providing a high refraction index of around 5 at mid-IR frequencies. Two Huygens' metasurfaces for bending the transmitting waves are designed with a phase change between two consecutive metaatoms of π/4 and π/3, respectively. The proposed design concept is verified by the simulation results. The proposed all-dielectric Huygens' metasurfaces can find numerous applications in optical devices, including beam-forming, beam-steering, holography and dispersion control.

9742-57, Session 13

**Enhancement of effective quality-factor using asymmetric Mach-Zehnder interferometer with ring resonator for optical bio and chemical sensor**

Tae-Ryong Kim, Tae-Kyeong Lee, Myung-Gi Ji, Chung-Ang Univ. (Korea, Republic of); Hong-Seung Kim, Electronics and Telecommunications Research Institute (Korea, Republic of); Guem-Yoon Oh, Korea Electronics Technology Institute (Korea, Republic of); Byung-Hee Son, Chung-Ang Univ. (Korea, Republic of); Doo-Gun Kim, Korea Photonics Technology Institute (Korea, Republic of); Mi Jung, Young-Wan Choi, Chung-Ang Univ. (Korea, Republic of)

In this paper, we propose an asymmetric Mach-Zehnder interferometer (AMZI) combined with ring resonator (RR) structure to achieve high effective Q-factor for optical biological and chemical sensing, and demonstrate the device using silica substrate.

The structure of AMZI is composed of two arms, one of which has an additional length called phase delay line (PDL). Output signal of AMZI has out-of-phase condition due to PDL. Another of which combined with RR induces a resonance signal. Signals that come from AMZI and RR are interfered at the output end port of AMZI merged into one port. The interference signal at the output of AMZI with RR (AMZI-RR) present double peak signals when the out-of-phase condition is satisfied. As a result, the double peak shows a narrow full-width at half maximum compared to RR signals, and thereby effective Q-factor shows higher than the Q-factor of RR.

The AMZI-RR is designed with a 600 um of optical path length in RR, and lengths of PDL which is varied by 1, 2 and 3 times of RR, respectively. They are fabricated using silica substrate in which core and cladding are similar with optical fiber. Experiments of AMZI-RR based on silica show that the free spectral ranges of RR and AMZI are distinguished when resonance peaks of AMZI and RR are far from each other.

9742-58, Session 13

**Temperature-insensitive chemical sensor using a microfiber Mach-Zehnder interferometer**

Yeon-Jun Kim, Min-Seok Yoon, Jong Cheol Shin, Young-Geun Han, Hanyang Univ. (Korea, Republic of)

Fiber-optic sensors based on Mach-Zehnder interferometers (MZIs) have attracted much attention and have been widely used in many fields such as biosensor, pressure, and strain sensor because of its electro-magnetic immunity, fast response, easy fabrication, and low weight. However, since the conventional MZI sensors are significantly sensitive to temperature, it is required to suppress the temperature sensitivity for improvement of measurement accuracy. Many techniques to realize temperature-insensitive MZIs based on photonic crystal fibers have been proposed. In this paper, we propose a novel temperature-insensitive chemical sensor based on a microfiber MZI. The microfiber was fabricated by using a flame brushing technique with the motorized stage and computer-controlled heater. Since the effective refractive index of the microfiber is affected by its diameter, the thermo-optic effect and thermal expansion effect in the microfiber MZI can be dramatically reduced by adjusting the diameter and length of the microfiber. When the length and diameter of the microfiber were 4 cm and 5 um, respectively, the temperature sensitivity of the spatial frequency peak was successfully mitigated, which was measured to be 1.14 x10^-4 nm°C^-1. Since the strong evanescent field of the microfiber makes the microfiber-based MZI sensitive to the ambient index change, the proposed microfiber MZI can be applied to detection of the chemical concentration.

9742-59, Session 14

**Efficient and accurate modelling of quantum nanostructures**

Marina A. Ayad, Mohamed A. Swillam, The American Univ. in Cairo (Egypt); Salah Sabry A. Obayya, Zewail City of Science and Technology (Egypt)

An efficient sensitivity analysis approach for quantum nanostructures is proposed. The imaginary time propagation method (ITP) is utilized to solve the Time Dependent Schrödinger’s Equation (TDSE). Using this method, an extraction of all the modes and their sensitivity with respect to all the design parameters have been performed with minimal computational effort. The sensitivity analysis is done using the Adjoint Variable Method (AVM) and results are comparable to those obtained using Central Finite Difference Method (CFD) applied directly on the response level.
**9742-60, Session 14**

**Enhancing accuracy with subpixel smoothing for multiband effective-mass Hamiltonians of semiconductor nanostructures**

Chi-Ti Hsieh, Tung-Han Hsieh, Academia Sinica (Taiwan); Shu-Wei Chang, Academia Sinica (Taiwan) and National Chiao-Tung Univ. (Taiwan)

The spatial discontinuity of physical parameters at an abrupt interface may increase numerical errors when solving partial differential equations. Rather than generating boundary-adapted meshes for objects with complicated geometry in the finite-element method, the subpixel smoothing (SPS) replaces discontinuous parameters inside square elements that are bisected by interfaces in, for example, the finite-difference (FD) method, with homogeneous counterparts and matches physical boundary conditions therein. In this work, we apply the idea of SPS to the eight-band effective-mass Luttinger-Kohn (LK) and Burt-Forman (BF) Hamiltonians of semiconductor nanostructures. Two smoothing approaches are proposed. One stems from eliminations of the first-order perturbation in energy, and the other is an application of the Hellmann-Feynman (HF) theorem. We employ the FD method to numerically solve the eigenvalue problem corresponding to the multiband Schrödinger’s equation for circular quantum wires (QWRs). The eigenenergies and envelope (wave) functions for valence and conduction states in various III-V circular QWRs are examined. We find that while the procedure of perturbation theory seems to be more robust than that of HF theorem, the errors of both schemes are considerably lower than that without smoothing or with direct but unjustified averages of parameters. On the other hand, even in the presence of SPS, the numerical results for the LK Hamiltonian of nanostructures could still contain nonphysical spurious solutions with extremely localized states near heterostructure interfaces. The proper operator ordering embedded in the BF Hamiltonian mitigates this problem. The proposed approaches may improve numerical accuracies and reduce computational cost for the modeling of nanostructures in optoelectronic devices.

**9742-62, Session 14**

**Numerical analysis using 2D modeling of optical fiber poled by induction**

Ding Huang, A*STAR Institute of High Performance Computing (Singapore); Francesco De Lucia, Costantino Corbari, Noel Healy, Pier J. Sazio, Univ. of Southampton (United Kingdom)

Thermal poling, a technique to introduce effective second-order nonlinearities in silica optical fibers, has found widespread applications in frequency conversion, electro-optic modulation, switching and polarization-entangled photon pair generation. Since its first demonstration around 25 years ago, studies into thermal poling were primarily based on anode-cathode electrode configurations. However, more recently, superior electrode configurations have been investigated that allow for robust and reliable thermally poled fibers with excellent Chi(2) properties [1, 2]. Very recently, we experimentally demonstrated an electrostatic induction poling technique that creates a stable second-order nonlinearity in a twin-hole fiber without any direct physical contact to internal fiber electrodes whatsoever [3]. This innovative technique lifts a number of restrictions on the use of complex microstructured optical fibers (MOF) for poling, as it is no longer necessary to individually contact internal electrodes, thus, permitting arbitrary electrode configurations in MOFs. The optical mode confinement, dispersion and effective group index engineering possible using photonic crystal fibers poled via this method could open up completely new areas of highly efficient chi(2)-based fiber device applications.

In order to systematically implement these more advanced device embodiments, it is first necessary to develop comprehensive numerical models of the induction poling mechanism itself. To this end, we have developed 2D simulations of space-charge region formation using COMSOL finite element analysis. This work builds on current numerical models [4] that describe the migration of charge carriers inside silica fibers. We find good agreement between our simulations and real experimental conditions, thus forming the basis for novel developments in complex, thermally poled fiber geometries.


**9742-61, Session 14**

**Fine controlling of organic semiconductor by charged-beam irradiation effect**

Seokho Kim, Hyeong Tae Kim, Ho Jin Lee, Dong Hyuk Park, Inha Univ. (Korea, Republic of)

We study for fine controlling of characteristics about nano structures (e.g. particle, rod, ring, plate) which are irradiated by charged beam and consist of inorganic, organic materials. A charged-beam generated from a linear electron is irradiated onto inorganic and organic semiconductor. From laser confocal microscope (LCM) PL experiments, significant enhancements in the PL intensity are observed. The luminescent color of the inorganic semiconductor changes from blue to red color depending on the variation of charged-beam dosage. These results might originate from the de-doping effect and the conformational modification through charged-beam irradiations. Conformational changes of the charged-beam irradiated organic semiconductor are confirmed by LCM single Raman and ultraviolet-visible (UV/Vis) absorption spectra. From UV/Vis absorption spectra, it is observed that the π-π* transition peak and the doping induced bipolaron peaks of the inorganic or organic semiconductor dramatically vary with charged-beam irradiating conditions.
9743-1, Session 1

High-efficiency photoelectrochemical water-splitting on III-nitride nanowire arrays (*Invited Paper*)

Zetian Mi, McGill Univ. (Canada)

Solar water splitting is one of the key steps of artificial photosynthesis for the conversion of solar energy into fuels. We have demonstrated that the quantum efficiency of water splitting on InGaN nanowires can be enhanced by nearly two orders of magnitude by tuning the surface Fermi-level. An apparent quantum efficiency of >12% is achieved for overall pH-neutral water splitting under visible light illumination. Moreover, we have demonstrated p-type InGaN/GaN tunnel junction nanowire photocathodes on Si solar cell wafer, which exhibit relatively stable hydrogen generation with an applied bias photon-to-current efficiency of 8.7% and unity Faradic efficiency for hydrogen generation.

9743-2, Session 1

Polycrystalline absorbers: unraveling grain boundary properties (*Invited Paper*)

Mariana Bertoni, Arizona State Univ. (United States)

No Abstract Available

9743-3, Session 1

Advances with vertical epitaxial heterostructure architecture (VEHSA) phototransducers for optical to electrical power conversion efficiencies exceeding 50 percent (*Invited Paper*)

Simon Fafard, Francine Proulx, Azastra Opto Inc. (Canada); Mark C.A. York, uSherbrooke (Canada); Matthew Wilkins, Christopher E Valdivia, University of Ottawa (Canada); Michal Bajcsy, Dayan Ban, University of Waterloo (Canada); Abdelatif Jaouad, Bousairi Bouzazi, richard Ares, Vincent Aimez, uSherbrooke (Canada); Karin Hinzer, University of Ottawa (Canada) and uSherbrooke (Canada); Denis Masson, Azastra Opto Inc. (Canada)

A monolithic compound semiconductor phototransducer optimized for narrow-band light sources was designed for achieving conversion efficiencies exceeding 50%. The III-V heterostructure was grown by MOCVD, based on the vertical stacking of a number of partially absorbing GaAs n/p junctions connected in series with tunnel junctions. The thicknesses of the p-type base layers of the diodes were engineered for optimal absorption and current matching for an optical input with wavelengths centered for example near 830nm. The device architecture allows for improved Voc generation in the individual base segments due to efficient carrier extraction while simultaneously maintaining a complete absorption of the input photons with no needs for complicated fabrication processes or reflecting layers. Progress for device outputs achieving in excess of 12V will be reviewed in this talk.

9743-4, Session 2

Energy and entropy currents for nanoscaled optoelectronics (*Invited Paper*)

Fabienne Michelini, Katawoura Beltako, Institut Matériaux Microélectronique Nanosciences de Provence (France); Adeline Crépieux, Ctr. de Physique Théorique (France)

Following the pioneering works of Jauho and Mahan, we derived the formal expressions of all particle, energy and heat currents inside a nanodevice only interacting with light. We relied on the Keldysh’s methodology within the self-consistent Born approximation for the electron-photon interaction (electron-phonon and electron-electron scattering are ignored here), and we tackled these derivations through the knowledge of mixed Green functions that combine electron and photon operators.

As a matter of fact, these expressions allow to formulate the entropy current flowing in the three reservoirs of the optoelectronic nanodevice, namely the two electronic reservoirs (e.g. electrical lines) and the photon bath (e.g. the sun). Interestingly, we show that the entropy current results from a competition between the reversible Carnot efficiency and the photovoltaic (or electroluminescent) device efficiency, in other words, between the thermoelectric engine made by the three thermal reservoirs and the electron-photon energy conversion. Such a competition makes the entropy production in the reservoirs change sign.

The obtained current expressions bring new insights into optoelectronics at the nanoscale, in particular about the definition of the optoelectronic efficiency, the meaning of the entropy current and the effective and local thermodynamic parameters that could be defined inside the active part of the device, here the absorber.

These results naturally combine optoelectronics and thermodynamics for a unified picture of energy harvesting at the nanoscale.
9743-5, Session 2

Numerical modeling of photon recycling and luminescence coupling in non-ideal multijunction solar cell

Mengyang Yuan, Zheng Lyu, Tsinghua Univ. (China); Jieyang Jia, Yusi Chen, Stanford Univ. (United States); Yi Liu, Peking Univ. (China); Yijie Huo, Yu Miao, James S. Harris, Stanford Univ. (United States)

For solar cells composed of direct bandgap semiconductors such as GaAs, the performance can be significantly improved by utilizing photon recycling and luminescence coupling effects. Accurate modeling with those effects may offer insightful guidance in designing such devices. Previous research has demonstrated different numerical models on photon recycling and luminescent coupling. However, most of those works are based on complicated theoretical derivations and idealized assumptions, which made them hard to implement. In addition, very few works provide method to model both photon recycling and luminescent coupling effects. In this paper, we demonstrate an easy-to-implement but accurate numerical model to simulate those effects in multijunction solar cells. Our numerical model can be incorporated into commonly used equivalent circuit model with high accuracy. The simulation results were compared with experimental data and exhibit good consistency. Our numerical simulation is based on a self-consistent optical-electrical model that includes non-ideal losses in both the single junction and the tandem device. Based on the numerical analysis, we modified the two-diode circuit model by introducing an additional current control current sources to represent the effects of both photon recycling and luminescence coupling. The effects of photon recycling on the diode equation has been investigated based on detailed-balance model, accounting for internal optical losses. We also showed the practical limit of performance enhancement of photon recycling and luminescent coupling effects. This work will potentially facilitate the accurate simulation of solar cell with non-ideal effects, and provide more efficient tools for multijunction solar cell design and optimization.

9743-6, Session 2

Nanostructured plasmonic electrode design guided by simulation for enhanced performance of ITO-free organic solar cells

Beau J. Richardson, Qiuming Yu, Univ. of Washington (United States)

Organic solar cells (OSCs) offer significant potential to lower manufacturing costs of photovoltaics and enable large area, lightweight, and highly flexible devices. Integrating plasmonic nanostructures into OSCs is one promising way to both maximize light absorption and replace the high cost and brittle indium tin oxide (ITO) that is typically used as a transparent electrode. In this work, we designed and fabricated plasmonic nanostructured electrodes to replace ITO in high efficiency OSCs. We used Finite-Difference Time-Domain (FDTD) electromagnetic simulations to design the nanohole size and pitch to maximize both the intensity of plasmon-induced electric fields and light absorption near the bandgap of the active layer. FDTD simulations were also used to determine the optimal layer thicknesses of the active and interfacial layers to maximize light trapping via plasmonic cavity effects. We used a blend of [6,6]-phenyl C71-butyric acid methyl ester (PC71BM) and the low-bandgap semiconducting polymer thiophene[3,4-b]thiophene/benzothiophene (PTB7) to make the bulk heterojunction active layer in both inverted and conventional devices. Nanostructured plasmonic electrodes were deployed in devices fabricated on bare glass and on bare flexible PET and compared to control devices on ITO-coated glass and ITO-coated PET. The effects of these plasmonic electrodes on light absorption and omnidirectional light harvesting, and increased robustness of the flexible devices will be discussed. To our knowledge, this is the first time nanostructured plasmonic electrodes have been applied to ITO-free, flexible OSCs and the learnings presented here can be utilized to fabricate high performance electrodes for widespread photovoltaic systems.

9743-7, Session 2

Development of numerical modeling program for organic/inorganic hybrid solar cells by including tail/Interfacial states models

Kuan-Ying Ho, I-Hsin Lu, Yuh-Renn Wu, National Taiwan Univ. (Taiwan)

A simulation software is developed for modeling the organic/inorganic hybrid solar cells. The simulation software is based on solving the Poisson’s and drift-diffusion equation by utilizing the 1D/2D finite element method (FEM). As we know, to present the hopping behavior of carriers in the organic material and organic/inorganic interface is critical for modeling organic/inorganic hybrid solar cells. Hence, a Gaussian distribution function or an exponential decay of tail states model is added to simulate the carrier transportation in the inorganic material. Such Gaussian distributed tail states are placed around the LUMO and HOMO of the organic material and provide a path for carriers generated in the organic material to hop in and then move to adjacent inorganic material for further transportation. Also, the function of field dependent mobility is developed and considered to better describe the carriers in the organic material.

In this research, a planar hybrid solar cell is set up as the simulation model. The simulation model is constructed with PEDOT:PSS as the organic material and silicon substrate as the inorganic material. Influences of the different Gaussian distribution of tail states are studied and analyzed, including the effects of various values of the full width at half maximum (FWHM) as well as the various density of tail states. To verify the software developed for simulating the organic/inorganic hybrid solar cells, experimental results are set as the reference for J-V curve fitting, where a good agreement is reached by the fitting experimental results.

9743-8, Session 3

Nanospectroscopy of PV devices (Invited Paper)

Marina S. Leite, Univ. of Maryland, College Park (United States)

As of today it is still unclear where non-radiative recombination takes place within polycrystalline photovoltaic (PV) devices, such as CdTe and CIGS. Despite the remarkable work on investigating the electrical properties of grains and grain boundaries in both materials, there is still debate weather the boundaries act or not as centers for non-radiative recombination, which ultimately constrains the open-circuit voltage (Voc) of these PV technologies. Here we apply scanning photocurrent microscopy and illuminated Kelvin probe force microscopy to resolve the external quantum efficiency (EQE) and the Voc in both types of device, with nanoscale spatial resolution. For that, we use NSOM probes a local source of excitation, allowing for spatially and spectrally resolved measurements of the local optoelectronic response of the devices, while mimicking the power density operation conditions of real devices. Combined, these new tools provide a full picture of the local response of PV devices, including an indirect measurement of carrier local recombination and collection properties within the material. We apply our new metrology to thin-film compound PV and find that the EQE and Voc in CIGS devices varies locally by more than 50% and 200 mV between grains, respectively. We correlate these variations with the different grain orientations present in the samples, and find a direct correlation between the material and the device local performance. For CdTe, we find that at short wavelengths (<600 nm), when light is absorbed near the exposed surface, the EQE is relatively small because of surface recombination. However, close to the material bandgap (860 nm), the EQE...
9743-11, Session 3

**Local transport properties investigation by correlating hyperspectral and confocal luminescence images**

Gilbert El-Hajje, Daniel Ory, Myriam Paire, Electricité de France (France); Jean-Francois Guillemoles, Tokyo Univ. (Japan); Laurent Lombet, Ctr. National de la Recherche Scientifique (France)

The study presents a correlation between two imaging setups: The Hyperspectral Imager (HI) and the Scanning Confocal Microscope (SCM). These techniques are capable of measuring crucial photovoltaic parameters such as maps of the bang gap energy [2][3], external quantum efficiency [1] and the quasi-Fermi levels splitting [4].

On one hand, the SCM yields micrometric maps of time-resolved photoluminescence (TRPL) decays on a CIGS solar cell. Based on these TRPL decays and the analysis of transport properties in CIGS solar cells [6], the authors extracted both maps of recombination centers-related and trapping lifetimes. A map of the spatial distribution of the shallow trap states density is also established. Excitation wavelength dependence shows the impact of the front layers on the PV properties.

On the other hand, contactless mapping of the absolute quasi-Fermi levels splitting (??) was performed using the HI imager on the same, previously investigated, solar cell area. The ?? map is correlated with the SCM map that illustrates the spatial dominance of the underlying shallow trap states density. This original approach provides a better understanding of the spatial fluctuations of ?? induced by local fluctuations of the charge carriers transport properties.

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9743-9, Session 3

**Characterization and modeling of chalcogenide materials and the resulting photovoltaic devices (Invited Paper)**

Angus A. Rockett, M. Tuteja, X. He, P. Martin, D. Heinzel, Y. Liu, N. Johnson, Univ. of Illinois at Urbana-Champaign (United States)

This talk presents selected results of characterization of CdTe and (Cu,Ag) (In,Ga)Se₂ (“CIGS”) materials and the connection of the characterization results to photovoltaic device performances. Examples of characterization include photo modulated scanning microwave impedance microscopy of CdTe produced by sputtering and closed space sublimation, and nanochemical, nanostructural, and optoelectronic analyses of CIGS device materials and single crystal epitaxial layers. The results are connected to device performances through drift-diffusion and stochastic modeling developed by our group.

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9743-10, Session 3

**Direct observation of electrons transported in second conduction mini-band of a semiconductor superlattice by visible-light photoemission spectroscopy**

Fumiaki Ichihashi, Kenji Nishitani, Xinyu Dong, Takahiko Kawaguchi, Makoto Kuwahara, Takahiro Ito, Shunta Harada, Miho Tagawa, Toru Ujihara, Nagoya Univ. (Japan)

Intermediate-band solar cells (IBSCs) have attracted much attention for their potential to achieve high conversion efficiencies. The concept of IBSC is to increase photocurrent by utilizing electrons excited to a conduction band via intermediate bands. Mini-bands formed in an ordered superlattice structure are often utilized for the intermediate-bands. Higher-order mini-bands are expected to operate as “path ways” for conduction electrons with high energy. However, because the electrons in the higher-order mini-bands have not been measured directly, it is not clear whether the higher-order mini-bands can be used as the path ways or not. Thus, it is required to establish a groundbreaking method to evaluate the conduction electrons. We have proposed visible-light photoemission spectroscopy (VPS), which is a novel angle-resolved photoemission spectroscopy to directly observe conduction electrons. In the VPS, a surface with a negative electron affinity state, which can be realized by the deposition of Cs atoms, is utilized to emit the conduction electrons into a vacuum from a semiconductor. In this study, we obtained energy distribution spectra of conduction electrons in an InGaAs/GaAsP superlattice by VPS. When the excitation light with higher energy than a band gap between the second conduction mini-band and the first heavy-hole mini-band was irradiated, the electrons with energy in the range of the second conduction mini-band appeared. Furthermore, the conduction electrons in the second conduction mini-band increased with increasing the excitation photon energy. These results indicate that a part of electrons were actually transported in the second conduction mini-band.

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9743-12, Session 3

**Calibration standards and measurement accuracy of absolute electroluminescence and internal properties in multi-junction and arrayed solar cells**

Masahiro Yoshita, Lin Zhu, Changsu Kim, The Univ. of Tokyo (Japan) and Japan Science and Technology Agency (Japan); Toshimitsu Mochizuki, National Institute of Advanced Industrial Science and Technology (Japan); Tetsuya Nakamura, Mitsuuru Imaizumi, Japan Aerospace Exploration Agency (Japan); Shaoqiang Chen, East China Normal Univ. (China); Hidehiro Kubota, ATTO Corp. (Japan) and Japan Science and Technology Agency (Japan); Yoshihiko Kanemitsu, Kyoto Univ. (Japan) and Japan Science and Technology Agency (Japan); Hidefumi Akiyama, The Univ. of Tokyo (Japan) and Japan Science and Technology Agency (Japan)

We developed methodology and calibration standards of absolute electroluminescence (EL) measurement for CONTACT-LESS evaluations of various internal properties of multi-junction (MJ) and arrayed solar cells, such as internal current-voltage curves, open-circuit voltages, external and internal radiative efficiencies, and luminescence-coupling efficiency. Though relative EL measurements are now very widely used particularly for MJ...
solar cells, the relative EL only gives relative voltages or relative radiative efficiencies, for example, and thus needs additional voltage measurements in CONTACT with samples. To establish characterizations based on absolute EL measurement, calibration methods and accuracy are crucially important. We compared several independent calibration methods, such as 1) step-by-step-calibrated EL imaging system, 2) face-to-face proximity measurement with a large-area photodiode, 3) integration-sphere systems, and 4) homemade planar LEDs with a circular aperture that we propose to supply as useful and convenient calibration standards. The comparison clarified both advantages and disadvantages of respective methods, and consistency within 30% uncertainty. This results in measurement accuracy within 7 meV uncertainty for current-dependent internal voltages including open-circuit voltages, and that within 30% uncertainty for external and internal radiative efficiencies, and luminescence-coupling efficiency. We applied these methods to measure absolute EL and various internal properties of subcells in monolithic satellite-use InGaP/GaAs/Ge 3J cells, reference 2J and 1J cells, and crystal-Si solar-cell arrays. It turned out that 1J cells have shown acceptable agreement between open-circuit voltages measured via contact-less absolute EL and via a voltmeter, but that MJ cells have shown distinguishable deviations beyond the above-mentioned uncertainty.

9743-13, Session 3
Carrier collection mechanism in the strain-balanced InGaAs/GaAsP super-lattice solar cells by investigating the temperature changes of the surface photovoltage, photoluminescence, and piezoelectric photothermal signals
Atsuhiko Fukuyama, Tsubasa Nakamura, Univ. of Miyazaki (Japan); Takanori Usuki, The Univ. of Tokyo (Japan); Kouki Matsuoichi, Univ. of Miyazaki (Japan); Kasidit Toprasertpong, Masakazu Sugiyama, Yoshiaki Nakano, The Univ. of Tokyo (Japan); Tetsuo Ikari, Univ. of Miyazaki (Japan)

To investigate the carrier collection mechanism in the strain-balanced InGaAs/GaAsP multiple-quantum-well (MQW-) or super-lattice (SL-) inserted GaAs p-i-n solar cell structure samples, three non-destructive methodologies, surface photovoltage (SPV), photoluminescence (PL), and piezoelectric photothermal (PPT) spectroscopies, were adopted. They detect the thermal carrier escape from quantum well and radiative and non-radiative carrier recombination, respectively. For MQW-inserted sample, PL and PPT signal intensities increased with decreasing temperature, whereas SPV decreased. Based on the rate equations considering above three relaxation processes, the temperature dependencies of all PL, PPT, and SPV were well fitted by using the activation energies of thermal escape $E_{th} = 72$ and non-radiative recombination $E_{rr} = 20$ meV. A value of $E_{th}$ corresponded to the potential barrier height of electron. On the contrary, for SL-inserted sample, SPV signal intensity also increased with decreasing temperature. To explain, alternative process of tunneling within the mini-band formed by the overlapping of electron wave functions were considered. In this fitting procedure, we assumed $E_{th} = 0$ meV in the above rate equations to represent the carrier tunneling without thermal escape to outside of barrier. Tunneled carriers accumulate the surface and finally cause the surface potential changes (SPV). As a result, temperature dependent PL, PPT, and SPV signal intensities for SL-inserted sample could be well explained by considering carrier tunneling. The combination of the three non-destructive methodologies provided us new insights for optimizing the MQW and SL components to further improve the cell performance.

9743-50, Session 3
A novel measurement method of luminescent coupling in multijunction solar cells based on small signal method
Zheng Lyu, Mengyang Yuan, Tsinghua Univ. (China); Jieyang Jia, Stanford Univ. (United States); Taner Bilir, Solar Junction (United States); Yi Liu, Peking Univ. (China); Yu Miao, Yijie Huo, James S. Harris, Stanford Univ. (United States)

Luminescent coupling effects are considered crucial for the performance of multijunction solar cells. To model the luminescent coupling effects, luminescent coupling efficiency is commonly introduced into the model to indicate the strength of luminescent coupling. Therefore, the measurement of luminescent coupling efficiency is crucial for multijunction solar cell modeling and design.

Previous research works have demonstrated the extraction of luminescent coupling efficiency from isotype J-V curves, or from sun-Jsc measurement. However, those methods typically require additional cell fabrication or special experimental setup, and the measurement results are limited in accuracy. In this work, we report a novel approach based on external quantum efficiency (EQE) measurement. The method can directly measure the luminescent coupling efficiency of a multijunction solar cell without extra fabrication. In addition, this method can measure the wavelength dependence of luminescent coupling efficiency. We conducted measurements using this method on two-junction and three-junction solar cells, and showed that the results are consistent with the simulation results and measurement results using the sun-Jsc method. We also observed the wavelength dependence of luminescent coupling efficiency from the measurement results.

In conclusion, we reported a novel approach in measuring luminescent coupling efficiency of multijunction solar cells, and demonstrated the wavelength dependence of the coupling efficiency. Our work provides verification to other currently used luminescent coupling efficiency measurement methods, and can potentially lead to a deeper understanding of luminescent coupling effects as well as more effective design of multijunction solar cells.

9743-14, Session 4
Computational optimization and solution-processing of thick and efficient luminescent down-shifting layers for photovoltaics
Anastasiia Solodovnyk, Christopher Kick, Bayerisches Zentrum für Angewandte Energieforschung e.V. (Germany); Andres Osvet, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Hans J. Egelhaaf, Edda Stern, Bayerisches Zentrum für Angewandte Energieforschung e.V. (Germany); Miroslaw Batentschuk, Karen K. Forberich, Friedrich-Alexander-Univers. Erlangen-Nürnberg (Germany)

Luminescent down-shifting (LDS) is a simple, powerful tool for increasing the range of solar irradiance that can be efficiently utilized by photovoltaic devices. We developed an optical model to simulate the ideal optical properties (absorbance, transmittance, luminescence quantum yield, etc.) of LDS layers for solar cells. We evaluated which quantum efficiencies and which optical densities are necessary to achieve an improvement in solar cell performance. In particular we considered copper indium gallium diselenide (CIGS) devices. Our model relies on experimentally measured data for the transmission and emission spectra as well as for the external quantum efficiency (E QE) of the solar cell. By combining experimental work with this
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Optical model, we aim to propose an environmentally friendly technology for coating thick (300-500 nm), efficient luminescent down-shifting layers. These layers consist of polyvinyl butyral (PVB) and organic UV-converting fluorescent dyes. The absorption coefficients and luminescence quantum yields of the dyes were determined both in a solution of the solvent benzyl alcohol and in the solid polymer layers. This data shows that the dyes retain luminescence quantum yields of approximately 90% after solution-processing. The produced layers were then applied to CIGS solar cells, thereby improving the EQE of the devices in the UV region. At a wavelength of 390 nm, for instance, the EQE increased from 18% to 53%. These values closely agree with the theoretically calculated ones. The proposed technology, thus, provides a pathway toward efficient, fully solution-processable encapsulated photovoltaic modules.

9743-15, Session 4

Light-trapping in ultra-thin solar cells fabricated by direct nanoimprint of sol-gel derived films
Andrea Cattoni, Alexandre Gaucher, Nicolas Vandamme, Julie Goffard, Lab. de Photonique et de Nanostructures (France); Marco Faustini, Collège de France (France); Nathalie Bardou, Aristide Lemaitre, Lab. de Photonique et de Nanostructures (France); Negar Naghavi, Institut de Recherche et Développement sur l’Energie Photovoltaïque (France); Pere Roca i Cabarrocas, Ecole Polytechnique (France); Jean-François Guillemoles, Institut de Recherche et Développement sur l’Energie Photovoltaïque (France); Stéphane Collin, Lab. de Photonique et de Nanostructures (France).

Light trapping in solar cells based on dielectric and metallic nanostructures has the potential for improving light absorption thus reducing the thickness of the semiconductor absorber. In this work we apply a new replication technique called Degassing Assisted Patterning to the direct nano-embossing of high refractive index TiO2 sol-gel derived films. The technique makes use of soft polymeric stamps to nanoimprint nanostructures at 15 nm scale over large surface area and without the use of an imprinter machine. We design and fabricate different light trapping structures based on diffractive anti-reflection coatings and nanostructured TiO2/metal mirrors on Silicon, GaAs and CIGS solar cells. We demonstrate short-circuit current of 25.3 mA/cm2 in 3µm-thick crystalline Silicon solar cell and 21.5mA/cm2 in 220 nm-thick GaAs solar cell.

9743-16, Session 4

Up-conversion equivalent circuit for photovoltaic and photo-electrolysis cells
Gavin Conibeer, Santosh Shrestha, Shujuan Huang, Binesh Puthen-Veettil, The Univ. of New South Wales (Australia).

Up-conversion has been applied to silicon solar cells using erbium doped phosphors with up to 0.5% increase in efficiency (Goldschmidt 2014), but only at very high effective concentration ratios. Problems of this high concentration and the very narrow band width for absorption are inherent for Er based UC. An alternative is to use the equivalent circuit of an up-converter, two below bandgap solar cells connected in series to pump an above band gap LED, as suggested by Trupke SOLMAT 2005, but not yet attempted experimentally. The advantages are: a much wider absorption band width in the long wavelength PV cells and a reduction in the dependence on the square of the light intensity, as carriers generated in the long wavelength cell have very long lifetimes. This approach is demonstrated for both absorption of below Si band gap light in long wavelength cells to pump a GaAs LED so as to sensitize a Si solar cell and for the more optimal absorption in in-series Si cells pumping a GaN LED for electrochemical cell sensitisation. Results on the current enhancement in such devices will be presented, on the optical optimisation required and on modelling of the whole system. Routes to fabricating more realistic devices will also be discussed.

9743-17, Session 4

Rapid 2D incoherent mirror fabrication by laser interference lithography and wet etching for III-V MQW solar cells
Wei Wang, Alexandre Freundlich, Univ. of Houston (United States).

Optimization of non-planar antireflective coating and back- or front- surface texturing is widely studied to further reduce the reflection losses and increase the sunlight absorption path in solar cells. Back reflectors have been developed from perfect mirror to textured mirror in order to further increase light path, which can significantly improve the efficiency and allow for much thinner devices. A Lambertian surface, which has the most random texture, can theoretically raise the light path to 4n2 times that of a smooth surface. It’s a challenge however to fabricate ideal Lambertian texture, especially in a fast and low cost way. In this work we have developed a method to overcome this challenge that combines the use of laser interference lithography (LIL) and selective wet etching. The approach allows for a rapid wafer scale texture processing with sub-wavelength (nano-) scale control of the pattern and the pitch. The technique appears as being particularly attractive for the development of ultra-thin III-V devices, or in overcoming the weak sub-bandgap absorption in devices incorporating quantum dots or quantum wells. Preliminary results on the technique for the development of incoherent back reflector for 113 eV MQW solar cells will be presented. And this application is especially useful for MQWs embedded in the bottom cell, which enables longer effective light path as well as absorption without adding the number of QWs that has a trade-off in Voc.

9743-18, Session 4

Silicon solar cell using optimized intermediate reflector layer
Mohamed A. Swillam, Ahmed Emad, The American Univ. in Cairo (Egypt).

Thin film silicon based photovoltaic cells, have the advantages of using low cost nontoxic abundant constituents and low thermal manufacturing budget. However, better long-term efficiencies need to be achieved overcoming its inherent bad electrical properties of amorphous and/or microcrystalline Silicon. For the goal of achieving best results, multijunction cells of amorphous and microcrystalline silicon thin layers are industrially and lab utilized in addition to using one or more light management techniques such as textured layers, periodic and plasmonic back reflectors, flattened reflective substrates and intermediate reflector layer (IRL) between multijunction cells. The latter, IRL, which is the focus of this paper, serves as spectrally selective layer between different cells of the multijunction silicon thin film solar cell. IRL reflects to the top cell short wavelength while permitting and scattering longer ones to achieve the best possible short circuit current.

In this study a new optimized periodic design of intermediate reflector layer in micromorph (two multijunction cells of Microcrystalline and Amorphous Silicon) thin film solar cells is proposed. The optically simulated short circuit current reaches record values for some thickness designs when using all-ZnO design and even better results is shown if Lacquer material is used in combination with ZnO. The design methodology used in the paper can be easily applied to different types of IRL materials and also extended to triple and the relatively newly proposed quadruple thin films solar cells.
Design and fabrication of a micro CPV system based on Cu(In,Ga)Se₂ microcells array

Sebastien Jutteau, Myriam Paire, Laurent Lombez, Institut de Recherche et Développement sur l’Energie Photovoltaïque (France); Jean-François Guillemoles, Institut de Recherche et Développement sur l’Energie Photovoltaïque (France)

Miniaturized cells are increasingly used in CPV systems due to the lower influence of the temperature on series resistance. In parallel to the development of ultra-small III-V concentrator cells, we propose in this work microconcentration systems adapted to thin film microcells arrays. Due to the miniaturization, the complete system is expected to be very compact, lightweight, enabling a simple tracking.

First, a numerical study has been performed to evaluate an optimal design with only plano-spherical microlenses with a geometrical ratio of 100x and an acceptance angle around +/− 3°. The final design, with two levels of optics, achieves a concentration ratio of 85x at 0° and 84x at 3° of incidence. Tolerances of fabrication and alignment have been investigated.

Second, a fabrication process has been developed to realize the designed system. This process is based on photolithography to create cylinders and reflow of the photoresist to achieve a spherical shape. The geometry of the lens, and so the radius of curvature, is controlled by the initial volume of the cylinder. Arrays of 2500 microlenses with a diameter between 300 and 500μm and a focal length around 1mm have been created.

Finally, we propose a first prototype coupling 2500 microcells and microlenses arrays for middle concentration applications. Characterizations under solar simulator have been performed and we obtained a concentration ratio of 55x. Additional experiments are being realized to improve the alignment of the optics and come closer to the theoretical concentration ratio of 85x.

Carrier scattering processes and low energy phonon spectroscopy in hybrid perovskites crystals (Invited Paper)

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Solution-processed organometallic perovskite based solar cells have emerged as the most promising thin-film photovoltaic technology. There have been few reports on understanding the photo-stability in perovskite solar cell devices which have attributed the hysteresis and degradation in the device performances to either UV assisted degradation of the active layer, ion migration, ferroelectric domains. Such degradation over time with solar illumination has the potential to seriously undermine the commercialization of perovskite-based solar cells. Here we report on the photo-degradation and fast self-healing of the photocurrent in large grain perovskite solar cells of methyl ammonium (MA) lead iodide under constant illumination [1]. We attribute the photocurrent degradation to the formation of light-activated meta-stable trap states. Experimental characterization and theory suggest their origin to the formation of localized charged states strongly coupled with local structural lattice distortions and MA quasiatomic orientational configurations. A DFT [2] and symmetry-based analysis [3] of the fundamental processes leading to electron-phonon and electron-MA coupling will be presented. Our results provide insight towards the material design for photo-stable perovskite solar cell and a better understanding of the fundamental properties of these materials.

Dielectric properties of hybrid perovskites and drift-diffusion modeling of perovskite cells

Laurent Pedesseau, Institut National des Sciences Appliquées de Rennes (France); Mikaël Kepenekian, Institut des Sciences Chimiques de Rennes (France); Daniel Saporì, Yong Huang, Alain Rolland, Alexandre Beck, Charles Cornet, Olivier Durand, Shijian Wang, Institut National des Sciences Appliquées de Rennes (France); Claudine Katan, Institut des Sciences Chimiques de Rennes (France); Jacky Even, Institut National des Sciences Appliquées de Rennes (France)

A new method [1] is introduced to understand the dielectric properties of both 3D and layered hybrid organic-inorganic perovskites (HOP). It shows the real influence of inorganic as well as organic layers, beyond the standard approximation for dielectric constant profiles with abrupt interfaces. Then, this method is applied for 3D HOPs, including or not the influence of ionic relaxation. The influence of the electronic surface states is also revealed for different thicknesses of MAPbI₃ nanoplatelets.

A one dimensional numerical simulation of a drift diffusion model is performed for a Perovskite on Si tandem cell structure, with an all-made Si tunnel junction. A perfect current matching between top and bottom cells is required to obtain the optimum efficiency of the tandem cell. Therefore, the performances of the cell in terms of short circuit current Jsc, open circuit voltage Voc, filling factor FF as well as cell efficiency are analyzed with a maximum efficiency of 27% for a MAPbI₃ alloy.

Design optimization of thin-film/wafer-based tandem junction solar cells using analytical modeling

Lauren M. Davidson, Fatima Toor, The Univ. of Iowa (United States)

There is no modeling software available which can successfully simulate a tandem solar cell consisting of both wafer and thin-film absorbers without modification of the source code. PCID and SCAPS solar cell modeling software are only suitable for either just wafer-based or just thin-film absorbers and convergence errors occur when a tandem cell that is based on a thin-film absorber and a wafer-based absorber is modeled. We have developed an analytical model, designed using Matlab coding and solar cell physics presented in Sze and Ng, Physics of Semiconductor Devices. 3rd ed. 2006: Wiley-Interscience, to model single junction and tandem junction solar cells. In our model we can parametrize solar cell inputs, such as surface reflectivities, doping densities, minority carrier lifetimes, diffusion lengths,
Due to quantum confinement, different lines of the spectral current may contact the absorber, tunnel coupled to a double barrier heterostructure, the selective function formalism (NEGF). We want to decipher these effects by means of the first quantum transport effects that makes the concept. We have found that a weak interaction with phonons may favor the spectral current line on the resonant level of the selective contact, which leads to highest currents. For a stronger electron-phonon interaction, carriers fill the absorber well and the current decreases. Besides, when the barrier height of the selective contact increases, non-resonant tunnelling through the shallow absorber levels decreases until an upper level falls in the absorber well. It is thus possible to tune the non-resonant tunnelling line and then channel the spectral current through the resonant level of the selective contact, which maximizes the current. Our work thus shows possible hot carrier cell working and avenues to control and optimize it.

9743-26, Session 6
Third generation hot carrier solar cells: paths towards innovative energy contacts structures
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Hot carrier solar cells [1] are very promising for the achievement of high yield photovoltaic systems [2]. The community has first successfully focused on the required material properties to optimize the generation of hot carrier populations [3, 4]. The next challenge is the development of a new type of contact enabling to convert the excess of kinetic energy of the carriers [4]. Different structures and characteristics have been proposed in the literature [4], and some successful experiments have been done [5].
We have modeled in details such contacts with self-consistent coherent transfer matrix for the study of resonant tunneling diodes (RTDs), and non-equilibrium Green function technique (NEGF with ASE-GPAW) has been used to find suitable structures involving colloidal quantum dots.
We found that the transmission function of the contact is the most relevant quantity to characterize all transport properties: a clear fundamental relationship between thermoelectricity and photovoltaics is shown. The models will be discussed in view of the experimental results on structures being now characterized. This approach sheds new light on the complementarities of thermoelectricity and photovoltaics for hot carrier solar cell design.

9743-25, Session 6
Hot-carrier solar cell NEGF-based simulations
Nicolas Cavassilas, Fabienne Michelini, Marc Bescond, Thibault Joie, Institut Matériaux Microélectronique Nanosciences de Provence (France)
Since Ross and Nozik showed that hot carrier cells have a huge potential beating the Shockley-Queisser limit in 1982, very few improvements have been achieved toward its realization likely due to the intricate nanoscale effects that makes the concept.
We want to decipher these effects by means of the first quantum transport simulations of a hot-carrier solar cell using the non-equilibrium Green’s function formalism (NEGF). We focus on InAs-based junctions made of a large quantum well, the absorber, tunnel coupled to a double barrier heterostructure, the selective contact. Due to quantum confinement, different lines of the spectral current may carry hot electrons through the junction. We remarked the line on the lower-lying resonant level of the selective contact, and lines pinned on absorber levels close to the barrier top of the selective contact.
We then found that a weak interaction with phonons may favour the spectral current line on the resonant level of the selective contact, which leads to highest currents. For a stronger electron-phonon interaction, carriers fill the absorber well and the current decreases.
Besides, when the barrier height of the selective contact increases, non-resonant tunnelling through the shallow absorber levels decreases until an upper level falls in the absorber well. It is thus possible to tune the non-resonant tunnelling line and then channel the spectral current through the resonant level of the selective contact, which maximizes the current.
Our work thus shows possible hot carrier cell working and avenues to control and optimize it.

9743-27, Session 6
Practical absorber and energy-selective contacts for hot carrier solar cells
Santosh Shrestha, Simon Chung, Yuanxun Liao, Wenkai Cao, Qiuyang Zhang, Gavin Conibeer, The Univ. of New South Wales (Australia)
The Hot carrier solar cell (HCSC) is a promising third generation photovoltaic concept with predicted efficiency of 65% under one sun
illuminated and over 85% at maximal concentration [1-3]. HCSC can achieve such high efficiencies by extracting the photo-generated carriers at energies higher than band edges (hot carriers) before they thermalize. Hot carriers within a very narrow energy range are extracted to the external circuit through Energy Selective Contacts (ESCs)- carriers with other energies are reflected to the absorber where their energies are renormalized, thus re-filling the depleted carriers at the extraction energy. For the absorber, low band gap materials with a large phonon gap; and for ESCs double barrier quantum well/ quantum dots resonant tunneling structures have been suggested as promising approaches [4]. We have investigated Al2O3/ Si (Ge)/ Al2O3 and HIN thin films for ESCs and absorber, respectively. These materials and structures are interesting as they are relatively abundant and can be fabricated by thin film deposition methods such as sputtering and atomic layer deposition. Results on resonant tunneling behaviors of ESCs and carrier cooling rates in HIN will be presented. Routes to optimize ESCs and absorber and integration of these two to fabricate complete HCSC devices will also be discussed.


9743-29, Session 7

Optical and electronic characterization of InAlAs and InAlAsSb grown by MOVPE for photovoltaic applications
Brittany L. Smith, Zachary S. Bittner, Staffan D. Hellström, Michael A. Slocum, George T. Nelson, Seth M. Hubbard, Rochester Institute of Technology (United States)

III-V materials lattice-matched to InP are of interest for high efficiency concentrator photovoltaics as well as radiation tolerant space photovoltaics. The alloy InAlAsSb has a bandgap between 1.4-1.9 eV when lattice-matched to InP which becomes indirect above 1.6 eV. This material comprises the 1.74 eV top cell of a high efficiency triple junction cell. However, metal organic vapor phase epitaxy (MOVPE) growth of Sb containing compounds is known to require low growth temperatures and alternative precursors that pyrolyze at low temperatures. Initially, InAlAs was studied as a baseline for growth conditions, then Sb was incorporated thereafter.

Single-junction InAlAs cells were grown using tritertiarybutylaluminum (TTBAI) and fabricated in parallel to cells grown with the standard trimethylaluminum (TMAI). Lifetimes were extracted from quantum efficiency data using a modified Hovel-Woodall model based on solutions to minority carrier drift and diffusion equations. Devices grown with TTBAI showed more than double the lifetimes of TMAI devices. These lifetimes will also be verified by time-resolved photoluminescence of bulk doped samples. Transmission electron microscopy images indicate compositional variation in TMAI-InAlAs, which correlates with band tailing seen in quantum efficiency measurements.

When incorporating Sb, growth conditions had to be adjusted dramatically including lower growth temperature, which made use of TTBAI critical. Initial growths ranged in composition from In0.6Al0.4As0.94Sb0.06 to In0.1A0.9As0.52Sb0.48, targeting In0.2A0.8As0.7Sb0.3. Lattice-matched unintentionally doped InAlAsSb was slightly n-type and these samples were characterized by SIMS for impurity incorporation levels. Photoreflectance and photoluminescence will also be performed to determine the optical parameters of this rarely studied material.

9743-30, Session 7

Performance impact of luminescent coupling on monolithic 12-junction phototransducers for 12 V photonic power systems
Matthew M. Wilkins, Christopher E. Valdivia, Univ. of Ottawa (Canada); Sanmeet Chahal, Dept. of Physics, University of Ottawa (Canada); Masanori Ishigaki, Toyota Motor Engineering and Manufacturing North America, Inc. (United States); Denis P. Masson, Simon Fafard, Azastra Opto Inc. (Canada); Karin Hinzer, Univ. of Ottawa (Canada)

A five-junction monolithically-integrated GaAs phototransducer device with > 61% power conversion efficiency and > 5 V open-circuit voltage under monochromatic illumination is presented. Drift-diffusion based simulations including a luminescent coupled generation term are used to study photon recycling and luminescent coupling between each junction.

We find that luminescent coupling effectively redistributes any excess generated photocurrent between all junctions leading to reduced wavelength sensitivity, and allowing relaxed manufacturing tolerances. Using the full width of the quantum efficiency at 90% of its maximum as a metric, spectral response of this device is broadened by a factor of 3.5 when luminescent coupling is included in the simulation. This broadened response is consistent with experimental measurements of devices with high-quality materials exhibiting long carrier lifetimes. Photon recycling is also found to significantly improve the voltage of all junctions, in contrast to multi-
junction solar cells which utilize junctions of differing bandgaps and where high-bandgap junctions benefit less from photon recycling. We go further by studying the limiting factors in creating very thin GaAs junctions, and consider the use of p-i-n heterojunctions rather than p-n homojunctions. We also study the optimization of the junction thicknesses in the presence of luminescent coupling.

9743-31, Session 7
Thin-film vapor-liquid-solid growth of InP for III-V photovoltaics

Christopher G. Bailey, Sean Babcock, Marlene Lichty, Grace Rajan, Tasnuva Ashraftee, Sylvain Marsilliac, Old Dominion Univ. (United States); Sergey I. Maximenko, Robert J. Walters, U.S. Naval Research Lab. (United States); Elisabeth L. McClure, Brittany L. Smith, Seth M. Hubbard, Rochester Institute of Technology (United States)

State-of-the-art III-V photovoltaic (PV) devices are typically used for unique applications such as a space PV and concentrated source PV, due to their high cost of manufacturing. This cost is largely due to the maintenance and chemical consumption of typical epitaxial deposition tools such as metal organic chemical vapor deposition or molecular beam epitaxy systems. In addition, III-V substrates can also provide an additional cost burden. Reducing the cost of III-V material manufacturing could benefit other PV applications, by shifting typical high performance devices into an affordable technology bracket. In order to effectively do this, cheaper methods of deposition and substrate synthesis need to be explored.

In this investigation, polycrystalline InP material has been produced using a thin-film (TF) adaptation of the vapor-liquid-solid (VLS) crystal growth method abbreviated TF-VLS. Electron dispersive spectroscopy of this material indicates the presence of both In and P. Preliminary photoluminescence measurements show emission of 1.34 eV indicative of the InP bandgap. Powder x-ray diffraction measurements have been made resulting in known InP peaks. In addition, photovoltaic simulation software being developed, employs numerical methods to solve for coupled drift-diffusion equations, and the transfer matrix method to compute optical generation. This will be used to investigate the effects on performance of various electronic materials properties typical of polycrystalline materials. Both experimental and theoretical attention will be given to the evaluation of the TF-VLS method as a cheap alternative to existing III-V growth infrastructures.

9743-32, Session 7
Enhanced photocarrier extraction mechanisms in ultra-thin photovoltaic GaAs n/p junctions

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Thin GaAs n/p photovoltaic (PV) heterostructures have been grown by metal-organic chemical vapor deposition with various p-GaAs base thicknesses, ranging from partially absorbing (smaller than 200nm) to quasi-fully absorbing (a few microns thick.) PV devices with active areas of -3.4mm² were fabricated and tested with top electrodes having different emitter gridline spacings with active area shadowing values between 0% and 1.8%. As expected, the thicker n/p junctions exhibit hindered photocarrier extraction, with low fill factor (FF) values, for devices prepared with sparse gridline designs. However, this study clearly demonstrates that for thin n/p junctions the photocarrier extraction can still be efficient (FF > 80%) even for the extreme case in which devices are designed with no gridlines. The variation in FF with base layer thickness is explained using a TCAD model through which we observe that thicker configurations are distinguished by the presence of a large void in the electric field intensity towards the center of the p-GaAs base layer, which disappears with a thinner base layer. The void in electric field strength coincides with a region of relatively increased Shockley-Read-Hall recombination density which in turn yields the observed reduction in FF. Open circuit voltage (Voc) between -1.125V and -1.155V were measured and modeled, and we further present measurements of quantum efficiency spectral responses and short circuit currents (Isc), valuable for precise determination of the spectral dependence of the absorption and the photocarrier extraction properties of optoelectronic devices utilizing such thin GaAs n/p junctions.

9743-33, Session 7
Modeling of effects of using polycrystalline substrates for low-cost III-V photovoltaics

Zachary S. Bittner, Michael A. Slocum, Elisabeth L. McClure, Seth M. Hubbard, Rochester Institute of Technology (United States)

Current high-efficiency III-V photovoltaic technologies depend on high-quality crystalline substrates such as Gallium Arsenide, Indium Phosphide and Germanium as growth templates for the chosen epitaxial deposition technique. The substrate contributes to the bulk of both the semiconductor material used, and the total cost of the cell. A recrystallized thin-film virtual substrate is much more attractive both from a cost-specific power and a mass-specific power perspective because it consumes less semiconductor material, and contains less unneeded mass, but the effects of polycrystallinity and surface roughness on epitaxial material quality are not quantitatively understood. Ge is an attractive candidate for recrystallization because, as a group IV element phase segregation and out-diffusion is not a problem, bit it introduces the challenge of suppressing anti-phase domains across a wide range of crystallographic orientations. Previously, spectral responsivity has been modeled, but precise open circuit voltage prediction presents a greater challenge. For this study, (In)GaAs solar cells will be grown on crystalline (001) and polycrystalline GaAs and Ge substrates in order to assist in modeling the impacts of anti-phase domains, crystal size, and preferential orientation on epitaxial material quality. A comprehensive model accounting for grain size effects will be developed for use as a predictive tool when moving towards recrystallized “virtual” substrates, with a final model predicting solar cell efficiency across a variety of average crystal grain sizes and surface morphologies.

9743-34, Session 7
1.7eV Al_{0.2}Ga_{0.8}As solar cells epitaxially grown on silicon by SSMBE using a superlattice and dislocation filters

Arthur L. Onno, Jiang Wu, Qi Jiang, Siming Chen, Mingchu Tang, Univ. College London (United Kingdom); Yurii Maidaniuk, Mourad Benamara, Yuriy I Mazur, Gregory J Salamo, Institute for Nanoscience and Engineering - University of Arkansas (United States); Nils-Peter Harder, TOTAL Marketing Services - New Energies Division (France); Lars Oberbeck, Total S.A. (France); Huiyin Liu, Univ. College London (United Kingdom)

Lattice-mismatched Al_{0.2}Ga_{0.8}As photovoltaic solar cells have been grown on silicon substrates by Solid Source Molecular Beam Epitaxy. The
Quantum well for high-efficiency photovoltaics (Invited Paper)

Diego Alonso-Álvarez, Imperial College London (United Kingdom)

Over the last couple of decades, there has been an intense research on strain balanced semiconductor quantum wells (QW) to increase the efficiency of multi-junction solar (MJ) solar cells grown monolithically on germanium. So far, the most successful application of QWs have required just to tailor a few tens of nanometers the absorption edge of a given subcell in order to reach the optimum spectral position. However, the demand for higher efficiency devices requiring 3, 4 or more junctions, represents a major difference in the performance of the cell. An AlGaAs/GaAs superlattice followed by a set of dislocation filters were used in order to reduce the TD density to about 10^7cm-2. Lattice-matched Al0.2Ga0.8As cells have been grown on GaAs substrates alongside as a reference. The best cell grown on Si exhibits an open-circuit voltage of 964mV representing an offset-voltage Woc, defined as Woc=EQ-Eg-Voc of 736mV. In comparison the best reference cell on GaAs had a Voc of 1128mV translating in a Woc of 572mV. Both cells exhibit high fill factors of respectively 77.6% and 80.3%. Due to the lack of an anti-reflection coating, relatively low short-circuit currents have been measured: 7.30mA.cm-2 on Si and 6.64mA.cm-2 on GaAs. Using the detailed balance limit model developed by Schockley and Queisser, adapted with the NTT model from Yamaguchi et. al. to take into account the impact of TDs, a comprehensive model has also been developed.

Carrier dynamics in QW and bulk bismide materials and epitaxial lift off InGaP double heterostructures grown by MOVPE for multi-junction solar cells

Yongkun Sin, Zachary Lingley, Mark Peterson, Stephen LaLumondiere, Steven C. Moss, The Aerospace Corp. (United States); Honghyuk Kim, Kamran Forghani, Yingxin Guan, Univ. of Wisconsin-Madison (United States); Kangho Kim, Jaejin Lee, Ajou Univ. (Korea, Republic of); Luke Mawst, Thomas Kuech, Univ. of Wisconsin-Madison (United States); Sudersena Rao Tatavarti, MicroLink Devices, Inc. (United States)

The most promising 1 eV materials for III-V multi-junction solar cells are dilute-bismide QW materials, such as GaAsBi, strain-compensated with GaAsP barriers. We employed time-resolved photoluminescence (TR-PL) techniques to study carrier dynamics in MOVPE-grown bulk dilute-bismide double heterostructures (DH), where carrier lifetime measurements are crucial in optimizing MOVPE materials growth. We also studied carrier dynamics in GaAsBi QW structures with different barrier layers including GaAs, AlGaAs, and GaAsP. Carrier lifetimes were measured from GaAsBi DH samples at different stages of post-growth thermal annealing steps. Post-growth annealing yielded significant improvements in carrier lifetimes. Based on this study, single-junction solar cells were grown and annealed under the optimized and unoptimized conditions and were characterized. The SJSC annealed under the optimized condition exhibited the improved response in EQE spectra.

In addition, it will be beneficial for space satellite applications if III-V multi-junction solar cells can significantly reduce weight and can be manufactured cost effectively while maintaining high efficiency. The most attractive approach to achieve these goals is to employ full-wafer epitaxial lift-off (ELO) technology, which can eliminate the substrate weight and also enable multiple substrate re-usages. We studied carrier dynamics in MOVPE-grown InGaP DH samples grown on GaAs substrates. The structures were grown on top of a thin AlAs layer, which allowed epitaxial layers grown on top of the AlAs layer to be removed from the substrate. The InGaP active layers
had various doping densities and thicknesses. We will present our TR-PL results from both pre- and post-ELO processed InGaP DH samples.

9743-38, Session 8

High performance 1 eV dilute nitride solar cells using quantum wells with cascaded thermally-assisted resonant tunneling design

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Tandem devices based on III-V semiconductors have shown excellent promise for boosting solar cell conversion efficiencies. In particular the use of a bottom subcell made with dilute nitrogen alloys of these semiconductors in a 3-cells series-connected tandem configuration has already shown practical conversion efficiencies in the range of 44%. Nevertheless thus far access to higher efficiencies in this material system has been limited by the relatively poor open-circuit voltages associated with dilute nitride solar cells.

Here we report the demonstration of 1.05 eV, 1.1 eV and 1.25 eV solar cells with open circuit voltages that exceed significantly the prior art (by nearly 10%). To make this breakthrough possible we have designed devices that incorporate sets of carefully crafted ultra-thin resonantly coupled multi-quantum wells of dilute nitrides [1]. Devices were fabricated by nitrogen-plasma-assisted molecular beam epitaxy. A modification of the nitrogen plasma source injector that includes a differentially pumped run-vent system [2] and the optimization of flux profiles were found critical to enable a superior interface and composition control. These optimizations led to the fabrication of GaAsN/GaAs quantum wells with superior interface sharpness and allowed for nearly two order of magnitude enhancement of quantum well luminescence intensities (by comparison to samples grown with traditional N plasma injector).

Devices fabricated with appropriate carrier extraction design [1] and under optimal MBE growth conditions, exhibit near ideal carrier collection efficiency (QE ~1). Another remarkable feature of these devices is their open circuit voltage that approaches the radiative limit of Eg-0.4eV and suggests efficiency (QE ~1). Another remarkable feature of these devices is their open circuit voltage that approaches the radiative limit of Eg-0.4eV and suggests potential for boosting the practical efficiency of triple junction solar cells to beyond 49%.


9743-39, Session 8

Effective drift mobility approximation in multiple quantum-well solar cell

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Multiple quantum well (MQW) solar cells have been explored as one promising next-generation solar cells toward high conversion efficiency. However, the dynamics of photogenerated carriers in MQWs are complicated, making it difficult to predict the device performance. Our purpose of this study is to investigate a model for the photocurrent component characteristics of MQW cells based on experimental findings.

Using our proposed carrier time-of-flight technique, a method for estimating carrier transport time across the MQW region, we have found that the carrier averaged drift velocity has linear dependence on the internal field regardless of complicated carrier cascade dynamics in MQW. This behavior is similar to carriers in bulk materials, allowing us to approximate the MQW region as a quasi-bulk material with specific effective drift mobilities. In this way, the device complexity is reduced, and the characteristics of such MQW cells can be simulated using the conventional drift-diffusion model.

We have confirmed this model with experimentally obtained photocurrent characteristics. The cell photocurrent has been analyzed using carrier collection efficiency (CCE)—a ratio of the number of carriers extracted after photogeneration in the cell active region. The simulation of CCE based on the effective mobility approximation agrees well with the experimental results when the carrier lifetime is set to be in the order of tens to hundreds of nanoseconds, a plausible value for carrier lifetime in III-V nanostructures. This simplified model enhances our understanding of the MQW cell operation and helps design the optimal structure for better performance.

9743-40, Session 8

Quasi-Fermi level splitting evaluation based on electroluminescence analysis in multiple quantum-well solar cells for investigating cell performance under concentrated light

Tomoyuki Inoue, Kasidit Toprasertpong, Amaury Delamarre, The Univ. of Tokyo (Japan); Kentaroh Watanabe, RCAST, The Univ. of Tokyo (Japan); Myriam Paire, Laurent Lombet, Institut de Recherche et Développement sur l’Energie Photovoltaïque (France); Jean-François Guillemoles, Institut de Recherche et Développement sur l’Energie Photovoltaïque (France) and RCAST, The Univ. of Tokyo (Japan); Masakazu Sugiyama, Yoshiaki Nakano, The Univ. of Tokyo (Japan)

Insertion of InGaAs/GaAsP strained-balanced multiple quantum wells (MQWs) into i-regions of GaAs p-i-n solar cells show several advantages against GaAs bulk p-i-n solar cells. Particularly under high-concentration sunlight condition, enhancement of open-circuit voltage with increasing concentration ratio in thin-barrier MQW cells has been reported to be more apparent than that in GaAs bulk cells.

We prepared the reference GaAs p-i-n cells and MQW cells. However, the preliminary investigation of the MQW cell performance under high-concentration sunlight suffered from the increase in cell temperature. In order to investigate the mechanism of this fast voltage enhancement in MQW cells under high-concentration sunlight without the temperature effect due to thermalization loss, the quasi-Fermi level splitting was evaluated by analyzing electroluminescence (EL) from a cell. In addition, since a cell under current injection with a density Jinj has similar excess carrier density to a cell under concentrated sunlight with an equivalent short-circuit current Jsc = Jinj, controlling of Jinj in the EL measurement can approximately evaluate a cell performance under a variety of concentration ratio.

In addition to the evaluation of quasi-Fermi level splitting, the external luminescence efficiency was also investigated with the EL measurement. The MQW cells show higher external luminescence efficiency than the GaAs reference cells especially under high-concentration light condition. The results suggest that since the MQW region can trap and confine carriers, the excess carriers localize inside the cells and smaller differences can be obtained between estimated bandgap from EL spectra and quasi-Fermi level splitting, making radiative recombination more dominant.
 Carrier dynamics in type-II quantum dots for wide-bandgap intermediate-band solar cells (Invited Paper)

Takeshi Tayagaki, Takeyoshi Sugaya, National Institute of Advanced Industrial Science and Technology (Japan)

Type-II quantum dots (QDs) have attracted attention for the QD-based intermediate-band (IB) cells. Due to spatial separation between electrons and holes in type-II potential alignment, carrier recombination is strongly suppressed, which results in enhanced carrier lifetime. Enhanced carrier lifetime in IB is necessary for an efficient two-step two-photon excitation that is required to IB cells. In addition, suppressed carrier recombination in type-II QDs preserve the temperature coefficient of open-circuit voltage in the QD-based solar cells [1].

So far, however, QDs in narrow bandgap host, such as InAs(Sb)/GaAs and Ge/Si QDs, have been used to study the operation principle of IB solar cells. We clarified that the photocarriers are extracted by thermal carrier escape from Ge/Si QDs that is caused by thermal excitation and built-in filed of the host p-n junction, which decreases carrier lifetime in QDs and prevents efficient two-step two-photon absorption [1].

In this work, to realize the long carrier lifetime and suppressed thermal escape, we focus on the type-II QDs in wide bandgap InGaP host and investigate carrier dynamics by using time-resolved optical spectroscopy. We found that the photoluminescence spectra in QDs exhibit high energy shift with increasing excitation power density, indicating enhanced carrier lifetime and suppressed carrier recombination in this type-II QDs. We will show the carrier dynamics in type-II QDs studied by time-resolved photoluminescence measurements and discuss its impact to the IB cell operation.


Design optimization for two-step photon absorption in quantum dot solar cells by using infrared photocurrent spectroscopy

Ryo Tamaki, Yasushi Shoji, Yoshitaka Okada, RCAST, The Univ. of Tokyo (Japan)

We have conducted research on intermediate band solar cells by focusing multi-stacked In(Ga)As quantum dot solar cells (QDSCs). In recent years, lots of effort has been made to evaluate and understand the photo-carrier response of two-step photon absorption in QDSCs. One crucial issue today is to suppress thermal excitation of photo-carriers out of QDs, which obscures the QD filling under quasi-equilibrium at room temperature. Here, we have investigated infrared photocurrent spectra of the QD state to conduction band (CB) transition by using Fourier-transform infrared (FTIR) spectroscopy. Multi-stacked In(Ga)As QDSCs with different barrier materials, such as GaAs, GaNAs, GaAsSb, and AlGaAs, were fabricated by molecular beam epitaxy (MBE). The IR absorption edge of the QD to CB transition was evaluated at 9 K by analyzing the low energy tail of the FTIR spectra. The threshold temperature of the two-step photon absorption in In(Ga)As QDSCs was determined by observing temperature dependence of IR photoresponse. A universal linear relationship between the threshold temperature and the IR absorption edge was obtained in In(Ga)As QDSCs with different barrier materials. The threshold temperature at 295 K was estimated for the absorption edge at 0.45 eV by extrapolating the linear relationship. It reveals some strategy for cell optimization to achieve efficient two-step photon absorption competing against thermal carrier escape at ambient conditions.

Device simulation of thin-film intermediate-band solar cell using drift-diffusion model and FDTD method

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Thin film photovoltaic technologies have the potential to reduce material costs. Moreover, we can expect the enhanced light intensity because multipath reflection, Fabry-Perot interference effect, efficiently happens inside thin film solar cells. On the other hand, light absorption will be inefficient in the wavelength range of low absorption coefficient. Therefore, it is important to consider the light management technologies. Intermediate band solar cells have we investigated utilize the long wavelength to pump electrons in intermediate band states (IB) to conduction band (CB). Since the absorption coefficient of this process is relatively weak, it is necessary to enhance the two step absorption process. In this paper, we present the device simulation combining FDTD method with drift-diffusion model. FDTD method can analyze the light interference effect inside the cell, and drift-diffusion model can simulate carrier transportation under steady state. In this simulation, the electron occupancy in IB is determined self-consistently between FDTD method and drift-diffusion model. The calculation is repeated until the light intensity and electron density in IB are not changed. As a result, we can observe the change of electron occupancy in IB strongly affected by the light interference effect inside solar cells. This method enables us to suggest more appropriate structure in order to increase the two step absorption process.
Simulation study of GaAsP/Si tandem cells including the impact of threading dislocations on the luminescent coupling between the cells

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A model, derived from the detailed balance model from Shockley and Queisser, has been adapted to monolithically grown GaAsP/Si tandem dual junction solar cells. In this architecture, due to the difference of lattice parameters between the silicon bottom cell - acting as the substrate - and the GaAsP top cell, threading dislocations (TDs) arise at the III-V/Si interface and propagate in the top cell. These TDs act as non-radiative recombination centers, degrading the performances of the tandem cell. Our model takes into account the impact of TDs by integrating the NTT model developed by Yamaguchi et. al. Two surface geometries have been investigated: flat and ideally textured, the former corresponding to ideal light-trapping conditions. Finally the model considers the luminescent coupling between the cells due to reemitted photons from the top cell cascading to the bottom cell. Without dislocations, this luminescent coupling allows a greater flexibility in the cell design by rebalancing the currents between the two cells when the top cell presents a higher short-circuit current. However we show that, as the TD density (TDD) increases, non-radiative recombinations take over radiative recombinations in the top cell and the luminescent coupling is quenched. As a result, non-optimized tandem cells with higher short-circuit current in the top cell experience a very fast degradation of efficiency for TDDs over 104 cm-2. On the other hand optimized cells with matching currents only experience a small efficiency drop for TDDs up to 105 cm-2. High TDD cells therefore need to be current-matched for optimal performances as the flexibility due to luminescent coupling is lost.

Down-conversion of solar photons using alkali vapors

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One approach to overcome efficiency limitations of single junction solar cells is to split high energy photons to lower energy photons that can be absorbed by the cell material. Since silicon (Si) is widely adopted in the industry, photons targeted for down conversion are those that have energies greater than twice the bandgap of Si (1.12 eV).

Alkali elements are known for their multi-photon emissions from excited states. For example in sodium (Na) lamps used in outdoor lighting, excited Na atoms make cascade emissions from 3d to 3p (818 nm) and 3p to 3s (589 nm). Though the first photon is not visible.

In this research, optical spectra of alkali elements from lithium to cesium (Cs) were analyzed for down conversion of high energy photons of the solar spectrum. The spectra suggest that Cs is the most suitable for the down conversion [1]. Cs absorbs at 456 nm & 459 nm which covers near UV and most of the blue. Primary emissions of Cs are at 852 nm & 894 nm and secondary emissions at 917 nm & 876 nm. All of those emissions are within the absorption range of Si.

Cs melts at 28°C, therefore it can be vaporized with the heat generated by the sunlight and the solar cell. Melting and evaporation of Cs creates a cooling effect as a secondary benefit.

The behavior of series resistance of a p-n junction: the diode and the solar cell cases
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This paper presents a comparison of the impact of the internal parasitic series resistance of a p-n junction, as seen from the microelectronics and photovoltaic communities. The elusive thermal behavior of the aforementioned resistance gave this work its origin. Both communities use different approaches to describe the operation of p-n junctions, which might lead to confusion, since scientists and engineers of these two realms seldom interact. An improvement in the understanding of the different approaches will help to better model the performance of p-n junctions based devices and therefore will advance the performance predictions of photovoltaic cells. For diodes, series resistance is usually determined from a specific region of the I-V curve on a semi-logarithmic scale. However, in Photovoltaics this region is not found and therefore other methods to determine Rs have to be utilized. We mathematically modeled an experimentally obtained I-V curve with various n-Rs pairs and found that more than one pair accurately synthesizes the measured curve. We furthermore show that in photovoltaic cells the series resistance decreases with an increase in temperature due to its lightly doped base, as opposed to diodes in the microelectronics community which have highly doped bases and therefore much higher temperatures are needed to exhibit the same effects. We can conclude that the series resistance not only depends on physical parameters, e.g. temperature or irradiance, but as well on fitting parameters, i.e. the ideality factor. Generally the behavior of a p-n junction depends on its operating conditions and electrical modeling.

Metal/metal-oxide nanocoatings on black silicon nano-grass for enhanced solar absorption and photochemical activity
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Black silicon is a material with a high-aspect ratio sub-micrometer features obtained by high-power RIE etching or pulsed laser irradiation of crystalline silicon wafers. It has been demonstrated as a highly absorbing material for applications in microbolometers and photovoltaics. In this work we present our experimental results on the optical absorption enhancement of metal/metal-oxides nanocoatings on black silicon fabricated by reactive ion etch, atomic layer deposition and magnetron sputtering. Our results are compared to finite-difference time domain simulations based on the actual fabricated structures, as obtained by focused ion beam milling slice&view and TEM imaging. A study of the influence of various process parameters on the geometry of the fabricated micro and nanostructures and the corresponding change in optical properties is also presented. The application of such highly-absorbing, broadband metamaterials to full solar photocatalysis and water-splitting energy production is discussed, on basis of hot-carrier injection, plasmonic field enhancement and light trapping due to texturing.

Organic solar cells with various plasmonic nanostructures using titanium nitride
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Organic photovoltaics have already reached 10% power conversion efficiency which, with further increase, could put them in direct competition with currently commercial solar cells. This could be achieved by overcoming their absorption limitations using plasmonic nanostructures. In this work, polarization independence and broadband light absorption enhancement has been obtained by incorporating TiN in different plasmonic nanostructures. The first structure consists of periodic nanoholes array in TiN back electrode, and the second consists of TiN nanoparticles inside the active layer. Excitation of short range surface plasmon polaritons in the “nanoholes” structure and localized surface plasmon polaritons in the “nanoparticle” structure enhanced the absorbed power inside the active layer in the visible and near infrared range.

Three dimensions full wave analysis using finite difference time domain simulator is exploited for calculating the optical absorption. The geometric parameters of the structure are optimized to enhance the efficiency and short circuit current. For the case of nanohole array, an enhancement of 15% and 25.6% in absorbed power is obtained for P3HT:PC70BM and pBBTDPP2:PCBM active layers, respectively. For the case of TiN nanoparticles, 38% and 60% enhancement is calculated for P3HT: PC70BM and pBBTDPP2:PCBM, respectively. This enhanced performance is promising due to its ability to improve the absorption using CMOS compatible, cheap and abundant materials. Moreover, addition of TiO2 on top of the organic active layer will be examined to prevent high energy photons, which are the most harmful for polymers, from reaching the active layer and maintaining its stability, in addition to enhancing the absorption of the cell by absorbing the UV range.

Numerical analysis of the supercontinuum spectrum generation in a couple of photonic crystal fibers with different structure by using the RK4IP method
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In this work, we performed a numerical analysis of the supercontinuum spectrum generation in a couple of photonic crystal fibers with different structure. The proposed configuration initially has an input pulse with hyperbolic secant profile to generate noise-like pulses as output signal, by the Runge-Kutta method (RK4IP). By using the same configuration, now these noise-like pulses are used as pump for supercontinuum generation obtaining a broad and good flatness spectrum. The numerical analysis presented here demonstrates the potential of noise-like pulses from a passively mode-locked fiber laser for broadband spectrum generation combining two different photonic crystal fibers. Besides this paper helps to understand the phenomena of supercontinuum generation which is mainly related to Raman self-frequency shift.
Nanostructure-based enhancement of performance in thin-film photovoltaic devices

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Nano-scale light scattering can enable enhancement of light absorption, which might be possible to achieve by incorporating nanostructures in thin film solar cells. This can further result in an enhanced efficiency in a device with lesser active volume. Based on this idea, in this paper, we first consider the problem of designing nano-structured solar cells. We study the coupled response of the nano-scale geometry and the optical properties of the active material in terms of refractive indices and band-gap and consider the problem of spatially engineering the photo-generation in a device. This is expected to create a synergistic contribution to the charge transport, which is governed by the charge carrier mobility and therefore enhance the device performance. Based on the simulation results, we identify design rules for photo-active materials to work in conjunction with nanostructures.

In the second part of this paper, we discuss a computational approach to design light trapping and enhanced absorption in subwavelength-scale device architectures. Here we consider a statistical approach to model light trapping in random device-structures which exhibit locally periodic nano-structures but which are random at larger length-scales. In this approach we separately study the optical transport behavior of the constituent nano-structural phases using simulations. Subsequently we use modeling scheme to study the optical transport due to a random spatial arrangement of these nano-scale building blocks. This would allow identification of important length-scales, which are critical for enhancing light trapping.

Green solar cells using natural pigments having complementary absorption spectrum

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Conventional silicon solar cells require energy intensive manufacturing and are expensive. Dye Sensitized Solar Cells (DSSCs) are third generation solar cells having several advantages over first generation solar cells such as potential low cost due to ease of fabrication, low energy pay-back time and flexibility. DSSCs typically use ruthenium bipyridyl-based dyes having favourable photo-electrochemical properties and efficiencies close to 15% have been demonstrated. However, these dyes are toxic, expensive and require complex synthesis. Compared to synthetic dyes, natural dyes found in plants can be easily extracted, non-toxic, inexpensive and biodegradable; and are being explored as alternative photosensitizers. However, DSSCs using natural pigments have low efficiencies due to narrow absorption bands.

In order to broaden the absorption spectrum and increase the efficiency, two natural pigments – betanin and chlorophyll, absorbing in complementary regions of the solar spectrum have been used in the DSSC. Betanin is a natural pigment, having an absorption peak at 537 nm (green) and Chlorophyll is a natural pigment, having absorption peaks at 435 nm (blue) and 668 nm (red). DFT studies confirmed the band gap of the pigments and verified that the LUMO and HOMO of the pigments were aligned appropriately with respect to TiO2 and the electrolyte respectively, which is necessary for effective charge transfer. Solar cells with individual and co-sensitized pigments were fabricated and results showed higher efficiency of 3.24% for the co-sensitized solar cell compared to the betanin and chlorophyll solar cells, with efficiencies of 1.79% and 0.96% respectively. This is the highest achieved efficiency for DSSCs using unprocessed natural dyes to the best of our knowledge. These studies will enable developing a new generation of green, flexible solar cells suitable for portable applications and building integrated photovoltaics.
Pulsed laser deposition of rare-earth-doped glasses: a step toward lightwave circuits (Invited Paper)

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The successful migration from electronic to photonic devices relies on the fabrication and integration of multiple optical components, including active devices such as lasers or amplifiers, on a common planar substrate to reduce their size, cost and power consumption, while maintaining their compatability with the current fiber technology. Doped glasses are among the most promising materials for the development of active integrated devices due to their excellent optical properties and ease of preparation at a reasonable cost. Yet, their application requires first the fabrication of high quality thin films a few microns thick with good photoluminescence performance.

In this contribution we will show that pulsed laser deposition (PLD) is very attractive for this purpose, since it allows the synthesis of metastable phases of complex oxides in thin film configuration as well as their nanostructuration through the incorporation of rare earth (RE) ions as functionalizing elements. Thus, opening a realm of material function and design possibilities. We will review how alternate PLD allows the synthesis of nanostructured film glasses with a controlled RE concentration and an in-depth distribution that can be predesigned at the nanometer scale. This approach will be illustrated in the case of germanate and tellurite film glasses doped and co-doped with different RE ions. We will focus on the experimental parameters that have a direct impact on the concentration and distribution of RE ions and their effect on the photoluminescent properties and, finally, their potential in light amplification applications will be discussed.

Large-scale growth of graphene by chemical vapor deposition (CVD) and electrostatic deposition characterized by global hyperspectral Raman imaging

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The synthesis of large scale graphene is currently a subject of intense research. Chemical vapor deposition (CVD) and electrostatic deposition are under the scope of numerous research groups. CVD is the primary technique of graphene deposition. However, despite many efforts, CVD graphene in different growth conditions exhibits various morphologies such as the presence of hillocks, defects, grain boundaries and multilayers island formation. We conducted a systematic study on CVD grown graphene by methane on copper and performed global hyperspectral Raman imaging of the layers in order to obtain structural and chemical mapping of the various structures of our samples at high resolution. The results show commensurate bilayers formed in oxidative environment and mostly twisted bilayers in more reductive environment. The preparation of complete bilayer films will also be presented and analyzed using global Raman characterization. We then turn to electrostatic deposition of graphene. By improving the cleaving process we show that large scale graphene deposition (120 µm x 120 µm) is achievable using electrostatic forces. The results show that electrostatic graphene consisted mainly of single and double layered graphene with occasional multi-layered graphene. The intrinsic specificity of Raman scattering combined with the analysis performed by the global imaging modality allow to assess large maps (hundreds of microns) of the spatial distribution of defects, number of layers and stacking order. The Raman signatures of the different configurations of graphene known in the literature are used in this framework to map the influence of the growth conditions on sample morphology.
for generating high brightness supercontinuum (SC) light from the near ultra-violet (UV) to the near infra-red (IR), with smooth and flat spectral power densities, and spatial – and sometimes temporal – coherence. However, fused silica suffers from strong material absorption in the mid-IR (>2500 nm), as well as UV-related optical damage (solarisation), which limits performance and lifetime in the UV (<380 nm). As a result, silica-PCF based supercontinuum generation has been restricted to the spectral range between these limits. A number of alternative glasses have been used to extend the mid-IR performance, including chalcogenides, fluorides and heavy-metal oxides, but none has extended the UV performance. Here we describe the successful fabrication, using the stack-and-draw technique, of a ZBLAN PCF with a high air-filling fraction, a small solid core, nanoscale features and near-perfect structure. Further, we report its use in generating ultrabroadband, long-term stable, supercontinua spanning more than three octaves in the spectral range 200 to 2500 nm, pumped by 800 nm and 1042 nm infrared pulses.

9744-8, Session 2

White-light emission studies of dysprosium-doped halide crystals

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Dysprosium ion has dense energy level structure. Consequently, luminescence quenching dominates at high dopant concentrations. Hence, dysprosium is not a popular candidate among laser community. Published literature on Dy³⁺-doped materials is very limited when compared to that of other ions such as, erbium or holmium. However, Dysprosium doped materials are useful for white light emission studies. Here, we compare the spectral characteristics of Dy³⁺ - doped CaF₂, KPb₂Cl₅ and KPb₂Br₅. The centers of gravity of the multiplets do not change by a large amount from one host to another. However, the crystal field levels and the transition probabilities are slightly dependent on the host materials. Potassium halide crystals (chlorides and bromides) are low phonon materials (203 and 138 cm⁻¹ respectively) when compared to CaF₂ or other crystals. Consequently non-radiative relaxation is minimized for several transitions. As a result radiative transitions occur from higher levels even for small energy gaps to the lower levels, -1000 cm⁻¹. At the same time, if the sample emits at several wavelengths covering the whole visible region then the emission is somewhat close to that of sunlight. Dy³⁺-doped potassium lead halide crystals fulfill the required criteria. Under 488 nm excitation the sample emission is very weak. However, under 405 nm excitation the sample emitted bright white light. The ions in the laser excited level partly relaxed in cascade to the lower levels, causing them to emit radiation. Consequently, emission occurred at several wavelengths in the visible region, thus generating white light. We will compare the relative efficiencies of Dy³⁺ -doped CaF₂, KPb₂Cl₅ and KPb₂Br₅ crystals. Absorption, emission and lifetime measurements are performed for different levels. All the spectroscopic measurements will be described in detail.

9744-9, Session 2

Near-infrared diode-pumped white-light emission from erbium-doped calcium fluoride crystal

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Now-a-days there is a growing trend to design energy efficient solid state white light emitters that are robust, compact, and free from pollution. After the advent of compact diodes fabrication of solid state emitters is becoming a reality. High power diodes are available for the near infrared region and low power diodes are available for the blue region. White light emission is more efficient if the sample absorbs all the pump power and the nonradiative relaxation is minimum. For a given energy level separation, nonradiative relaxation is minimum if the phonon frequency is smaller. Fluoride hosts are one class of materials that meet the above criteria. Development of commercial devices is feasible if compact diodes are an integral part of the design. So, we have investigated erbium doped fluoride crystals to check their feasibility for solid state lighting. Er doped CaF₂ revealed white light whereas Er doped LaF₃ and BaF₂ revealed green color luminescence. Under 800 nm excitation Er-doped CaF₂ revealed emission at 414, 550 and 670 nm and the color of the luminescence is white. The emission at 414 nm is maximum for 809 nm excitation. The intensity of blue emission at 414 nm depended on the pump laser wavelength and power. Under 405 nm excitation Er-doped CaF₂ revealed bright white light emission. The emission at 389 and 462 nm are much weaker. Excitation spectral recordings revealed broadband wavelength regions for which it emits blue, green and red emissions. This indicates that the choice of the pump wavelength is flexible. The sample efficiency is characterized from the absorption, emission, and excitation spectral recordings and lifetime measurements.

9744-10, Session 3

Spatial and geometry control of second-order optical properties in inorganic amorphous materials (Invited Paper)

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We report on the ability of a thermal poling treatment to be considered as an imprinting process modifying both linear and nonlinear optical properties as well as surface morphology of glassy materials. Micro-patterned second harmonic generation responses have been achieved on a variety of inorganic amorphous materials including bulk or thinfilms of various compositions (silicate, niobate, tantalate ...). Using particular micro-patterned anodic electrodes, the poling imprinting process allows (i) a geometry control of second order optical properties in isotropic materials and (ii) a control of the refractive index with large variations up to several 10⁻¹. In addition, large area (up to several centimeters square) can be successfully micro-patterned using this approach. It has been proven that field enhancement effects within the microstructured anode govern the charge density on the glass surface during the process and thus amplitudes of both implemented electric field (i.e. optical non linearity) and Maxwell stresses (surface topology).

9744-11, Session 3

Circular and linear birefringence in laser-grade single-crystal CVD diamond

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Synthetic diamond with its excellent thermal properties, high Raman gain coefficient, wide transparency and high damage threshold finds numerous applications such as in high power laser windows and heatspreaders, nanophotonics, radiation optics, quantum information processing and Raman lasers. Despite being an isotropic crystal, impurities and structural defects introduce substantial stress induced birefringence. Recently, advances in synthesis techniques have enabled lower birefringences to be achieved. However, the detailed birefringence properties, which are important pertinent in many optical applications, have not been characterized in detail.
Atomic clusters are the aggregates of a few up to thousands of atoms and molecules, which have structures and properties neither like single atoms nor bulk. Plasmon excitation and manipulation are important in surface science, nano-optics, nanoscale energy transportation and plasmonic/photic devices. However, the near-field component greatly increases when the gap spacing between the particles decreases. Local field enhancement of 103 falls within the gap. Most of work has been done for particle arrays with large sizes. Therefore, lack of knowledge is concerned for the dimer consisted of two atomic clusters with size less than 20 nm and the distance of less than a few nm in-between, even less known about the cluster chains and cluster array.

In this presentation we discuss the following our recent development: 1) Size effect of plasmon excitation for metal nano-clusters; 2) Multi-phase plasmon excitation on cluster dimmer and cluster chains; 3) Enhancement of Raman scattering for ordered cluster arrays, etc, including their possible applications.

References

9744-44, Session 3
Design of a double grating-coupled surface plasmon color filter
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Surface plasmon-based nanophotonic devices are advanced in high-sensitivity of wavelength, which can be used to fabricate narrow band color filters. But when SP is excited by grating-coupled structure, the evanescent wave is limited on the interface of metal and dielectric. We design a tunable transmissive filter, consisting of two substrates, two sinusoids metal gratings and a modulation layer. Herein the dielectric medium is used as the modulation layer and is sandwiched between two gratings which are respectively attached to their corresponding substrate. The whole structure is mirror symmetric with respect to the modulation layer. If the incident TM wave satisfies the momentum matching condition, SP is excited at the first metal-dielectric interface by the grating coupling, which then arouses the SP excitation with the same frequency on the second metal-dielectric interface and waves with a certain spectrum bandwidth transmit to the far field. The way to tune the selected wavelength is changing the distance between two metal gratings, i.e. changing the thickness of the modulation layer in the range of SP penetrating depth. We use finite element method to analyze the influence of the modulation layer thickness on the angular and wavelength selectivity. Results show that this novel color filter can realize a continuous shift of transmission peak in the visible range. The spectrum bandwidth is less than 50 nm and the transmissivity is higher than 50%. It can be applied to the high resolution display devices to improve the quality of color images.

9744-14, Session 4
Integrated compact optical current sensors with high sensitivity (Invited Paper)
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Optical current sensors are attractive due to their immunity to electromagnetic interference and wide dynamic range. While they have traditionally been used in bulk, high current systems, new applications call for sensors with high sensitivity as well as small size. One approach to solving this problem is to use fiber optic current sensors with high Verdet constant instead of silica fiber. We demonstrate a Sagnac based fiber optic sensor system operating at 20 kHz. We have also developed a novel design which allows the sensor to be used in association with a fiber optic sensor array.
current sensor using only 10cm of terbium doped fiber with a high Verdet constant of 15.5 rad/Tm at a wavelength of 1500nm. Measurements of the fiber inside a solenoid show over 40dB of open loop dynamic range as well as a minimum detectable current of 0.1mA. In order to decrease size while increasing sensitivity even further, we consider integrated magneto-optic waveguides as the sensing element. Using low-loss silicon nitride waveguides alongside magneto-optical material such as cerium doped yttrium iron garnet (Ce:YIG), we model the Verdet constant to be as high as 10000 rad/Tm. This improvement by three orders of magnitude shows potential for magneto-optic waveguides to be used in ultra-high sensitivity optical magnetometers and current sensors.

9744-15, Session 4  
Enhancement of Rayleigh scatter in optical fiber by simple UV treatment: an order of magnitude increase in distributed sensing sensitivity  
Sébastien Loranger, François Parent, Victor Lambin-lezzi, Raman Kashyap, Ecole Polytechnique de Montréal (Canada)

Rayleigh scatter in optical fiber has long been considered a nuisance in telecommunications as a loss mechanism, although applications have used such scatter to probe the fiber for faults using time domain reflectometry (OTDR). It is however only with the development of Fourier domain reflectometry (OFDR) and coherent-phase OTDR that Rayleigh scatter has been probed to its deepest and can now be used to measure strain and temperature along a fiber, opening the first distributed sensing applications. However, such scatter mechanism remains very weak giving rise to very small probing signals limiting the techniques. We showed how a new technique to extensively enhance the Rayleigh scatter signal by at least two orders of magnitude, in a standard optical fiber with simple UV exposure of the core. A study of various exposures with different types of fibers has been made and a phenomenological description developed. We demonstrate that such an increase in signal can enhance the temperature and strain sensitivity by an order of magnitude in distributed sensing with a OFDR technique. Such improved performance can lead to temperature/strain RMS noise level of 10 mK and 80 n? for 1 cm spatial resolution in UV exposed SMF-28, compared to the typical noise level of 100 mK for the same spatial resolution in the similar unexposed fiber.

9744-16, Session 4  
Spherical transceivers for ultrafast optical wireless communications  
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Optical wireless communications (OWC) offers the potential for high-speed and mobile operation in indoor networks. Such OWC systems often employ a fixed transmitter grid and mobile transceivers, with the mobile transceivers carrying out bi-directional communication via active downlinks (ideally with high-speed signal detection) and passive uplinks (ideally with broad angular retroreflection and high-speed modulation). It can be challenging to integrate all of these bi-directional communication capabilities within the mobile transceivers, however, as there is a simultaneous desire for compact packaging. With this in mind, the work presented here introduces a new form of transceiver for bi-directional OWC systems. The transceiver incorporates radial photoconductive switches (for high-speed detection) and a spherical retro-modulator (for broad angular retroreflection and high-speed all-optical modulation). Signal detection and all-optical retro-modulation are investigated by way of theoretical models and experimental testing, for spherical retro-modulators comprised of three glasses, N-BK7, N-LASF9, and S-LAH79, having differing levels of refraction and nonlinearity. It is found that the spherical retro-modulator comprised of S-LAH79, with a refractive index of n = 2 and a Kerr nonlinear index of n2 = (1.8 ± 0.1)? 10-15 cm2/W, yields both broad angular retroreflection (over a solid angle of 2pi steradians) and ultrafast modulation (over a duration of 120 fs). Such transceivers can become important elements for all-optical implementations in future bi-directional OWC systems.
mirror permits to calibrate the system as it directs toward the detector
the signal deriving from a calibrated blackbody. A ZnSe window permits
to measure normal radiance in 0.6-17 µm spectral range. In this device the
first test were carried out comparing the results obtained for HFC and TaB2
ultra-refractory ceramic samples to previous monochromatic measurements
performed in a research solar furnace, obtaining a good agreement. Then, in
order to confirm the reliability of the acquired spectral emittance curve, we
compared it to that calculated from the room temperature spectrum in 1.6-17
µm spectral range, showing a similar spectral trend. In addition, a sample
with a Nd deposition was tested in order to verify its spectral absorption
properties at high temperature. Emissivity does not show the typical Nd
band, however, spectrophotometric test before and after heating show a
sample change due to high temperature exposition.

9744-29, Session 5
IR-transmitting GRIN chalcogenide materials
Daniel J. Gibson, Shyam S. Bayya, Vinh Q. Nguyen, U.S.
Naval Research Lab. (United States); Mikhail Kotov, Sotera
Defense Solutions, Inc. (United States); Jasbinder S.
Sanghera, U.S. Naval Research Lab. (United States)
Graded index (GRIN) optical materials and novel lens offer numerous
benefits for infrared applications, where selection of conventional materials
is limited. For optical systems that must perform over wide spectral regions,
the reduction of size weight and complexity can be achieved through
the use of GRIN elements. At the Naval Research Laboratory (NRL) we are developing new technologies for IR gradient index (IR-GRIN) optical
materials. This paper will present the latest progress in the development of
these materials including their properties, and availability. Topics include
refractive index, dispersion, index and dispersion gradients, design space
guidelines and preliminary mechanical properties.

9744-30, Session 5
700 kHz beam scanning using electro-
optic KTN planar optical deflector
Shoko Tatsumi, Nippon Telegraph and Telephone Corp. (Japan); Yuzo Sasaki, Seiji Toyoda, Tadayuki Imai, Junya
Kobayashi, Tadashi Sakamoto, NTT Corporation (Japan)
For high-speed optical beam scanning, we propose a novel planar optical
deflector using KTa1-xNbxO3 (KTN) crystals. Enhancing the scanning speed
of deflectors enables us to improve the imaging speed of microscopy,
which is important in medical and other areas. KTN is one of the promising
materials for high-speed deflectors because of its huge second-order EO
(Kerr) effect and its unique operating principle. However, when operating at
high frequencies, heat generation in KTN increases. This causes a decrease
in its relative dielectric constant, which results in limiting the deflection
angle at frequencies above 200 kHz. To overcome this problem, we propose
a novel planar optical deflector. We decreased the thickness of KTN to
reduce its heat generation and arranged the two electrodes on the same
surface, whereas conventional structures have each electrode on opposite
surfaces. We simulated the electrical field distribution by changing KTN
thickness and clarified that the KTN thickness has to be less than 100 µm
for uniform deflection. Then we fabricated a deflector whose thickness
was reduced to less than 100 µm by polishing and measured its deflection
characteristics. The deflection angle at 700 kHz is 16.89 mrad, which is
more than half of that at 100 kHz, while the deflection angle in conventional
thick KTN rapidly decreases at more than 200 kHz. The experimental
results verified that our proposed planar optical deflector is effective for
suppressing heat generation in KTN and improving the scanning speed of
deflectors.

9744-27, Session 5
Photo-thermo-refractive glass with
sensitivity extended into the near-infrared
region
Fedor M. Kompan, George B. Venus, Larissa N. Glebova,
Helene Mingareev, Leonid B. Glebov, CREOL, The College
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States)
Photo-thermo-refractive (PTR) glass is a multicomponent silicate glass
doped with Ce3+ and Ag+. PTR glass is extensively used for holographic
recording of volume Bragg gratings (VBGs). A photosensitivity range of
PTR glass is determined by excitation of the 5d1 band of Ce3+ ions that
corresponds to the 280-340 nm spectral region. As a result, complex
holograms could be recorded for near UV spectral region, while only
trivial planar holographic elements, such as volume Bragg gratings, can
be recorded in PTR glass for applications in visible/IR spectral region.
We proposed a way to extend photosensitivity of PTR glass into the VI/
IR spectral region and demonstrated complex holograms in the PTR glass
operating in visible and near IR spectral regions. Tb3+-ions were chosen as
a new photosensitizer. They have a convenient 4f-levels structure, which
allows for excitation of 5d14f7 band at 4.90 eV by excited state absorption
(ESA). It was shown that Tb3+ ions excited into 5d14f7 band by ESA process
were converted to Tb4+ ions releasing an electron, which starts a chain of
structural transformations resulting in refractive index modulation. Exposure
to UV radiation at 375nm was used as a background illumination for ESA.
Value of the refractive index change was found to be over 200ppm between
the non-irradiated area and the irradiated area after exposure by light of
wavelength shorter than 850nm. Finally, reference-free complex holograms
were recorded in Tb doped PTR glass using green and blue lasers.

9744-28, Session 5
Expanding the optical design glass map
with new IR materials for multispectral
optics
Shyam S. Bayya, Daniel J. Gibson, Vinh Q. Nguyen,
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States); Mikhail Kotov, Sotera Defense Solutions, Inc. (United
States)
There is a strong desire to reduce size and weight of single and multiband
IR imaging systems in ISR operations on hand-held, helmet mounted or
airborne platforms. Current systems are limited by bulky optics. We have
recently developed a large number of new optical materials based on
chalcogenide glasses which transmit in SWIR to LWIR wavelength region
that fill up the glass map for multispectral optics and vary in refractive index
from 2.38 to 3.17. They show a large spread in dispersion (Abbe number) and
offer some unique solutions for multispectral optics designs. These glasses
were specifically designed to have comparable glass molding temperatures
and thermal properties to be able to laminate and co-mold the optics and
reduce the number of air-glass interfaces (lower Fresnel reflection losses).
These new NRL glasses also have negative or very low positive dn/dT
making it easier to athermalize the optical system. Our multispectral optics
designs using these new materials demonstrate reduced size, complexity
and improved performance. This presentation will cover discussions on the
new optical materials, multispectral designs, fabrication and characterization
of new optics.
Determination of the geometric ray contents of light propagating in highly-multimode optical fiber

Philippe Décoste, Nicolas Godbout, Ecole Polytechnique de Montréal (Canada)

A technique is proposed to characterize the power distribution of guided light in a highly multimode fiber. In the geometric propagation point of view, rays of light have two invariants related to axial and orbital momentum respectively. A measurement setup is presented that enables the measurement of power density with respect to these two invariants. The results yield a simple real-time representation of the multimode guided light properties.

The two invariants of the geometric representation can be uniquely mapped to the two modal indices of LP modes of optical fibers in the wave optics representation. It is shown that, in step-index multimode fibers, the LP mode density is constant across the permissible axial momentum invariant. Recognizing the fully filled condition (all modes excited equally) is therefore natural in the proposed representation.

Two-dimensional refractive index profiling of optical fibers by modified refractive near-field technique

Ali F. El Sayed, Univ. Bern (Switzerland); Sönke Pilz, Berner Fachhochschule Technik und Informatik (Switzerland); Manuel Ryser, Univ. Bern (Switzerland); Valerio Romano, Univ. Bern (Switzerland) and Berner Fachhochschule Technik und Informatik (Switzerland)

The refractive index distribution in the core-cladding of an optical fiber plays an important role in determining the transmission and dispersion properties of the waveguide. The refracted near-field technique (RNF) is among the most widespread techniques used for measuring the refractive index profile of optical fibers and is based on illuminating the entrance of a fiber with a focused beam whose vertex angle greatly exceeds the acceptance angle of the fiber immersed in an index matching liquid. What one observes are then the refracted unguided rays rather than the guided rays. Nevertheless, the standard refracted near-field technique cannot be applied to a wide range of optical fibers e.g. if their shapes are not axially symmetric. In this work we demonstrate a modified method which allows 2-D imaging of the refractive index profile and thereby overcoming the axial symmetric limitation of the standard RNF. The new system is operating at 630 nm and based on the same principle of the RNF, but the optical path is reversed and the light at the fiber end-facet is collected by an objective lens and detected by a CCD camera. The method does not require scanning over the fiber end-facet. Thus the system is faster and less sensitive to vibrations and external conditions compared to the standard RNF, furthermore it allows averaging to improve the signal to noise ratio. The spatial resolution of the system is determined by the numerical aperture of the objective and by the resolution of the CCD camera. To calibrate the setup, a multi-step index reference fiber provided by National Physical Laboratory was used.

Coherent perfect absorption in silicon

Lorelle N. Pye, Ayman F. Abouraddy, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

In this paper, by sculpting a material's photonic environment, we sever the link between the effective absorption of a structure and its intrinsic material absorption. Specifically, we embed a thin polycrystalline Si film in a Fabry-Pérot (FP) resonator comprising few-μm-thick, aperiodic, multilayer dielectric mirrors. Utilizing this structure, we demonstrate spectrally flat, coherent perfect absorption in a 2-μm-thick Si film achieved on resonance, across an octave of bandwidth in the NIR, ~ 800 – 1600 nm. A central insight for increasing the CPA bandwidth is provided by a theoretical model: the decline in Si absorption at longer wavelengths necessitates the use of cavity mirrors whose reflectivity amplitude increases in-step with wavelength. Our work introduces decisive advances in addition to our record CPA bandwidth achieved. In contrast to previous studies in which two coherently interfering beams were necessary [1], we use a single-beam configuration in symmetric structures to obtain the same total absorption as in two-beam-CPA, or twice that of two-beam-CPA in optimized asymmetric structures. This approach thus facilitates utilizing incoherent – rather than coherent – light, thereby expanding the scope of potential applications. Our strategy for coherently enhancing absorption is amenable to a wide range of materials other than Si and uses only planar technology, readily allowing implementation on large surface areas and flexible substrates.

Highly nonlinear chalcogenide optical fibers with flattened chromatic dispersion invariant to the core fluctuation and their performances of parametric amplification

Hoang Tuan Tong, Kenshiro Nagasaka, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

Highly nonlinear chalcogenide double-clad fibers with flattened chromatic dispersion were studied for optical parametric amplification (OPA). When the core diameter varied from 2 to 8 μm and the inner cladding diameter was 9 μm, very broad and flattened anomalous dispersion regions (<10 ps/km-nm) were obtained from 5.0 μm to 11.5 μm and the suppression of dispersion fluctuation was observed. The OPA calculation was performed using a 3-cm-long fiber with 2-μm-diameter core. A very broad and flattened gain spectrum was obtained (about 31 ± 2 dB) from 3.3 to 4.0 μm and from 7.0 up to 11.0 μm.

KY3F10:Er3+/Yb3+ nanocrystals doped laser-induced self-written waveguide for optical amplification in the C band

Xiaojie Xue, Tonglei Cheng, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

We successfully synthesized Er3+/Yb3+ co-doped KY3F10 nanocrystals by a facile hydrothermal method. The average size of the as-prepared nanocrystals was about 20 nm based on the observation of scanning electron microscope and transmission electron microscope. FTIR spectrum indicates citrate ligands were adsorbed on the surface of the obtained nanocrystals. Under the excitation of a 976 nm laser, the Er3+/Yb3+ doped KY3F10 nanocrystals showed intense near-infrared emission band centered at 1530 nm. The optimal concentrations of Yb3+ and Er3+ were carefully decided according to the quantum yield and fluorescence lifetime measurement for a stronger emission in the C band. The as-prepared nanocrystals were dispersed into a monomer, bisphenol A ethoxylate diacrylates in which self-written waveguides can be fabricated under the irradiation of the induced laser at 488 nm. The 65 mm long laser cavity was formed by a dichroic pump mirror. The 65 mm long laser cavity was formed by a dichroic pump mirror. The 65 mm long laser cavity was formed by a dichroic pump mirror. The 65 mm long laser cavity was formed by a dichroic pump mirror.
A key challenge for silicon photonic systems is the development of compact on-chip light sources. Thulium-doped fiber and waveguide lasers have recently generated interest for their highly efficient emission around 1.8 \( \mu m \), a wavelength range also of growing interest to silicon-chip based systems. Here, we report on highly-compact and low-threshold thulium-doped microdisk lasers integrated with silicon-compatible silicon nitride bus waveguides. The 200-\( \mu m \)-diameter thulium microlasers are enabled by a novel high-Q design, which includes two silicon nitride layers and a silicon dioxide trench filled with thulium-doped aluminum oxide. Similar, passive (undoped) microcavity structures exhibit quality factors as high as 5.7 \( \times 10^5 \) at 1550nm. We show lasing around 1.8-1.9 \( \mu m \) in aluminum oxide microdisks doped with 2.5 \( \times 10^20 \) cm\(^{-3}\) thulium concentration and under either 785- or 1614-nm diode laser pumping. Under resonant pumping around 1.6 \( \mu m \) and at optimized waveguide-microdisk gap, we observe laser thresholds as low as 775 \( \mu W \) and slope efficiencies as high as 23.5%. The entire fabrication process, including back-end deposition of the gain medium, is silicon-compatible and allows for co-integration with other silicon-based photonic devices for applications such as communications and sensing.

9744-34, Session 9

**Optical Excitation of Er Centers in GaN Epilayers grown by MOCVD (Invited Paper)**

Vin Nguyen, Deepu K George, Matt D Hawkins, Virginia Polytechnic Institute and State Univ. (United States); Hongxing X Jiang, Jingyu Y Lin, Texas Tech University (United States); John M Zavada, NYU Tandon School of Engineering (United States)

We report direct evidence of two mechanisms responsible for the excitation of optically active Er\(^{3+}\) ions in GaN epilayers grown by metal-organic chemical vapor deposition. These mechanisms, resonant excitation via the higher-lying inner 4f shell transitions and band-to-band excitation of the semiconductor host, lead to narrow emission lines from isolated and the defect-related Er centers. However, these centers have different photoluminescence spectra, decay dynamics, and excitation cross sections. The isolated Er optical center, which can be excited by either mechanism, has the same decay dynamics, but possesses a much higher cross-section under band-to-band excitation. In contrast, the defect-related Er center can only be excited through band-to-band excitation but has the largest cross-section. These results explain the difficulty in achieving gain in Er doped GaN and indicate new approaches for realization of optical amplification, and possibly lasing, at room temperature.

9744-35, Session 9

**Luminescence of lanthanide-doped nanocrystals**

Andries Meijerink, Freddy T. Rabouw, Tim Senden, Yiming Zhao, Celso Donega, Utrecht Univ. (Netherlands)

In nanocrystalline semiconductors (also known as quantum dots, QDs) quantum size effects are responsible for a change in the electronic structure in the nanocrystals as a function of particle size. Doping luminescent lanthanide ions in quantum dots gives further control over the optical properties and to test theoretical models, e.g. on the influence of refractive index on optical properties. Incorporation is however not trivial \cite{1}. Several classes of lanthanide doped nanocrystals will be discussed, including II-VI semiconductors like CdSe, CaS and SrS nanocrystals and LaPO\(_4\) insulators. Nanocrystals doped with luminescent lanthanides are promising e.g. in the field of bio-medical, also using afterglow or upconversion nanocrystals, and efficient solar cells.

In this presentation special attention will be given to the influence of the refractive index on radiative decay rates and energy transfer. We report photonic effects on the radiative decay rates and energy transfer rates in luminescent doped NCs using 4 nm LaPO\(_4\) NCs doped with Ce\(^{3+}\) or Tb\(^{3+}\) ions in different refractive index solvents and bulk crystals. The measured influence of the refractive index on the radiative decay rate of the Ce\(^{3+}\) emission, with near unity QY, is in excellent agreement with the theoretical nanocrystal-cavity model \cite{2}. Finally, experiments on Ce\(^{3+}\), Tb\(^{3+}\) co-doped LaPO\(_4\) NCs demonstrates that the absolute energy transfer rate is not affected by the refractive index of the medium surrounding the NC which makes it possible to tune the energy transfer efficiency by embedding the NC in different photonic environments \cite{3}.

References


9744-36, Session 9

**Efficient 800nm upconversion luminescence emission in 1.319\( \mu m \) excited thulium-doped fluorogermanate**

Artur S. Gouveia-Neto, Marcos V. D. Vermelho, Carlos J. Silva, Evandro J. T. A. Gouveia, Univ. Federal de Alagoas (Brazil); Luciano A. Bueno, Univ. de Sorocaba (Brazil)

Rare-earth doped frequency up-converters have drawn much scientific and technological interest lately owing to their potential application in color displays technology, optical sensing devices, visible solid-state lasers, biological markers, biomedicine, amongst many. Particularly, for applications in biomedicine such as fluorescence based nano-thermometers and fluorescence based bio-imaging, one has to take into account the requirement of producing and/or using light sources within the two biological windows. For such application, the penetration depth of the excitation light source is a major concern, and 1.319 \( \mu m \) is within the vicinity of the minimum absorption of the second biological window. Furthermore, the fluorescence emission light within one of the two biological windows is desirable.

The generation of near-infrared light within the first biological optical window via frequency upconversion in Tm\(^{3+}\)-doped PbGeO\(_3\)-PbF\(_2\)-CdF\(_2\) fluorogermanate glass excited at 1.319 \( \mu m \) is reported. The upconversion emission signal at 800 nm is the sole light emission observed in the entire UV-VIS-NIR spectral region. Luminescence emission around 1480, and 1800 nm was also observed. The proposed excitation mechanism for the 800 nm thulium emitting level is assigned to a multphonon-assisted excitation from the ground-state 3H\(_6\) to the 3H\(_4\) excited-state level, a rapid relaxation to the 3H\(_4\) level and followed by an excited-state absorption of the pump photons mediated by multophonons connecting the 3H\(_4\) level to the 3F\(_4\) emitting level. The dependence of the 800 nm signal upon the temperature was investigated and results showed an increase by a factor of 2.5 when the sample temperature increased in the 25 \( ^\circ\)C - 270 \( ^\circ\)C range. Generation of detectable 690 nm and 480 nm emission for temperatures above 100 \( ^\circ\)C in addition to the intense 800 nm main signal, was also observed. The 690 nm signal increases by a factor of x5, in the 100 - 270 \( ^\circ\)C temperature range. The dependence of the 800 nm emission upon excitation power, and thulium content was also investigated.

9744-37, Session 9

**Light emission in the NIR and VIS from SIALON rare-earth-doped thin films for integrated optical devices**

Ivan Camps, Antonio Mariscal, Rosalia Serna, Consejo Superior de Investigaciones Científicas (Spain)

The design of planar integrated light emitting devices requires the suitable choice of a functional matrix and emitter. SiO\(_2\), Si\(_3\)N\(_4\), and Al\(_2\)O\(_3\) matrices
in thin film configuration are suitable hosts to develop compatible CMOS devices as they show excellent transparency in the NIR-VIS range and high stability. Light emission is achieved by embedding rare-earth (RE) ions. RE-doped mixed compounds such as oxyvitrides are attractive due to the possibility of varying the matrix composition in order to tune its optical and electric properties and recently light emission both under electrical and optical excitation has been reported [1]. Wavelength tunability is also possible since RE-doped nitrides show a longer wavelength emission compared to oxides due to the smaller electronegativity of N3− over O2−. Addition of AI2O3 helps to decrease RE ion clustering. Therefore bulk crystalline mixed compounds known as SIALONs have been studied as phosphors.[2]

In the present work we will show successful emission in the NIR- VIS range of SIALON amorphous thin films doped with Er3+, Eu3+ or Eu2+ ions. Their light emission can be modified as a function of the RE distribution and concentration. Furthermore proper deposition conditions and thermal treatments allow controlling the Eu oxidation state to obtain either a narrow red peak or a wide white band emission. These glassy films are promising to develop planar integrated components with tunable properties.


9744-38, Session 10
Metamaterial nanostructures with tuneable properties for optical switching
Johann Toudert, Alexander Cuadrado, Rosalía Serna, Consejo Superior de Investigaciones Científicas (Spain)

Optical metamaterials are engineered using nano-elements as building blocks in order to provide different ways of manipulating light with the aim to develop of lightweight and ultracompact photonics solutions. Most of the existing optical metamaterials operate in the near infrared to microwave range and are based on noble metal plasmonic nanostructures. However these noble metal nanostructures are not reconfigurable or tuneable. However the development of optical components showing typical field enhancement plasmonic properties and that at the same time can be tuned under external excitation is desirable in order to develop devices such as optical switches, optical limiters or active filters. These functionalities can be achieved by identifying non-conventional elements and compounds that show plasmatic-like properties and that show tuneable properties.

In this presentation, we will first discuss the properties of some of the most promising non-conventional nano-elements for building reconfigurable plasmonic metamaterials. Among them, semi-metallic nano-elements (Bi, Ga, Sb) are especially relevant due: i) to their solid-liquid phase transition that can be activated by thermostatic, laser, Joule or plasmonic heating, ii) the strong optical contrast between the nanoparticles with solid interband polaritonic phase and liquid plasmonic phase in the near infrared, visible, and extending to the ultraviolet range. Finally we will show simulation and experimental results of optical switching and reconfigurability in metamaterials built from Bi nanoparticles.1


9744-39, Session 10
Dynamic control of a Fano resonance with a fully integrated silicon nanostructure
Arijit Bera, Matthieu Roussye, Markku Kuittinen, Seppo Honkanen, Univ. of Eastern Finland (Finland)

Integrated silicon photonics promises to offer versatile platforms for electro-optic as well as all-optical interconnects, to meet the ever-growing demand for faster data transfer and logic operations (in the chip-scale), with lower power consumption compared to electrical interconnects. In addition, it caters efficient on-chip solutions for chemical and bio-molecule sensing for faster and reliable disease diagnostics.

A Fano resonance is generated by the interference of a Lorentzian response with the background radiation continuum. Compared to the resonant structures showing a Lorentzian lineshape, the structures with Fano response offer faster switching dynamics and higher modulation contrast at low power levels, because of its sharp spectral feature. It also promises superior sensing capability. Moreover, the dynamic tunability of the Fano resonance by electro-optical means can be useful for on-chip realization of electro-optical modulators with faster response and lower power consumption.

With a view to develop a dynamically controllable Fano-resonant platform, we have employed a merged photonic crystal – slot waveguide (MPCSW) structure. It involves silicon slot waveguides merged with Bragg mirror sections, formed by periodically patterning the rails. A defect between the two Bragg mirror sections creates a resonant cavity with a Lorentzian response. To achieve the Fano response, we have arranged three MPCSW structures in a parallel-coupling scheme. For the dynamic tunability of the resonance, an electro-optic chromophore is considered as the cover material for the slotted geometry. The evolution of the Fano line-shape with the variation of different structural parameters as well as its dynamic control by electro-optical means are studied.

9744-40, Session 10
Spectral selective perfect light absorption in ultra-thin silicon films on aluminum for color filters
Seyed Sadreddin Mirshafieyan, Junpeng Guo, The Univ. of Alabama in Huntsville (United States)

Silicon and aluminum are two most abundant and low cost materials in the nature. In this work, we use silicon on aluminum and have demonstrated wavelength selective perfect light absorption in single ultra-thin silicon films deposited on aluminum surface in the visible spectral range. The perfect light absorption is due to the critical coupling of the incident light to the second-order Fabry-Perot mode of the optical cavity formed by the silicon nanolayer deposited on aluminum surface. Perfect light absorption wavelength varies with the thickness of the silicon film. Spectral selective perfect light absorption results in vivid optical colors which vary with the silicon film thickness. The optical colors of devices do not change with the increase of the viewing angle. The demonstrated silicon optical filter technology, which is intrinsically low cost and compatible with silicon processing platform, can be used for optical displays.

9744-41, Session 10
Pseudo-circulator implemented as a multimode fiber coupler
Francis Bulota, Philippe Bélanger, Mikaël Leduc, Caroline Boudoux, Nicolas Godbout, Ecole Polytechnique de Montréal (Canada)

We present a linear all-fiber device exhibiting the functionality of a circulator. We define a pseudo-circulator as a linear three-port component that transfers most of a multimode light signal from Port 1 to Port 2, and from Port 2 to Port 3. Unlike a traditional circulator which depends on a nonlinear phenomenon to achieve a non-reciprocal behavior, our device is a linear component that seemingly breaks the principle of reciprocity by exploiting variations of etendue of the multimode fibers in the coupler.

The pseudo-circulator is implemented as a 2x2 asymmetric multimode fiber coupler, fabricated using the fusion-tapering technique. The coupler is asymmetric in its transverse fused section. The two multimode fibers differ in area, thus favoring the transfer of light from the smaller to the bigger fiber. The desired difference of area is obtained by tapering one of the fiber before the fusion process.
Using this technique, we have successfully fabricated a pseudo-circulator surpassing in efficiency a 50/50 beam-splitter. The transmission exceeds 87% from Port 1 to Port 2 (the rest nearly all going to Port 4), and 88% from Port 2 to Port 3 (the rest going to Port 1).

9744-43, Session 10
Lithium-niobate-integrated photonic crystal and waveguides
Soon Thor Lim, Thomas Ang, A*STAR Institute of High Performance Computing (Singapore); Ching Eng Png, A*STAR Institute of High Performance Computing (Singapore) and Optic2Connect Pte Ltd. (Singapore); Jun Deng, Siemens Ltd. (China); Aaron J. Danner, National Univ. of Singapore (Singapore)

We have successfully fabricated and measured PhCs patterned on a Lithium Niobate (LiNbO3) annealed photon exchanged (APE) waveguide. To improve the etching of photon exchanged (PE) LiNbO3, we used a SF6/Ar inductively coupled plasma (ICP) technique to achieve deep anisotropic etching and a smooth surface. Our results suggest that a high etching rate and a smooth post-etch surface condition can be obtained without He cooling. Higher reactive ion etching (RIE) power can improve the etching rate and surface condition, also leading to highly anisotropic etching. Total gas flow is a key parameter that affects etching results, and an optimized gas flow (50 sccm) was used for lengthy etching processes (30 min). Deep (> 3 µm) and highly anisotropic etching, as well as ultra smooth LiNbO3 surfaces can be achieved in a single-step run, with parameters of 30 minutes at 800 W ICP power, 90 W RIE power, 7mTorr chamber pressure and 50 sccm total gas flow. Our SIMS data indicate that after 5 hours exchange time a PE layer of 3?m can be obtained. The depth of holes was 2 µm by applying a large milling current. We presented theoretical and experimental characterization of the PhC waveguide and a well-defined PBG was observed from the transmission spectra. The extinction ratio was estimated to be approximately 15 dB. Optical transmission results indicate that deep air holes can lead to a sharp band edge. This PhC waveguide is a good candidate for further development of an ultra-compact, low-voltage LiNbO3 modulator.

9744-6, Poster Session
Coherent mid-infrared supercontinuum generation in all-solid chalcogenide microstructured fibers with all-normal dispersion
Lai Liu, Tonglei Cheng, Kenshiro Nagasaka, Hoang Tuan Tong, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

All-normal dispersion fibers as the best candidate for coherent supercontinuum (SC) light sources have been studied extensively in recent years. A feasible method for extending the spectral bandwidth is the use of nonlinear all-solid soft glass microstructured fibers (MSF). The idea is to use a holey fiber design, in which the air-holes are filled with solid rods made of glass with thermal properties matched to the core and lattice glass, but with a different value of the refractive index. Their advantage over the air-hole MSFs is the additional flexibility of dispersion engineering, which is achieved not only through manipulation of waveguide dispersion, but also is influenced by the material dispersions of the pair of glasses. Klimczak et al. reported a coherent SC generation with the long wavelength edge extended to 2.3 µm in a non-silica MSF with all-normal dispersion. We report the first demonstration of coherent mid-infrared SC generation in all-solid chalcogenide MSF with all-normal dispersion. The chalcogenide MSF is four-hole structure with core material of AsSe2 and air holes are replaced by As2S3 glass rod to achieve all-normal dispersion profile.

Coherent mid-infrared SC light expanding from 2.25 - 3.3 µm is generated in a 2-cm-long chalcogenide MSF pumped by a 2.7 µm laser. The simulated and experimental results have a good match and the coherence property of SC light in the chalcogenide MSF has been studied by using the complex degree of coherence theory. This work further extended the coherent mid-infrared SC generation to 3.3 µm.

9744-7, Poster Session
Supercontinuum generation in a suspended core birefringent tellurite microstructured optical fiber pumped in telecommunication band by a picosecond laser
Lei Zhang, Hoang Tuan Tong, Harutaka Kawamura, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

Based on a suspended core birefringent tellurite microstructured optical fiber (BTMOF), the supercontinuum spectra are generated by pumping near the zero dispersion wavelengths (ZDWs) in the telecommunication band with a tunable picosecond laser. The ZDWs of the suspended core BTMOF are calculated to be 1532 nm and 1560 nm for the X-axis and Y-axis, respectively. When the pump is polarized along the X-axis, the supercontinuum broaden is governed by the nonlinear effects of stimulated Raman scattering (SRS) and dispersive wave (DW) generation. When the pump is polarized along the Y-axis, the supercontinuum broaden is governed by the nonlinear effects of four-wave mixing (FWM) and cross-phase modulation (XPM).

9744-42, Poster Session
Low polarization dependent loss of InP-based waveguide photodetector integrated with spot-size converter for 100Gb/s coherent receiver
Young-Ho Ko, Joong-Seon Choe, Won-Seok Han, Jong-Hoi Kim, Yong-Hwan Kwon, Electronics and Telecommunications Research Institute (Korea, Republic of)

The rapid increase of data traffic has led the optical communication to adopt the digital modulation techniques such as dual-polarization quadrature phase shift keying (DP-QPSK), and quadrature amplitude modulation, etc. Such advanced modulation techniques require complicated coherent receiver combined with the optical hybrid and balanced photodetector (PD) arrays. Because the integration of the PD arrays and planar lightwave circuit is important, the spot-size converter (SSC) is introduced to enhance the coupling efficiency with evanescently-coupled waveguide (WG) PD. However, semiconductor-based SSC and WG cannot normally have symmetric cross-section between lateral and vertical direction. So they have different propagation behavior between TE- and TM- polarization, resulting in polarization dependent loss (PDL). Therefore, reducing the PDL is critical issue in SSC-integrated with WG PD as well as increasing the responsivity. In this study, we successfully realized low PDL and high responsivity by adopting the laterally-tapered structure for SSC-integrated WG PD. The WG PD integrated with SSC was designed as the diluted WG, dual taper, and absorber of PD, respectively. The shape and thickness of each structure were determined through the simulation of 3D finite-difference beam propagation method. Although the evanescent coupling was highly sensitive, we optimized the structures with simulated responsivity and...
PDL as 0.75 A/W and 0.12 dB, respectively. We successfully obtained the SSC-integrated W6 PD through numerous fabrication processes including photolithography. Fabricated PDs had almost similar responsivity and PDL with the simulation results. The responsivity and PDL were measured as 0.7 A/W and 0.3 dB respectively. The 3 dB-bandwidth was measured as 35 GHz. Finally, we demonstrated the coherent receiver operated at more than 100 Gb/s DP-QPSK.

9744-45, Poster Session

**Freeform lens for uniform illumination by an extended light source**

Sina Babadi, Roberto Ramirez-Iniguez, Tuleen Boutaleb, Glasgow Caledonian Univ. (United Kingdom); Tapas Mallick, Univ. of Exeter (United Kingdom)

This paper presents an efficient and practical design process for a first or secondary optic to be used with an LED to increase uniform illumination. The design method of the freeform lens is explained by assuming two scenarios: (i) the use of an isotropic or Lambertian point source as the source of illumination (ii) the use of an isotropic or Lambertian extended source as the source of illumination.

This freeform lens structures provide uniform illumination based on the energy mapping between the light source and the target plane. This energy mapping is considered in the solid angle calculation to transfer the specified amount of energy to the specific areas to provide uniform illumination. The iterative algorithm uses semi-automated schemes where the designer can interactively modify the optimisation parameters until a satisfactory pattern is achieved.

The percentage of the uniformity will be improved by increasing the number of the divisions on the target plane. Then, ZEMAX ray tracing simulations evaluate the uniformity with different light sources. Finally ZEMAX shows the uniformity decreases gradually by increasing the size of the light source. In addition, two methods have been proposed to tackle the effect of the extended light sources on the uniformity. The simulation results show that it is possible to obtain over 98% uniformity when the free-form lens is combined with the point source.

9744-46, Poster Session

**SiPM optimization for 3D ranging applications**

Carl Jackson, Stephen J. Bellis, Steve Buckley, Deborah Herbert, SensL. (Ireland)

The Silicon Photomultiplier (SiPM) is a single-photon sensitive, high performance, solid-state sensor. It is formed of a summed array of closely-packed SPAD sensors with integrated quench resistors, resulting in a compact sensor that has high gain (>1e6), high detection efficiency (>50%) and fast timing (sub-ns rise times) all achieved at a bias voltage of ~30V. There are an increasing number of ranging & sensing applications looking to benefit from low-power, high-performance SiPM technology. In particular, LiDAR (light detection and ranging) applications that use NIR wavelengths such as ADAS (Advanced Driver Assistance Systems), gesture recognition and autofocus.

SensL’s existing SiPM technology was designed for blue-green detection, but has now been optimized for NIR sensitivity. This new sensor fabrication process is based on an N-on-P structure that maximizes the detection of the longer wavelength photons. The process is capable of fabricating both SPAD and SiPM sensors, and sensor arrays.

SensL has demonstrated the ranging abilities of SiPM and SPAD sensors with 905nm laser with 4ns wide pulse width in full daylight conditions. Furthermore, a study has been undertaken to compare ranging results possible with SiPM and SPAD sensors manufactured with improved red sensitivity. Results will be presented using different lasers and comparing the results from a variety of sensor types. It was found that particular sensor types may be more suited to certain applications and measurement techniques (leading edge time of flight, or TCSPC).

9744-47, Poster Session

**Gain control dynamics of thulium-doped fibre amplifier at 2 μm**

Mustafa A. Kharnis, Karin M. Ennser, Swansea Univ. (United Kingdom)

Thulium doped fibre amplifiers (TDFAs) have been characterized and developed for optical communications, indicating low noise amplification and high gain in 2μm spectral region. The emission spectrum of the SF4 – 3H6 transition in T DFA covers about 30 THz (1700-2100 nm) of amplification bandwidth in a single device more than two times that of the Erbium doped fibre amplifier (EDFA) with the same configuration and complexity. In order to explore the large amplifier bandwidth, wavelength division multiplexing (WDM) technology can be used. However, as a result of channel add or drop in WDM networks, the average input power to T DFA varies with time which causes the dynamic gain variation of T DFA. Consequently, gain variations lead to increase power excursion which is defined as the ratio of maximum power to minimum power of the surviving channel. As a consequence, they restrict the distance of WDM transmission system and cause problematic transients and bit errors at the receiver.

This work investigates the dynamics behavior of optical gain control T DFA in reconfigurable WDM system at 2μm. The model of the T DFA as a two-level energy system is proposed. A recirculation lasing signal is injected in the amplifier to control the gain. The investigated system consists of 20 WDM channels with -15dBm peak power per channel. The simulation results show that about 1dB power excursion is produced after dropping 18 channels under unclamped gain amplifier. With only 10% increase of the pump power in a clamped configuration a significant reduction from 1dB to less than 0.01dB power excursion is obtained.

9744-48, Poster Session

**Optical and electrical properties of graphene/polymer heterostructure for optoelectronic applications**

Anjali Yadav, Saral Gupta, Chandra M. Negi, Gayatri Chauhan, Ajay Verma, Banasthali Univ. (India)

Recently, graphene has attracted the enormous research interest for a number of potential applications due to its remarkable electrical and optical properties such as high mobility and optical transparency. The application of graphene in optoelectronics can truly exploit its physical properties and enhance the device characteristics like optical detection over a wide spectral range from infrared to visible. However, the low optical absorption coefficient of graphene can restricts its applications in optical devices. To overcome this issue the graphene can be integrated with the polymer to form the polymer graphene heterostructure, which can enhance the optical and electrical properties. In this work, P3HT-graphene heterostructure was formed by depositing the thin films of organic polymer on the glass substrates coated with the Graphene. We investigate the optical and electrical properties of P3HT-graphene heterostructure for optoelectronic applications. The UV/VIS/NIR spectroscopy was used to determine the optical properties of the heterostructure. Morphological study of this heterostructure has been performed with the help of field emission scanning electron microscopy (FE-SEM). The electrical properties were investigated by Keithley source meter. The experimental results demonstrate the enhancement in absorption and conductivity of P3HT-graphene heterostructure in comparison with the P3HT thin films.
9744-49, Poster Session

Evolution of the mid-infrared higher-order soliton fission in a tapered tellurite microstructured optical fiber

Tonglei Cheng, Xiaojie Xue, Lai Liu, Weiqing Gao, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

The novel property of the mid-infrared (MIR) higher-order soliton fission in a tapered tellurite microstructured optical fiber (TMOF) is experimentally investigated. The TMOF is tapered to offer an ideal environment for the formation of optical solitons. From 30 to 80 mW, the redshift of the first fundamental soliton (SSFs) is obvious. From 80 to 120 mW, two fundamental solitons are obtained by the fission of the higher-order solitons. The redshift of the first fundamental soliton almost stops because the increased pump power is preferentially distributed to the second fundamental soliton. From 120 to 180 mW, obvious redshift of the first fundamental soliton is observed again, and a third fundamental soliton is obtained at 180 mW. With the average pump power increasing to 220 mW, five fundamental solitons are observed.

9744-50, Poster Session

Electric field sensor using long pitch cholesteric liquid crystals

Myeong Ock Ko, Sung-Jo Kim, Jong-Hyun Kim, Min Yong Jeon, Chungnam National Univ. (Korea, Republic of)

Liquid crystal (LC) devices can be used as electric field sensors in the electric power industry because the molecular orientation of LCs is highly dependent on the external field. By inserting LC into the Fabry-Perot etalon, it is used to investigate the relation between field intensity and LC’s optical properties. The cholesteric LC (CLC) material has almost the same properties as the nematic LC except for a helical structure of the director. The CLC phase is obtained when a nematic phase is doped with chiral molecules. When non-polarized beam is normally incident on the cell, the circular polarization beam, which is identical in shape to the cholesteric helix, is reflected.

In this presentation, we propose a fiber-optic electric field sensor using CLC device, which has long pitch length. A compound of 4-cyano-4'-pentylbiphenyl (5CB, from Merck) nematic LC and chiral dopant S811 is used as a CLC cell. It consists of glass substrates, polyimide layers, electrodes, and CLC layer. The transmitted optical spectra as a function of the applied electric field to the CLC Fabry-Perot etalon were measured. The CLC cell is prepared using 10.34 wt% of S811 in the nematic LC. There is a threshold behavior for CLC cell and no change in the transmitted wavelength until a threshold value is reached. The threshold value is about 0.8 V/7m for fabricated CLC cell in the experiments.

9744-51, Poster Session

Multi-wavelength fiber laser based on liquid crystal Fabry-Perot device

Hyun Ji Lee, Myeong Ock Ko, Sung-Jo Kim, Jong-Hyun Kim, Min Yong Jeon, Chungnam National Univ. (Korea, Republic of)

Liquid crystals (LCs) are widely used for various applications such as electronic imaging, displays, and optoelectronics. In general, Fabry-Perot filters with LC have been developed for use in wavelength-division-multiplexing communication systems as they can be used as wavelength-tunable elements.

In this presentation, we report a multi-wavelength fiber laser using a nematic liquid crystal Fabry-Perot etalon. The device consists of glass substrates, indium tin oxide (ITO) layers as the electrodes, dielectric layers as highly reflective surfaces, polyimide layers as the planar alignment layers, and a liquid crystal layer. The thickness of the device is about 50 μm. The laser comprises a semiconductor optical amplifiers (SOA) as a gain medium, a polarization controller, two optical isolators, an optical output coupler, and a nematic liquid crystal Fabry-Perot filter. There are several lasing modes for the multi-wavelength fiber laser. The peaks of lasing wavelength move to shorter wavelength as the applied voltage to the LC increases.

9744-54, Poster Session

Design methods for tunable notch filters in shortwave infrared

Neelam Gupta, U.S. Army Research Lab. (United States); Mark S. Mirotznik, Univ. of Delaware (United States)

Tunable spectral filters are a key optical component in many applications such as optical communication systems, spectroscopic systems for chemical and biological sensing and in visible and infrared multispectral and hyperspectral imaging systems. As a result, a variety of tunable filters have been explored including acousto-optic tunable filters (AOTFs), liquid crystal tunable filters (LCTFs), Fabry-Perot (FP) filters, micro-electro-mechanical systems (MEMS) based tunable filters, metamaterial based filters, exotic non-linear optical materials based filters, etc. Not much research has been carried out to develop tunable notch filters useful for narrow spectral line rejection such that all the radiation is transmitted except a narrow spectral band that can be tuned in the spectral region of interest. Available commercial products offer fixed notch filtering operation which is inadequate for current application that uses a spectrally tuned light source. Design and simulation of tunable notch filters in the 1 to 2 micron shortwave infrared (SWIR) spectral region is investigated based on modeling layered optical materials with periodic structures using rigorous electromagnetic theory to find suitable optical materials and nanophotonic device structures that meet the spectral bandwidth, size, and optical density requirements. Both the rigorous coupled wave (RCW) and the finite difference time domain (FDTD) methods have been used to design metamaterial based tunable notch filters. Here, we will present design of tunable notch filters that transmit all wavelengths except the wavelength that needs to be rejected operating in 1 to 2 micron spectral region where the notch wavelength can be tuned over the entire region.

9744-55, Poster Session

Erbium-doped zinc-oxide waveguide amplifiers for hybrid photonic integrated circuits

Lawrence O’Neal, Deion Anthony, Carl E. Bonner Jr., Demetris L. Geddis, Norfolk State Univ. (United States)

CMOS logic circuits have entered the sub-100nm regime, and research is on-going to investigate the quantum effects that are apparent at this dimension. To avoid some of the constraints imposed by fabrication, entropy, energy, and interference considerations for nano-scale devices, many have begun designing hybrid and/or photonic integrated circuits. These circuits consist of transistors, light emitters, photodetectors, and electrical and optical waveguides.

As attenuation is a limiting factor in any communications system, it is advantageous to integrate a signal amplifier. There are numerous examples of electrical amplifiers, but in order to take advantage of the benefits provided by optically integrated systems, optical amplifiers are necessary. The erbium doped fiber amplifier is an example of an optical amplifier which is commercially available now, but the distance between the amplifier and the device benefiting from amplification can be decreased and provide greater functionality by providing local, on-chip amplification.

Zinc oxide is an attractive material due to its electrical and optical
properties. Its wide bandgap (~3.4 eV) and high refractive index (~2) make it an excellent choice for integrated optics systems. Moreover, erbium-doped zinc oxide (Er:ZnO) is a suitable candidate for optical waveguide amplifiers because of its compatibility with semiconductor processing technology, 1.54 µm luminescence, transparency, low resistivity, and amplification characteristics.

This research presents the characterization of radio frequency magnetron sputtered Er:ZnO, the design and fabrication of integrated waveguide amplifiers, and device analysis.

9744-56, Poster Session

Design of intrinsically single-mode double-clad crystalline fiber waveguides for high-power lasers

Da Li, Stephanie K. Meissner, Helmut E. Meissner, Onyx Optics Inc. (United States); Mark Dubinskii, U.S. Army Research Lab. (United States)

Recently, double-clad crystalline fiber waveguides (CFWs), consisting of single crystalline or ceramic RE3+:YAG cores of square cross section and inner claddings of either undoped or laser-inactive-ion-doped YAG and outer claddings of sapphire, have been successfully demonstrated. These waveguides, manufactured by an Adhesive-Free Bonding (AFB®) technique, can be precisely engineered and fabricated with very predictable beam propagation behavior. In this work, with high power laser designs in mind, minimum thicknesses for inner cladding are derived for different core cross sections and refractive index differences between the core and inner cladding and sapphire as outer cladding material for common laser core dopants such as Nd3+, Yb3+, Er3+, Tm3+ and Ho3+. All designs are intended to use high NA high power laser diode pumping to obtain high power intrinsically single transverse mode laser output. The obtained data are applicable to any crystalline fiber waveguide design, regardless of fabrication technique. As an example, a CFW with 40 µm × 40 µm 4% Tm:YAG core, 5% Yb:YAG inner cladding, and sapphire outer cladding was calculated to be intrinsically single transverse mode, with the minimum inner cladding width of 21.7 µm determined by the effective index technique [1].


9744-57, Poster Session

Power scaling analysis of crystalline fiber waveguides based on RE3+-doped YAG cores

Da Li, Stephanie K. Meissner, Helmut E. Meissner, Onyx Optics Inc. (United States); Mark Dubinskii, U.S. Army Research Lab. (United States)

Power scaling analysis based on the comprehensive model by Dawson et al. [1] has been applied to crystalline fiber waveguides (CFWs) with RE3+-doped single crystalline or ceramic YAG (RE=rare earth; Yb, Er, Tm and Ho). Considered power scaling limits include stimulated Brillouin scattering, thermal lensing effect, and limits to coupling of pump light into CFW. The CFW designs we considered consist, in general, of a square doped RE3+:YAG core, an inner cladding of either undoped or laser-inactive-ion-doped YAG and an outer cladding of sapphire. The presented data were developed for the structures fabricated using the Adhesive-Free Bonding (AFB®) technique, but the results should be essentially independent of fabrication technique, assuming perfect core/inner cladding/outer cladding interfaces.

Hard power scaling limits exist for a specific CFW design and are heavily based on the physical constants of the material and its spectroscopic specifics. For example, power scaling limit was determined as ~16 kW for 2.5% ceramic Yb:YAG/YAG (core material/inner cladding material) at fiber length of 1.7 m and core width of 69 µm. Considering manufacturing limit for CFW length to be, e.g., 0.5 m, the actual maximum output power will be limited to ~4.4 kW for Yb:YAG/YAG fiber composition. Comprehensive power limit estimates have also been computed for Er3+, Tm3+ and Ho3+doped core based CFWs.


9744-58, Poster Session

Polarization Confocal Raman Spectroscopy and AFM for Evaluation of Sidewalls in Type II Superlattices FPAs

Alexander A. Ukhanov, Pranav Rathi, Kevin J. Malloy, Actoprobe LLC (United States); Marvin Jaime-Vasquez, U.S. Army RDECOM CERDEC NVESD (United States); Dmitri A. Tenne, Boise State Univ. (United States); Elena Plis, SKInfrared LLC (United States); Fei-Hung Chu, Actoprobe LLC (United States); Sanjay Krishna, SKInfrared LLC (United States); Doug V Pete, Sandia National Laboratories, CINT (United States)

Long-wave (LW) and multicolor infrared (IR) detectors are desirable in a variety of applications related to remote sensing and object identification. Detectors based on mercury cadmium telluride (MCT) and quantum well infrared detectors (QWIPs) have been the dominant technologies for such applications. InAs/GaSb type-II strained layer superlattice (T2SL) detectors are predicted to have a number of advantages over MCT devices, including lower tunneling currents, suppressed Auger recombination, and an improved bandgap uniformity over large areas. By optimizing the oscillator strength in T2SL, a large quantum efficiency may be obtained that surmounts the inherent problem of QWIP detectors. Moreover, the commercial availability of substrates with good electro-optical homogeneity, and without large cluster defects, also offers advantages for T2SL technology.

However, due to complexity of InAs/GaSb system, etch and passivation of T2SL detectors is still an issue especially in LWIR spectral range. We propose to utilize the confocal Raman spectroscopy combined with the high resolution AFM technique to access the sidewall profiles of etched and passivated small (24 µm x 24 µm) focal plane array (FPA) features fabricated using LW/LWIR T2SL detector material. Special high aspect ratio Si and GaAs AFM probes, with tip length of 13 µm and tip aperture less than 7°, allow imaging of sidewall profile through optical sectioning. Raman spectra measured on etched T2SL FPA single pixels allow to quantify the non-uniformity of mesa delineation process. More experimental details on non-destructive characterization of T2SL FPAs will be discussed during the presentation.

9744-59, Poster Session

Low-power compact hybrid plasmonic double-microring electro-optical modulator

Aya O. Zaki, Nourhan H. Fouad, The American Univ. in Cairo (Egypt); Dimitrios C. Zografopoulos, Romeo Beccherellic, Consiglio Nazionale delle Ricerche (Italy); Mohamed A. Swillam, The American Univ. in Cairo (Egypt)

In this work, we present an electro-optical modulator based on electromagnetically induced transparency (EIT). Our modulator employs a conductor-gap-silicon (CGS) microring resonator on each side of the input...
waveguide in a push-pull configuration utilizing the embedded electro-optical polymer. CGS waveguides support hybrid plasmonic modes offering a compromise between mode confinement and propagation loss. The modulator is designed and analyzed using 3D finite difference time domain simulations (FDTD). To have a high quality resonator, the rings are designed to have moderate waveguide propagation losses and a sub-micron radius of \(R=705\) nm. With a capacitance of just sub femtoFarad with applied voltage of \(2\) V, the energy consumption is estimated to be few femtoFarad To the best of our knowledge, our proposed structure outperforms its counterpart in the power consumption and speed power consumption than ever reported.

9744-60, Poster Session

**A 1280 x 1024 15\(\mu\)m pitch hybrid silicon FPA for NIR imaging**

Selim Eminoglu, Mikro-Tasarim San. ve Tic. Ltd. Sti. (Turkey)

This paper reports the development of a new miniature 1280 x 1024 format 15 \(\mu\)m pitch hybrid Silicon FPA for NIR imaging applications. This new FPA is called MT-FPA12815SNIR, and it has been fabricated using our MT12815CA-3G low-noise CTIA ROIC product together with our silicon photodiode arrays, which are all fabricated using standard CMOS technologies. To demonstrate the key features of this FPA, a new compact NIR demo camera has been developed. This new NIR demo camera is called MT-NanoCam-12815NIR, and it has key features such as high integration level, low-noise, and low-power in a small volume. The camera has three gain settings in the ITR and IWR snapshot operating modes with Full Well-Capacity (FWC) values of 10,000 e-, 20,000 e-, and 350,000 e- in the very high gain (VHG), high-gain (HG), and low-gain (LG) modes, respectively. The camera has an input referred noise level of 10 e- rms in the VHG mode at 1 ms integration time, suitable for low-noise NIR imaging applications. The FPA is operated in the 8-output mode together with MTAS1410X8, an 8-channel ROIC driver and digitizer ASIC also designed by Mikro Tasarim. MTAS1410X8 has on-chip input buffers, programmable gain amplifiers (PGAs), and Analog-to-Digital Converters (ADCs) and offers native support for direct video output in Camera-Link Base and Medium configurations thus enabling highly-integrated camera electronics with smaller volume with reduced power dissipation. MT NanoCAM 12815SNIR demo camera measures 40mm x 40mm x 40mm and dissipates less than 1.0 W using a 3.6 V supply.

9744-61, Poster Session

**Modern collinear LiNbO3 acousto-optical filter for optical spectroscopy: the exploration of efficiency and spectral resolution**

Alexandre S. Shcherbakov, Adan O. Arellanes, Emanuele Bertone, Instituto Nacional de Astrofisica, Optica y Electronica (Mexico)

Our work is devoted to the collinear acousto-optical filter governed by the acoustic waves of finite amplitude. It represents a novel bulk-optical component, namely, the dispersive element for optical spectroscopy. This filter is based on specifically doped lithium niobate single crystal that unexpectedly works in the near ultraviolet range as well as this material usually works in the visible range. We examine the phenomena affecting the filter transmission efficiency and its resolution, i.e. the light-induced absorption and photorefraction.

A new nonlinear approach is used to characterize performances of this collinear LiNbO3 acousto-optical filter exploiting our revealed specific acousto-optical non-linearity. We have carried out the experiments with the collinear filter based on the congruent LiNbO3 crystal of 6.3 cm length at \(\lambda = 405\) and 440 nm to verify our analysis and estimations. We also explore an opportunity to trade an amount of the efficiency to improve the spectral resolution. The transmission efficiency steeply increases with increasing light wavelength and with decreasing length of the filter, nevertheless the efficiency still remains higher than 30% in the near ultraviolet, if the spectral resolution is limited by \(\Delta \lambda = 0.28\) to 0.29 Å. Moreover, we demonstrate the possibility to reach a resolution as high as \(\Delta \lambda = 0.12\) to 0.15 Å (R > 24600), preserving at the same time an efficiency higher than 10% over the spectral interval that we considered. It looks like our filter holds the best to our knowledge experimentally confirmed spectral resolution for any collinear acousto-optical spectrometers dedicated to space/airborne operations.
9745-1, Session 1

Progress of DNA nucleobase passivation layers for photonics and electronics (Invited Paper)

Fahima Ouchen, Air Force Research Lab. (United States); François Kajzar, Ileana Rau, Univ. Politehnica of Bucharest (Romania); James G. Grote, Air Force Research Lab. (United States)

Nucleobases have shown promise for use as passivation layers in both photonic and electronic applications. This includes charge blocking layers for polymer capacitors, increasing energy densities by as much as 3X, nonlinear optical polariton electro-optic modulators, increasing nonlinearities by as much as 50%, and organic light emitting diodes, achieving record efficiencies. Used as an interface layer between graphene and the polymer gate dielectric for field effect transistors, charge carrier mobilities of the graphene have been maintained. Here we will report on the current progress of this research.

9745-2, Session 1

Studies of new optically active molecules interacting with DNA (Invited Paper)

Katarzyna Matczyszyn, Marco Deiana, Ziemowit Pokladek, Wrocław Univ. of Technology (Poland); Bastien Mettra, Ecole Normale Supérieure de Lyon (France); Joanna Olesiak-Banska, Wrocław Univ. of Technology (Poland); Cyrille Monnereau, Chantal Andraud, Ecole Normale Supérieure de Lyon (France); Marek Samoc, Wrocław Univ. of Technology (Poland)

Studies of the interactions between dye molecules and nucleic acids are crucial for any applications of the dyes for imaging or manipulating DNA. The intercalation or groove binding lead to optical changes which can be used for monitoring the binding processes. Host-drug complexation can be thus studied by numerous spectrophotometrical methods: UV-Vis absorption, fluorescence, circular dichroism. Analysis of the induced spectral effects reveals considerable detail about the host-drug binding site size as well as thermodynamics of complex formation.

A series of new photochromic aminoazobenzene molecules being potential DNA binders was synthesized and their spectroscopic properties were determined. The kinetics of photoisomerisation in solvents of various polarity and viscosity was measured. An important feature of the new molecules is their high water solubility which is crucial for any biological applications. Moreover, the molecules showed fluorescent properties, unusual for this class of materials, and very interesting from the application point of view, as potential markers in biology. It has been found that the cis compound is thermally stable and the energy of activation (Ea) of the dark cis-trans reaction is 133 kJ/mol which is about 30% higher than that for unsubstituted azobenzene and results in 4 days of the thermal recovery up to 50% of the trans form at room temperature.

A detailed description of the binding mode of another water soluble chromophore, with star-shaped oligomeric arms, an anthracenyl derivative, named Ant-PHEA, with salmon sperm DNA in physiological conditions (pH 7.25) is described. The results achieved by applying UV-vis absorption, fluorescence, Fourier transform infrared (FT-IR) and circular dichroism spectroscopy confirm that Ant-PHEA interacts mainly with the bases and the phosphate groups of DNA. The binding constants calculated at 298, 304 and 310K were 2.63x10³, 2.70x10³, and 4.67x10³ L mol⁻¹, respectively. The melting temperature (Tm) of DNA and the DNA-antHracenyl derivative were determined, respectively.

Acknowledgments

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9745-3, Session 1

DNA-based membranes for multiple applications (Invited Paper)

Ileana Rau, François Kajzar, Mihaela Mindroiu, Gratiela T. Tihan, Ana-Maria Manea, Univ. Politehnica of Bucharest (Romania); Agnieszka Pawlicka, Instituto de Química de São Carlos (Brazil); Cristian Pirvu, Univ. Politehnica of Bucharest (Romania)

In this presentation we will report the results of our research on developing deoxyribonucleic acid (DNA)-based conducting membranes for application in electrochromic devices. Improvements of performances of DNA-based solid bioelectrolyte in smart windows were achieved by adding plasticizer like glycerol and different amounts of photosensitive chromophores chromophores like Nile Blue, Lithium Perchlorate, Prussian Blue. The membranes obtained were analyzed by a variety of experimental tools and techniques such as FT-IR, UV–VIS spectroscopy, fluorescence, electric conductivity, contact angle, charge density measurements, and c cyclic voltammetry. The biomembranes with the highest ionic conductivity values were successfully applied in smart windows with glass/ITO/WO3/ DNA-based membranes/CeO2-TiO2/ITO/glass configuration which have shown a good change of transmittance under the applied electric field. The obtained results suggest that the DNA-based electrolytes are promising materials to be applied in electrochromic devices.

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9745-4, Session 1

Living materials-opportunities with biopolymers for technological applications (Invited Paper)

Fiorenzo G. Omenetto, Tufts Univ. (United States)

Biomaterials offer opportunities for devices that operate seamlessly at the interface of the biological and technological worlds. Stringent requirements on material form and function are imposed when operating at the nanoscale or when interfacing such materials with microelectronic circuitry. Silk fibroin is a very attractive biopolymer for use as the starting point for nanostructured optical materials and thin-film electronics. Devices such as silk-based photonic crystals, lasers, wireless antennas and resorbable electronics will be described as some examples of the possibilities that this water-processed, biocompatible material offers.
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9745-5, Session 2

Photothermally-Activated Polymer Films for Harvesting of Near IR Energy with a Hybrid Cell Structure (Invited Paper)

Eunkyoung Kim, Teahoon Park, Jongbeom Na, Byeonggwan Kim, Younghoon Kim, Haejin Shin, Yonsei Univ. (Korea, Republic of)

Photothermal effects in conducting polymers have great potentials in applications for therapy, photo catalysts, energy harvester, and actuators. In particular the heat generated by light could provide sizable static energy sources from the living environment, through several energy conversion methods including thermoelectric (TE) and pyroelectric (PE) methods. Although the energy harvesting efficiency from TE and PE conversion is generally low, those can be coupled with hybrid energy harvesters employing two or more energy sources. CPs are suitable materials for a hybrid energy system because of their transparency in the dye absorption range plus high PT conversion. Herein, we report a PT/PE and PT/TE conversion using a CP film, which is inserted in a hybrid energy harvester designed to improve the energy harvesting efficiency from a NIR source. As a light flashed, the new hybrid energy system converted both light and heat from the flash into electricity to take advantage of the full spectrum of the sun’s radiation. This could then be used to operate an electrochromic display, realizing a solar driven display.

9745-6, Session 2

Organic solar cells: recent advances in simplifying device architecture (Invited Paper)

Bernard Kippelen, Talha M. Khan, Vladimir Kolesov, F. Larrain, Canek Fuentes-Hernandez, Georgia Institute of Technology (United States)

Organic photovoltaic devices have reached power conversion efficiencies above 10 % in small area laboratory cells. However, manufacturing such devices on a large scale and at low cost remains a challenge due to the complexity of the device architecture. In this talk, we will discuss the results of recent studies aimed at developing new strategies for collecting the photogenerated holes and electrons efficiently in devices with simplified architecture and increased stability. We will also focus on the modeling of organic solar cells using engineering-inspired equivalent circuit models and discuss how parasitic resistance influences the shape of their current-voltage characteristics. In particular, we will show that when these effects are properly mitigated, organic solar cells can be modeled with a simple Shockley diode equation and they can exhibit low dark current densities in reverse bias that can yield high performance photodetectors. Finally, we will present a new module geometry that leads to high voltage with large fill factors and total-area efficiency.

9745-7, Session 2

Organic molecules for photo-isomeric storage

Hal Gokturk, Ecoken (United States)

Organic molecules which absorb light and store the photon energy as a change in molecular conformation are promising for harvesting of solar energy. Azobenzene (C6H5-N=N-C6H5) and stilbene (C6H5-C=C-C6H5) are two examples of such molecules. Unfortunately the fraction of stored photon energy is less than 20% in both cases. In this research two modifications to the mentioned molecules are proposed to improve storage properties. In modification A, benzene rings in each molecule are replaced by pyridine rings (C5H4N-N=C5H4N, C5H4N=C=C5H4N). In modification B, one of the hydrogens in each benzene ring is replaced by a chlorine (Cl) atom (C6H4Cl-N=N-C6H4Cl, C6H4Cl=C=C6H4Cl). The intention in both cases is to create isomers that are planar with less strain in the chemical bonds.

The proposed molecules are analyzed by quantum mechanical calculations using the DFT method with B3LYP functional and Pople type basis sets. Original azobenzene and stilbene molecules serve as test cases for the calculation. Calculated values of the stored energy for the original and the modified molecules A, B are as follows:

Azobenzene: 0.66 eV, A: 0.96 eV, B: 1.73 eV
Stilbene: 0.22 eV, A: 0.19 eV, B: 0.88 eV

Results obtained for the original molecules are within 10% of those reported in the literature [1]. Stored energy values of azobenzene and stilbene molecules with the chlorine ligands (B) are 2.6 to 4 times higher than those of the original molecules.


9745-8, Session 2

Investigation of the microstructures of F8T2:PC71BM blends and their effects on bulk heterojunction ultraviolet photodetectors

Monica Esopi, Qiuming Yu, Univ. of Washington (United States)

Organic semiconductors are a promising technology for optoelectronic devices, including photodetectors. Many current field-based ultraviolet photodetectors involve fragile components like vacuum tubes, which could be replaced by cheaper, more durable organic devices. Organic photodetectors adopt similar device architectures to those of organic photovoltaic devices, in which light absorption layers (active layers) are typically blends of p-type semiconducting polymers and n-type fullerences. The active layer microstructure is critical to device performance because it significantly influences the processes of absorbing photons, generating and separating excitons, and trapping and transporting charge carriers. Therefore, the microstructures must be controlled and optimized to develop organic photodetectors with comparable or superior performance relative to existing inorganic photodetectors. In this work, we used a wide-band gap liquid-crystal polymer with high hole mobility, poly(9,9-diptyfluorene-alt-bithiophene) (F8T2) blended with (6,6)-phenyl-C71-butyric acid methyl ester (PC71BM) as the active layer to develop efficient and sensitive ultraviolet photodetectors. We controlled the microstructures by varying the weight ratios, annealing temperatures, and film thicknesses. The microstructure, surface morphology, and optical properties were investigated using TEM, AFM, UV-Vis spectroscopy, photoluminescence, and ellipsometry. Photodetector devices were fabricated with the structure of glass/ITO/PEDOT:PSS/F8T2:PC71BM/LiF/Al. The current-voltage characteristics of devices under dark and illuminated conditions were measured, along with the external quantum efficiency over the relevant wavelength range under varied reverse bias. Figures of merit for photodetectors, including responsivity, noise equivalent power, and detectivity were also evaluated. Correlations between the active layer microstructure and photodetector device performance could provide insights to guide the development of high performance organic photodetectors.

9745-9, Session 3

Parity-time symmetry in organic thin films and waveguides (Invited Paper)

Noel C. Giebink, The Pennsylvania State Univ. (United States)
Photic crystals have led to numerous technological advances in areas ranging from optical communications to solid-state lighting by manipulating the flow of light through nanoscale variation in refractive index. Recently, exploration has begun to focus on a more generalized form of photonic crystal with independent variation of the real and imaginary refractive index components. Such ‘complex index modulation’ has recently become the focus of intense theoretical interest because it forms the basis for parity-time (PT) symmetric optical potentials that enable one-way scattering potentials as well as more exotic effects such as unidirectional invisibility. Here, we demonstrate organic composite thin films and waveguides that exhibit passive PT symmetry by engineering their complex refractive index profile to be of the form $\text{Re}(n) \sim \text{Im}(n)$, which maximizes when $n=\text{Im}(k)$, marking an exceptional point transition to the broken PT phase that is supported by modeling. These results establish the basis for organic PT media that can be tuned for operation throughout the visible to near-infrared spectrum and provide a direct pathway to incorporate gain sufficient to achieve active PT symmetric lattices and gratings.

9745-10, Session 3

**Functionalization of light induced self-written waveguides and their interactions in photopolymers.** *(Invited Paper)*

Loic Mager, Kokou Dodzi H. Dorkenoo, Alberto Barsella, Institut de Physique et Chimie des Matériaux de Strasbourg (France)

Photopolymerization comes with a densification of the medium and consequently an increase of the refractive index. This photoinduced refractive index variation can be considered as an optical nonlinearity enabling the observation of solitonic propagation of light. As photopolymerization is an irreversible reaction, the solitonic propagation writes a permanent channel acting as an optical waveguide. These light induced self-written waveguides (LISW) can also be inscribed in materials functionalized with optically active molecules enabling the integration of optical properties (phase modulation, fluorescence…). To achieve this goal, the full comprehension of the interacting processes leading to the construction of the LISW in photopolymers is needed in order to control their final properties and their interactions.

As the modelization of the LISW propagation found in the literature was not able to fully match our observations, we have improved the description introducing the diffusion of the monomer in the material. Taking into account the diffusion allows also a better description of the variation of the LISW index profile along the propagation direction and especially the oscillation of the guide diameter.

9745-11, Session 3

**Ultrahigh refractive index chalcogenide based copolymers for infrared optics**

Soha Namnabat, Laura E. Anderson, Jeffrey Pyun, The Univ. of Arizona (United States); Robert A. Norwood, College of Optical Sciences, The Univ. of Arizona (United States)

Current trends in technology development demand increased miniaturization and higher level integration of electronic and photonic components. Such needs arise in emerging imaging systems, optoelectronic devices, optical interconnects and photonic integrated circuits. Compact, integrated photonics requires high refractive index materials, which primarily comprise crystalline and amorphous semiconductors, as well as chalcogenide glasses, which can possess refractive indices higher than 4 and good infrared transparency. There is currently no high refractive index (n ~ 2 or above) that has the low cost production and ease of processing available in optical polymers. Such polymers would potentially cover applications that are not convenient or possible with crystalline and vitreous semiconductors. Examples of such applications include micro lens arrays for image sensors, optical adhesives for bonding and antireflection coatings, and high contrast optical waveguides. While much of the focus has been in the telecommunications transparency regions, significant new opportunities exist for a polymer which is capable of transmitting efficiently in the MWIR region. While there are polymers that have been synthesized with refractive indices as high as 1.75, these polymers are generally conjugated and incorporate heteroatoms such as sulfur or metals, and generally have complex and expensive syntheses. Here we report new chalcogenide based cocomomers with very high refractive index (n ~ 2) that also have good optical transmission properties in the near-, short- and mid-wave infrared up to 5um. These polymers are rich in sulfur, have low hydrogen content and were made using inverse vulcanization.

9745-12, Session 3

**Fabrication of polymer based integrated photonic devices by maskless lithography**

Maik Rahlves, Leibniz Univ. Hannover (Germany)

We present our recent results on the fabrication of photonic devices such as single-mode- and few-mode photonic bandgap structures, as well as integrated interferometric sensor devices. The photonic components were fabricated on a polymethylmethacrylate (PMMA) substrate, which was coated with photosensitive polymers such as OrmocompTM (Microresist Technology, Germany), among others. To generate light guiding structures and sensor elements, we utilized a novel maskless lithography setup, which consists of a conventional microscope and a spatial light modulator (SLM). The SLM generates a pattern of the desired photonic structure, which is projected onto the substrate. Using a light emitting diode with a center wavelength of 405 nm, we polymerize the photosensitive polymer in a defined pattern, thus, forming the cores of the wave guiding structures. After a development process and a hard bake of the core material, we apply a PMMA as upper cladding by a simple thermal bonding process. In contrast to common single point processes such as laser direct writing, we are able to structure a larger area of several square millimeters during one illumination step, which is then extended to several square centimeters by a stitching process. We demonstrated integrated photonic structures with feature sizes below one micron. In addition, we characterized the photonic devices with respect to attenuation, cross-talk, and general optical performance such as coupling efficiency and interference contrast. In future applications, we aim at small, cost-effective custom made lab-on-chip devices for biomedical applications and chemical sensing.

9745-13, Session 4

**3D printing of natural organic materials by photochemistry** *(Keynote Presentation)*

Patrice L. Baldeck, Ecole Normale Supérieure de Lyon (France)

The 3D printing of natural organic materials is important for biomedical applications, but also to develop green 3D water-based processes of natural and biodegradable materials. Polylactic acid, a thermoplastic polymer derived from corn starch, tapioca roots, or sugarcane, is one of the rare bioplastics that can be used in fused deposition modeling (FDM)
3D printing. Most organic materials are sensitive to heat treatment. Thus, 3D printing processes of natural organic materials will most likely use photochemistry steps to crosslink their macromolecules dispersed in water solutions.

Early works on photo-crosslinking natural biopolymers targeted the fabrication drug microcapsules, and biodegradable scaffolds by free radical polymerization of polysaccharides (alginate, chitosan, hyaluronic acid,...). Recently, researches on two-photon induced photochemistry have demonstrated the fabrication of bioactive 3D microstructures with polyurethanes (proteins, ...) by oxidation, then condensation of amino acid residues. Other researches on DNA from salmon waste have demonstrated the excellent optical and electronics properties of thin films.

In the first part of the lecture, I will review our works on two-photon fabrication of 3D microstructures based on proteins, anti-bodies, enzymes, and DNA with their applications: collagen lines to guide the movement of living cells, peptide modified GFP biosensing pads to detect Gram positive bacteria, red blood cell typing with anti-body pads, real time biochemistry with a 3D trypsin micro-reactor, 3D woodpiles and optical microscales with DNA.

In the second part of the lecture, I will present our first results on using commercial 3D photochemistry 3D printers to fabricate centimeter size objects made of different types of natural organic materials. Then, I will discuss their photochemistry reactions using Attenuated Total Reflectance (ATR) spectroscopy, and I will present the first characterizations of their thermal and mechanical properties.

9745-14, Session 4

Optical patterning and preparation of liquid crystalline elastomers: shape-changing materials (Invited Paper)

Timothy J. White, Air Force Research Lab. (United States)

Liquid crystalline elastomers are loosely crosslinked, anisotropic materials. Their salient features, with respect to other forms of stimuli-responsive soft matter, are exceptional actuation cycles of up to 400% as well “soft elasticity” (e.g. stretch at minimal stress). In this presentation, we summarize our recent efforts in developing materials chemistry amenable to arbitrary local control of the director profile within these materials. Enabled by these materials, we have demonstrated that complex actuators (including self-folding origami structures) and mechanical elements can be prepared by tailoring the local director profile including flexible devices in which soft and comparatively hard elastic segments can isolate sensitive electronic components.

9745-16, Session 4

Exploiting the intermolecular charge transfer state for organic near-infrared detectors

Bernhard Siegmund, Andreas Mischok, Johannes Benduhn, Donato F. Spoltore, Hartmut Fröb, Christian Körner, Karl Leo, Koen Vandewal, TU Dresden (Germany)

For organic solar cells, charge transfer (CT) states have been considered as free carrier recombination centers, limiting their open-circuit voltage [1]. Furthermore, CT absorption at photon energies below the optical gap of both donor and acceptor material has been utilized to enable near-infrared photo-detection between 650nm and 950nm [2]. However, due to the low absorption coefficient in the spectral region of CT absorption, such devices comprise photo-active layers exceeding 10 micrometers in thickness. This requires high external voltages on the order of 100V to extract the photo-generated carriers and implies very high dark currents limiting on-off ratios to below ten. Moreover, such thick devices are expected to exhibit slow response times.

In this work, we present a new photodetector device architecture of sub-micron thickness, based on organic materials, able to harvest long wavelength photons efficiently by absorption of the intermolecular charge-transfer state. We demonstrate external quantum efficiencies (EQE) measured at short-circuit exceeding 20%, on-off ratios in the order 10^4 due to low dark currents and specific detectivities in the order of 10^12 Jones. The peak detection wavelength is 950nm, using a blend of C60 and an electron donor with an optical gap of 850nm. This new type of photodetector competes in the near-infrared wavelength range with standard organic photo-detectors based on above gap absorption in terms of EQE and has the potential to extend their detection wavelength further into the infrared. The device is visible blind and can potentially be transparent. [1] Vandewal et al., Phys. Rev. B 81, 125204 (2010), DOI: 10.1103/PhysRevB.81.125204

have been made. Approaching the level of solutions provided by nature however is hindered by routine choice of materials. To this end recent years have witnessed a great effort to engineer mechanically flexible photonic devices using polymer substrates. On the other hand, biodegradability and biocompatibility still remains to be incorporated. Hence biomimetics holds the key to overcome the limitations of traditional materials in photonics design. Natural proteins such as sucker ring teeth (SRT) and silk for instance have remarkable mechanical and optical properties that exceed the endeavors of most synthetic and natural polymers. Here we demonstrate for the first time, toroidal whispering gallery mode resonators (WGM) fabricated entirely from protein structures such as SRT of Loligo vulgaris (European squid), its recombinant and silk from Bombyx mori. We provide here complete optical and material characterization of proteinaceous WGRMs, revealing high quality factors in microscale, tunability in thermo optic properties by hybrid material design and enhancement of Raman signatures. Our optical characterization demonstrates molecular level structural tunability with a recombinant SRT protein which cannot be achieved by traditional choice of materials. We also present a most simple application of a WGM as a natural protein add-drop filter, made of SRT protein. Our work shows that with protein-based materials optical, mechanical and thermal properties can be devised at the molecular level, and it lays the groundwork for future eco-friendly, flexible photonics device design.

9745-15, Session 5

Characterization of collagen liquid crystal organizations using polarization-resolved nonlinear optical microscopy

Claire Teulon, Ecole Polytechnique (France) and INSERM (France); Aurélien Titu, François Portier, Gervaise Mosser, Univ. Pierre et Marie Curie (France) and Collège de France (France); Marie-Claire Schanne-Klein, Ecole Polytechnique (France) and INSERM (France)

Collagen is the main component of connective tissues, including skin, cornea, arteries... and displays a highly organized 3D structure specific to each tissue. In situ visualization of this biopolymer is a major biomedical concern, as it can help to characterize its 3D distribution in healthy and pathological tissues and to guide tissue engineering. We are interested here in collagen model systems that display a liquid crystal organization, in order to decipher the physico-chemical conditions leading to a plywood-like structure similar to the one found in cornea [1].

Second harmonic generation (SHG) is a powerful technique to observe fibrillar collagen without any staining and with a good contrast. Two quantitative structural parameters can be gained with polarization-resolved second-harmonic generation (P-SHG) microscopy [2]: in-plane averaged orientation of molecules in the field of view and SHG signal anisotropy, which is related to the molecular structure and to the 3D orientation disorder inside the excitation volume (submicroscopic scale).

In this work, we use P-SHG microscopy to characterize those organized plywood-like structures, which is not possible with classic imaging modalities. We demonstrate the benefits of P-SHG microscopy to quantify the phase transitions and decipher their 3D structure, and in particular its good sensitivity to the orientation of collagen molecules.

Reference:

9745-17, Session 5

Photophysical properties and applications of functionalized acenes (Invited Paper)

John E. Anthony, Univ. of Kentucky (United States)

Acenes, the linearly-fused class of aromatic hydrocarbons, are most commonly exploited for their electronic properties in devices such as transistors and sensors. However, this class of materials also possess unique photophysical properties making them highly-tunable components for a number of photonic applications. The rapid decrease in optical gap as acene length increases makes changing oligomer length an effective tool for rough tuning of the color properties of acenes, while functionalization of the chromophore yields fine-tuning of the absorption properties. Other substituents have been disclosed that impact photostability, fluorescence quantum yield, and propensity to aggregate. In this talk, I will examine the various approaches to tuning the photophysical properties of acenes, and demonstrate how careful selection of oligomer size and functional group engineering yields a variety of acene systems for use in bio-imaging, light-emitting diode, wave-guiding and singlet fission applications.

9745-18, Session 5

Control of optical properties in metamaterial by nematic liquid crystals (Invited Paper)

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

Metamaterials are artificial optical materials with sub-wavelength inclusions designed to provide a novel macroscopic response not readily observed in nature. By incorporating a double-split ring resonator metamaterial possessing two orthogonal plasmonic resonances, we build polarization-sensitive optical elements operating in near IR spectral regime. When a twisted nematic cell is constructed with the metamaterial as one of two windows, transmission and reflection can be controlled by a photoisomerization process as well as by an electro-optic means. Furthermore, a phase-discontinuity metamaterial structure is employed to control the beam refraction electro-optically. Another example of 2D phase-discontinuity metamaterial will be introduced where optical spin Hall effect is demonstrated and explained in term of Berry phase and Berry curvature.

9745-20, Session 6

High-performance organic electro-optic materials enabling efficient optical modulation for dielectric photonics and silicon nanophotonics and plasmonics (Keynote Presentation)

Alex K. Y. Jen, Univ. of Washington (United States)

Recent research progress of organic electro-optic (OEO) materials with record-high Pockels coefficients, processing reliability and operational stability will be reviewed. These accomplishments are achieved through rational molecular design, concise synthesis, innovative in-device poling and processing of OEO materials. The attractive features of these high performance OEO materials and their hybrid photonic systems are extremely important for addressing the presently encountered limitations in optical interconnects with respect to bandwidth and power consumption, and can potentially transform technologies for ultrafast information processing and electromagnetic wave sensing.

9745-21, Session 6

Hybrid EO polymer modulator to CMOS compatible waveguides (Invited Paper)

Shiyoshi Yokoyama, Feng Qiu, Andrew Mark Spring, Kyushu Univ. (Japan)
Electro-optic (EO) polymers and their waveguide devices have received considerable attention in the photonics applications. In particular, compact EO modulators combined with the CMOS technology are desirable for a number of applications. This widespread compatibility enables the construction of the unique hybrid polymer device to the silicon waveguide. Therefore, the EO polymer has been explored to the silicon-organic-hybrid waveguide for the low driving voltage and large bandwidth applications.

The hybrid to silicon is the major challenge to demonstrate the novel EO polymer waveguide device. We used the ultra-thin silicon with a thickness of 30 nm and a width of 2 micro-m, and covered it by using the EO polymer. In such a hybrid waveguide, the optical field confines in the silicon and partly extends in to the EO polymer with the propagation loss of 4 dB/cm. Thus, we measured the half-wave voltage of 4.6 V at 1550 nm in the Mach-Zehnder modulator. TiO2 or Si3N4 is another potential substrate for the applications of the hybrid EO polymer waveguide devices. Their refractive indices are moderate, but higher than the EO polymer, so that we can manage the refractive index contrast to optimize the optical field confinement in the hybrid waveguide. We prepare the 300 nm-thick and 300 nm-width strip waveguide of TiO2, and measured the half-wave voltage of 2.4 V. We found that the EO activity can be increased to use the slot waveguide. The fabricated hybrid double slot TiO2 and EO polymer waveguide modulator shows the driving voltage of 1 V, and the propagation loss of 5 dB/cm.

9745-22, Session 6

Bias-free operation of EO polymer modulator using MMI coupler
Hiromu Sato, Kazuhiro Yamamoto, Hiroki Miura, Shiyoshi Yokoyama, Kyushu Univ. (Japan)

Electro-optic (EO) modulator is the important device for telecommunication, optical interconnect, millimeter and microwave photonics. The previous modulators made of lithium niobate (LiNbO3) have been widely acceptable and well investigated for the industrial application. Recently, telecommunication devices are required to reduce the power consumption because the communication traffic and electric power consumption in the photonic devices is increasing. The EO polymers have been exploited and utilized for the EO modulator due to their high EO activity. Therefore, the EO polymer Mach-Zehnder interference (M2I) modulators have been shown some better figure of the merits in materials and devices than those of inorganic crystals. In previous EO polymer MZI modulators, much attention has been focused on lowering the driving voltage and the high-bandwidth applications. Additionally high linear signal and voltage conversion becomes another device parameter of paramount importance. In this study, we designed and fabricated a bias-free MZI modulator by using a multimode interference (MMI)-splitter. The MMI splitter has a fine fabrication tolerance compared with the Y-splitter, and total power consumption of the bias-free device is lower than the conventional one. The measured half-wavelength voltage of the fabricated MMI modulator is 6.8 V at 1550nm. The insertion loss of the modulator can be reduced by further design and fabrication of the improved low-loss MMI structures.

9745-23, Session 6

Surface treatment of organic electro-optic polymers and devices for durability improvements
Yukihiro Tominari, Shukichi Tanaka, Isao Aoki, Akira Otomo, National Institute of Information and Communications Technology (Japan)

Organic electro-optic (EO) polymers have attracted much attention to their potential use of the ultra-high-speed optical modulators, optical frequency conversion devices, and many other applications. One of the reasons should be their excellent property for the applications of photonic devices, such as large EO coefficient (r33) and the capability of higher frequency operation, compared to the case of widely used inorganic materials such as LiNbO3. However, to take advantage of these features, there still exist some technical problems to be solved, such as physical and chemical instabilities in the use of atmospheric condition. Because those instabilities are caused by photochemical reaction mediated by water or oxygen in the atmosphere, separation of the surface of organic components from atmospheric condition outside should be important. Atomic layer deposition (ALD) technique is a unique process to produce thin films on the surface at low temperature, with pinhole-free, high-conformal coverage of atomic scale precision, and seems ideal treatment to produce gas diffusion barrier layers on organic polymers. In this study, we deposited Al2O3 thin films on the surface of organic EO polymer films by means of ALD technique, and investigated the stability of the EO properties of polymer films against photo-irradiation in air. Based on the results obtained, the effect of Al2O3 films on the durability of optical devices expected by ALD-treatment will be discussed.

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9745-24, Session 6

Hybrid plasmonic/electro-optic polymer modulator
Fanghui Ren, Oregon State Univ. (United States); Qian Gao, Oregon State Univ (United States); Jingdong Luo III, Alex K. Y. Jen, Univ. of Washington (United States); Alan X. Wang, Oregon State Univ. (United States)

Electro-optic (E-O) modulators have been identified as the key components in optical communication systems due to the advantages of high speed, and low power consumption. Recently, surface-plasmon modulators have attracted great attention due to their potentials in enabling nano-scale on-chip photonics for high-density integration. Periodic metallic structures, which exhibit extraordinary optical transmission (EOT), have been intensively investigated in modulation applications owing to their stronger optical mode confinement, smaller footprint, and excellent manipulation to photons. In recent years, dynamic control over surface-plasmon polaritons (SPPs) has been realized by modulating the refractive index of the dielectric layer adjacent to the metal structure. Compared with other E-O materials, polymers show large Pockels effect across the RF to optical frequencies and are good candidates for high-speed application. Hybrid structures based on polymer-infiltrated gratings allow the combination of the high nonlinear optical effect with the strong field confinement. E-O polymer plasmonic waveguide modulators have been demonstrated recently, but they only allow in-plane photon manipulation with high insertion loss. Surface-normal modulators could achieve out-of-plane modulation and allow board-to-board free-space communication. In this work, we demonstrate a surface-normal plasmonic modulator with E-O polymer infiltrated in the sub-wavelength metal slits. The active control of the Fano resonance in the Au/polymer/ITO structure is enabled by tuning the refractive index of the E-O polymer when applied an electric field to the electrodes. Such structure shows high optical confinement and low optical loss, which are expandable and can be used for free-space 3-D optical interconnects or spatial light modulation.

9745-25, Session 7

Optimization of electrospinning techniques for the realization of nanofiber plastic lasers (Invited Paper)
Luana Persano, Maria Moffa, Consiglio Nazionale delle Ricerche (Italy); Vito Fasano, Martina Montinaro, Univ. del Salento (Italy); Giovanni Morello, Consiglio Nazionale delle
Control of photon transport properties in nanocomposite nanowires (Invited Paper)

Maria Moffa, Consiglio Nazionale delle Ricerche (Italy); Vito Fasano, Univ. del Salento (Italy); Andrea Camposeo, Consiglio Nazionale delle Ricerche (Italy); Dario Pisignano, Univ. del Salento (Italy)

Active nanowires and nanofibers can be realized by the electric-field induced stretching of polymer solutions with sufficient molecular entanglements. The resulting nanomaterials are attracting an increasing attention in view of their application in a wide variety of fields, including optoelectronics, photonics, energy harvesting, nanoelectronics, and microelectromechanical systems. Realizing nanocomposite nanofibers is especially interesting in this respect. In particular, methods suitable for embedding inorganic nanocrystals in electrically charged jets and then in active fiber systems allow for controlling light-scattering and refractive index properties in the realized fibrous materials. We here report on the design, realization, and morphological and spectroscopic characterization of new species of active, composite nanowires and nanofibers for nanophotonics. We focus on the properties of light-confinement and photon transport along the nanowire longitudinal axis, and on how these depend on nanoparticle incorporation. Optical losses mechanisms and their influence on device design and performances are also presented and discussed. The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013)/ERC Grant Agreement n. 306357 (ERC Starting Grant “NANO-JETS”, www.nanojets.eu).

Improving quantum dot photo-stability via ligand exchange to optimize resonant energy transfer

Jose Amaral, Univ. of California, Merced (United States)

Embedding or dispersing semiconductor nanoparticles, or quantum dots (QDs), in photovoltaic devices is a continuing challenge, where there is a need to have a high concentration of QDs, but if they are too closely packed, increased Förster resonant energy transfer (FRET) can serve to destabilize the QDs. We aim to reduce this photodegradation of QDs by performing a ligand exchange with a liquid crystal-like ligand to control the inter-particle distance of the QDs, thereby mediating intra-ensemble energy transfer (ET) as the LC ligands allow close packing of QDs at distances that prevent energy transfer. To determine if the ligand exchange is providing optimal close-packing, we study photo-induced static and dynamic spectral changes in self-assembled CdSe/ZnS core-shell QD thin films under ambient conditions. Statically, we have observed reduced photoluminescence quenching by approximately 30% and minimized photo-oxidation of the QDs, where the net spectral blue-shift is reduced by almost 40% via this process. Dynamically, the smaller (donor) QDs exhibit an increased radiative lifetime of ~4 ns, while the larger (acceptor) QDs exhibit a decrease in lifetime of ~4 ns, indicative of preferential excitation of the larger QDs. We speculate that as a result of performing the ligand exchange, the inter-particle distance is tailored to the right distance to have the highest density of QDs without FRET causing excessive photobleaching of the QDs, thus allowing for uniform, macroscopic self-assembly of QDs and may provide an inexpensive option for improving the stability of QD-based photovoltaic devices. This work was funded by DMR 1056860.
Organic semiconductors: structuring light for visible light communications (Invited Paper)
Ifor D. W. Samuel, Univ. of St. Andrews (United Kingdom)

Organic semiconductors are an important display technology and an emerging lighting and solar cell technology. They combine the scope to tune their electronic and optical properties by changing the chemical structure with simple fabrication. In addition they have properties that are very useful for visible light communication (VLC), namely strong absorption, high fluorescence quantum yield and short radiative lifetime. In one major field of VLC, solid state lighting is modulated to encode information, enabling short range communication at higher bandwidths than are available from Wi-Fi. One barrier to achieving this is the long lifetime of phosphors used in commercial LED lighting. We show that the short radiative lifetime of conjugated polymers makes them attractive materials to overcome this limitation. The copolymer super-yellow was used in combination with a gallium nitride micro-LED to generate white light. This enabled a data transmission at 1.68 Gb/s over a distance of 3 cm, and 840 Mb/s over a distance of 2 m. These are the fastest results so far reported for a single white-source visible light communication system. In addition we show how emission can be directed by suitable microstructure, and how organic semiconductor optical antennae can enhance the receiver in the communication system.

Fully solution-processed organic light-emitting electrochemical cells (OLEC) with inkjet-printed micro-lenses for disposable lab-on-chip applications at ambient conditions
Zhe Shu, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena (Germany); Oliver Pabst, Erik Beckert, Ramona Eberhardt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena (Germany)

Microfluidic lab-on-a-chip devices can be used for chemical and biological analyses such as DNA tests or environmental monitoring. Such devices integrate most of the basic functionalities needed for the analysis on a microfluidic chip. When using such devices, cost and space intensive lab equipment is thus not necessary. However, in order to make a monolithic and cost-efficient/disposable sensing device, direct integration of the excitation light source for fluorescent sensing is often required. Hereby we introduce a fully solution processable deviation of OLEDS, organic light-emitting electrochemical cells (OLECs) as a low-cost excitation light source for a disposable microfluidic sensing platform. By mixing metal ions and a solid electrolyte with light-emitting polymers as active materials, an in-situ doping and in-situ PN-junction can be generated within a three layer sandwich device. Thanks to this doping effect, work function adaption is not necessary and air-stable electrode can be used. An ambient manufacturing process for fully solution-processed OLECS is presented, which consist of a spin-coated blue light-emitting polymer plus dopants on ITO anode and an inkjet-printed PEDOT:PSS transparent top anode. A fully transparent blue OLED is able to obtain light intensity > 2500 cd/m2 under pulsed driving mode and maintain stable after 1000 cycles, which fulfills requirements for simple fluorescent on-chip sensing applications. Moreover, because of the large refractive index difference between substrates and air, about 80% emitted light is trapped inside the device. Therefore, inkjet printed micro-lenses on the rear side are introduced here to further increase light-emitting brightness.

Switching azobenzene-functionalized surfaces with organic light-emitting diodes
Matthias Bremer, Christine Kallweit, Andre Iwers, Markus Köpke, Martina Gerken, Christian-Albrechts-Univ. zu Kiel (Germany)

Attaching photo-switchable molecules on surfaces allows for spatial control of physical properties such as wettability or binding properties of, for example, DNA or proteins. Azobenzene molecules are switchable between a trans and a cis isomer and can be attached to different substrates such as gold or silica. For integrated devices based on azobenzene photo-switchable surfaces, an integrated light source with wavelengths in the UV (trans-cis) and blue (cis-trans) range is needed. Here, we investigate the use of an array of blue organic light emitting diodes (OLEDs) in combination with a single UV anorganic light emitting diode (LED) for spatially controlled switching of azobenzene molecules. Blue OLEDs based on the emitter material DPVBi:BCzVBi are fabricated by thermal evaporation. Azobenzene molecules are attached to a glass surface via click chemistry. For encoding a spatially controlled switching pattern on the surface, first the complete surface is switched to the cis-state by illumination with the UV LED. Subsequently, selected parts of the surface are switched to the trans-state by illumination with the blue OLED matrix. Optimal switching intensities and times for both light sources will be presented. We achieved a pattern refresh rate of less than three minutes. The spatially controlled isomerization is observed by measuring the absorption differences of a UV laser beam with a wavelength in the middle of the ε-c transition band of the azobenzene.

Solution-processed inverted polymer light-emitting diodes
Jongjiang Park, Jaeheung Ha, Narkhyeon Seong, Changhee Lee, Yongtaek Hong, Seoul National Univ. (Korea, Republic of)

We fabricated solution-processed inverted polymer light emitting diodes (PLEDs) which have solution-processed multi-layers except for anode and cathode electrodes. A structure of our devices was ITO (Cathode, 150 nm) / ZnO (ETIL, 20 nm) / PEI (Interlayer, 10 nm) / SPG-DIT (EML, 60 nm) / diluted PEDOT:PSS (HITL) / Al (Anode, 150 nm). To obtain the multi-layer optoelectronic devices using a solution process, there are several technical issues such as wetting and intermixing between adjacent layers. To solve these issues, we used the orthogonal solvents between to-be-deposited and deposited layers and enhanced the wetting property of PEDOT:PSS on the super hydrophobic EML with a dilution method. Especially, a uniformly coated PEDOT:PSS layer is crucial to achieve a high efficiency and a uniform light emission in our inverted PLEDs. In addition, the thickness of the PEDOT:PSS layer could be tuned by multi-coating processes, which is closely related to device characteristics. We fabricated three types of inverted PLEDs. Device 1, device 2, and device 3 have one-layered, two-layered, and three-layered PEDOT:PSS layer, respectively. A current efficiency and power efficiency were enhanced with the increase of the coating times. Device 1 showed 7.86 cd/A and 4.02 lm/W at 1000 cd/m2, while device 2 and device 3 showed 8.66 cd/A and 4.49 lm/W at 1000 cd/m2 and 9.06 cd/A and 4.71 lm/W at 1000 cd/m2, respectively, which are comparable with those of the conventional PLED with ITO anodes. Since both anode and cathode electrodes are also currently fabricated by a solution process, high-performance all-solution-processed, potentially all-printed, inverted PLEDs will be also presented at conference.
Nanocarbon as versatile materials platform for photonics (Invited Paper)

Werner J. Blau, Trinity College Dublin (Ireland)

Nanocarbon materials are attractive building blocks for future nanoelectronic and nanoptic devices, because they allow achieving new degrees of both performance and functionality — a combination unachievable by most conventional materials. They possess a variety of nearly ideal, low-dimensional nanostructures with unique properties across a range of physical phenomena ranging from mechanics, thermal physics, and electrochemistry to optics. These, in turn, make them ideal not only for a wide range of applications but as a test bed for fundamental science. Their specific properties are chiefly governed by quantum physics and/or surface effects, and are significantly different from equivalent macroscopic objects.

Nanocarbon occurs in six different basic forms: graphene, graphite, fullerene, nanodiamond, nanotubes and nanocones. Recent linear and nonlinear spectroscopic and optoelectronic results prove that they have much to offer in the photonics arena. A primary objective is to develop a new, environmentally friendly and yet versatile materials technology platform for photonic and optoelectronic devices based on polymer composites of tailored Nanocarbons, targeted specifically to the eyesafe 2 μm near-infrared region, with enormous potential e.g. in industrial processing, free-space communications & medical procedures.

In this lecture, I will review selected target application demonstrations such as:
- Light trapping structures for improved photovoltaic devices
- Near Infrared (NIR) photomitting structures to demonstrate NIR OLEDs and possible NIR lasers
- Nonlinear optical applications including broadband optical limiters and mode-lockers, and ultrafast all-optical switches.

Quantum calculation of the second-order hyperpolarizability of chiral molecules in the “one-electron” model (Invited Paper)

Francois Hache, Lab. d’Optique et Biosciences (France)

Second-harmonic generation in chiral molecules has been thoroughly studied, especially in surface experiments and it has been shown that (i) the origin of the nonlinear response can lie in local (electric-dipole) or nonlocal (magnetic dipole) interactions and (ii) chiral contributions can be of the same magnitude than achiral ones. In this talk, we will concentrate on the “one-electron” mechanism where chirality arises from a skewed energy potential [1] and carry out the full quantum-mechanical calculation of the hyperpolarizability tensor. This calculation is performed by introducing a chiral perturbation term in the potential energy surface and deriving the nonlinear terms in the molecular response to an electromagnetic field [2]. We can deduce the dipolar-electric hyperpolarizability tensor components of such a chiral molecule and compare them to the ones obtained for an achiral molecule modeled by an anharmonic potential energy surface. The results of this calculation show on the one hand that such a “one-electron” chiral molecule is inherently chiral and displays a second-order local response and on the other hand that the chiral hyperpolarizability has the same order of magnitude than an achiral ones, in agreement with experimental findings [3].

self-writing) and waveguide-type device technologies for next generation integrated optical circuits. By combining high performance functional photonic polymer and silicon nanowire, we attempt to realize an integrated optical module for next-generation vehicle application.

9745-38, Session 10

3D building blocks for self-assembling chromophores on sp2-carbon based substrates (Invited Paper)
Ping Du, David Kreher, Fabrice Mathevet, Univ. Pierre et Marie Curie (France); Fabrice Charra, Commissariat à l’Énergie Atomique (France); André-Jean Attia, Univ. Pierre et Marie Curie (France)

In view of the demanding forthcoming applications in nanotechnology, it is of prime interest to create functions out-of-the plane and fully exploit the room above the substrate. Accessing the third dimension is so a mandatory step for nanoptics/electronics. Previously we introduced the Janus-like 3D tectons concept. It consists of a dual-functionalized unit presenting two faces linked by a rigid spacer: one face (A) is designed for steering 2D self-assembly, the other one (B) is a functional molecule. The objective is to take advantage of the in-plane self assembling of building blocks lying on face A to control the positioning of out-of-plane active unit B, linked to the base by a rigid pillar. Here we present a series of Janus tectons incorporating chromophores ranging from fluorescent dyes to photoswitchable molecules. We will present the optical properties in solution as well as the properties of the self-assembled functional monolayers on flat sp2-carbon based substrates like HOPG and graphene.

9745-39, Session 10

Printed optically transparent graphene cellulose electrodes
Dogan Sinar, George K. Knopf, Western Univ. (Canada); Suwas Nikumb, National Research Council Canada (Canada)

Optically transparent electrodes are a key component in variety of products including bioelectronics, touch screens, flexible displays, low emissivity windows, and photovoltaic cells. Although highly conductive indium tin oxide (ITO) films are often used in these electrode applications, the raw material is very expensive and the electrodes often fracture when mechanically stressed. An alternative low-cost material for inkjet printing transparent electrodes on glass and flexible polymer substrates is described in this paper. The water based ink is created by using a hydrophilic cellulose derivative, carboxymethyl cellulose (CMC), to help suspend the naturally hydrophobic graphene (G) sheets in a solvent composed of 70% DI water and 30% 2-butoxyethanol. The CMC chain has hydrophobic and hydrophilic functional sites which allow adsorption on G sheets and, therefore, permit the graphene to be stabilized in water by electrostatic and steric forces. Once deposited on the functionalized substrate the electrical conductivity of the printed films can be “tuned” by decomposing the cellulose stabilizer using thermal reduction. The entire electrode can be thermally reduced in an oven or portions of the electrode thermally modified using a laser annealing process. The thermal process can reduce the sheet resistance of G-CMC films to <100 Ω/sq. Experimental studies show that the optical transmittance and sheet resistance of the G-CMC conductive electrode is a dependent on the film thickness (i.e. superimposed printed layers). The printed electrodes have also been doped with AuCl3 to increase electrical conductivity without significantly increasing film thickness and, thereby, maintain high optical transparency.

9745-40, Session 10

Unusual electro-optic effects in liquid crystals
Mamatha Nagaraj, Univ. of Leeds (United Kingdom)

Although usually associated with rod or disk like molecules, liquid crystal phases have been observed for organic molecules with a variety of different and unconventional anisotropic shapes. Amongst these, bent-core mesogens have been considered as one of the most fascinating classes due to their wide range of unique mesophases and unusual physical properties not exhibited in more conventional liquid crystals.

I will present some of the unusual electric field-driven transformations seen in the lamellar mesophases formed by bent-core molecules. Particularly, a detailed investigation of unusual DC phases of achiral BLCs will be described. The DC phase exhibits amazing physical properties, including an electric field tunable chiral domain structure and a large reduction of refractive index while maintaining an optically dark texture when observed under crossed polarisers. The transformations are seen irrespective of the frequency of the applied electric field, type of the waveform and the thickness or the geometry of the device used. The nature of the behaviour has been investigated by various techniques such as optical microscopy, conoscopy, circular dichroic and Raman spectroscopies, electro-optics and dielectric spectroscopy and small angle X-ray scattering. Based on the results, a model of the DC phase will be described where in the ground state the nanostructure of phase exhibits an anticondiant antiferroelectric organization. Under an electric field, it undergoes a molecular rearrangement without any gross structural changes leading to an antilinic ferroelectric order while keeping the overall sponge-like structure of the DC phase intact. I will also explain interesting tunable properties of these mesophases and their possible practical applications.

9745-41, Session 11

Organic-inorganic composites for THz device fabrication (Invited Paper)
Cai Bin, Univ. of Shanghai for Science and Technology (China); Tian Ming Ye, University of Shanghai for Science and Technology (China); Bo Guo, Xuecheng Wang, Yunzhou Li, Univ. of Shanghai for Science and Technology (China); Yi Ming Zhu, University of Shanghai for Science and Technology (China); Okihiro Sugihara, Utsunomiya University (Japan)

Terahertz (THz) radiation is broadly defined from 0.1 to 10 THz, sandwiched between microwave and mid-infrared frequency ranges. The THz radiation has been shown to have considerable potential applications in security inspection, spectroscopic imaging, and future communication systems, etc. Currently, considerable breakthroughs are made; however, the devices for controlling or manipulating THz radiation still remains many hurdles need to be overcome, mainly because of the limited availability of suitable materials. For THz optics, the materials with high functionality, flexibility as well as processibility are highly requested. Organic-inorganic composites are considered to be a new class of advanced materials because of their versatile fabrication approaches and potentiality of novel property. In THz region, many polymers such as polyethylene (PE), polystylene (PS), and cyclo-olefin polymer (COP) etc. show relatively low propagation loss, however, their applications are limited by their low refractive indices etc. In this study, several polymer based organic-inorganic composites are fabricated and the applications for THz filtering and antireflection are proposed.

First, a two-layer structure was designed for fs-laser/THz radiation separation. The top layer is made of hollow quartz nano-particles which can diffuse the incident fs laser thus decrease the power intensity. The second layer comprises of silicon nano-particles and COP polymer, by which the fs laser light will be greatly scattered and absorbed but THz radiation will
temperature phase, which could be an upper bound on binding energy as rate. A binding energy of 105 meV was calculated from PL for the high temperature recombination is governed by excitons, leading to a faster recombination of the high temperature tetragonal phase. Power dependent emission study peaks reveal recombination rates an order of magnitude smaller compared to the high temperature tetragonal phase on cooling down below 140 K. These low temperature properties. In our studies, photoluminescence (PL) measurements show that CH₃NH₃PbClₓI₁₋ₓ undergo a phase transition from tetragonal to orthogonal phase. We discuss new nonlinear optical material – a thin crystal film grown by crystallization during photo polymerization on a surface of photopolymer film based on nonlinear optical co-crystal 2-amino pyridine-4-nitrophenol-4-nitrophenol (2APN). A technique and the preparation conditions of the polymer thin films and the crystal films based on a mixture of solutions of isodecyl acrylate and 1,6-hexanediol and 2APN co-crystals are discussed. Preparation method, poled and orientation conditions are described. Differential scanning calorimetry shows good quality and thermal stability of obtained materials. Absorption spectrum and second harmonic generation studies confirm the creation of noncentrosymmetric crystals in polymer matrices.

9745-44, Poster Session Nonlinear thin film organic co-crystal grown on a polymer substrate: a method and properties
Ilia M. Pavlovetc, ITMO Univ. (Russian Federation); Henryk J. Laszewski, Ecole Normale Supérieure de Cachan (France); Elizaveta B. Sheklianova, Maria I. Fokina, ITMO Univ. (Russian Federation)
Organic nonlinear optical materials with high level of second order nonlinear susceptibilities has found many applications, such as: second harmonic generation, electro-optic modulation, parametric oscillation and many others [1,2]. The organic nonlinear optical materials in the form of several types of polymeric materials or as organic crystals have been presented during last few decades. In recent years, new classes of nonlinear optical materials have been proposed: composite polymer materials, nanocrystals in polymeric matrices, thin polymeric and crystal films, which can combine the advantages of both organic crystals and polymeric matrices [3,4]. We discuss new nonlinear optical material – a thin crystal film grown by crystallization during photo polymerization on a surface of photopolymer film based on nonlinear optical co-crystal 2-amino pyridine-4-nitrophenol-4-nitrophenol (2APN). A technique and the preparation conditions of the polymer thin films and the crystal films based on a mixture of solutions of isodecyl acrylate and 1,6-hexanediol and 2APN co-crystals are discussed. Preparation method, poled and orientation conditions are described. Differential scanning calorimetry shows good quality and thermal stability of obtained materials. Absorption spectrum and second harmonic generation studies confirm the creation of noncentrosymmetric crystals in polymer matrices.

9745-43, Session 11
Exciton-dominated fast recombination in low-temperature CH₃NH₃PbClₓI₁₋ₓ perovskite thin films
Som Sarang, Univ. of California, Merced (United States)
Mixed halide Perovskite solar cells have been a popular topic of research in the last few years, due to low costs and high efficiency. In order to improve performance as an active material in thin film solar cells, it is important to understand the underlying physics governing the opto-electronic properties. In our studies, photoluminescence (PL) measurements show that CH₃NH₃PbClₓI₁₋ₓ undergo a phase transition from tetragonal to orthogonal phase on cooling down below 140 K. These low temperature phases are associated with more than one PL peak, indicating multiple recombination routes. Temperature dependent time-resolved PL of these peaks reveal recombination rates an order of magnitude smaller compared to the high temperature tetragonal phase. Power dependent emission study of these crystals reveal the high temperature recombination processes in perovskite crystals to be primarily bimolecular, whereas the low temperature recombination is governed by excitons, leading to a faster recombination rate. A binding energy of 105 meV was calculated from PL for the high temperature phase, which could be an upper bound on binding energy as free charge carriers seem to be dominating the recombination process at higher temperatures. These studies reveal a shift in the type of intrinsic charge carriers in different phases of perovskite thin films, indicating a possibility of use in new opto-electronic devices.
This work was funded by NSF DMR 1056860.

9745-45, Poster Session
Investigation of the nonlinear absorption spectrum of all-trans retinoic acid by using the steady and transient two-photon absorption-induced spectroscopy
Marcelo G. Vivas, Univ. Federal de Alfenas (Brazil); Jonathas De Paula Siqueira, Univ. de São Paulo (Brazil); Daniel Silva, Univ. Federal de São Carlos (Brazil); Leonardo De Boni, Cleber R. Mendonça, Instituto de Física de São Carlos IFSC-USP (Brazil)
This work investigates the two-photon absorption (2PA) spectrum of all-trans retinoic acid (ATRA) in DMSO solution, employing the wavelength-tunable Z-scan and white-light pump-probe techniques with femtosecond pulses. Our results showed that ATRA presents two 2PA allowed bands at 280 nm (hν = 560 nm) and 365 nm (hν = 730 nm) with 2PA cross-section values of 34 GM and 40 GM, respectively. The 2PA band at 280 nm
Two-photon absorption in branched molecular systems

Ruben Dario Fonseca Rodriguez, Univ. de São Paulo (Brazil); Marcelo G. Vivas, Univ. Federal de Alfenas (Brazil); Daniel Silva, Univ. Federal de São Carlos (Brazil); Leonardo De Boni, Cleber R. Mendonça, Instituto de Física de São Carlos IFSC-USP (Brazil)

Two-photon absorption (2PA) is a process in which an atom or molecule simultaneously absorbs two photons, which can have the same or different energies. Due to their remarkable features for various applications, such as three-dimensional (3D) optical data storage, photodynamic therapy, fluorescence imaging, optical limiting, and so on, considerable interest has been devoted to the development of organic materials with large TPA cross-sections. Organic compounds provide advantages in relation to other types of materials since their optical properties can be easily modified or optimized by molecular engineering. Various design strategies have been employed to synthesize organic molecules, in an attempt to achieve higher 2PA cross-sections. The purpose of this study is to investigate the 2PA of nine molecular branched systems arranged in dipolar, quadrupolar and octopolar geometries. This nonlinear optical measurements were carried out employing the open aperture Z-scan technique, using 120-fs laser pulses from an optical parametric amplifier pumped by 150-fs pulses (775 nm) from a Ti:sapphire chirped-pulsed-amplified system, operating at 1 kHz repetition rate. For each wavelength the pulse energy was kept between 20 and 120 nJ. 2PA was determined by translating the sample through the focal plane of a focused Gaussian beam, while transmittance changes in the far field intensity are monitored. The experimental data revealed well-defined 2PA spectra, with reasonable cross-section values in the visible and IR. Using the theoretical calculations, based on density functional theory (DFT), we were able to interpret the experimental 2PA spectra.
efficiency, EQE, and EL spectrum. The red emitting iridium(III) complexes will be used as a solution process dopant for the hybrid OLED devices.

### 9745-50, Poster Session

**New red phosphorescent iridium(III) complex with 4-tert-butylphenyl-boronic acid of organic borane**

Sang Wook Lee, Dong-Myung Shin, Hongik Univ. (Korea, Republic of)

A new phosphorescent (CQ-BP)2Ir(acac), (CMQ-BP)2Ir(acac), (BQ-BP)2Ir(acac) was synthesized for organic light-emitting diodes (OLEDs). OLEDs using phosphorescent iridium(III) complexes attract enormous attention because they allow highly efficient electro phosphorescence. The donor-acceptor type ligands for the iridium(III) complexes were synthesized by Suzuki coupling reaction. The ligands through changes in oxidative addition materials (electron-acceptor) and organic borane (electron-donor) to get the red color were to study the appropriate Iridium(III) complexes. Oxidative addition materials were used such as 2-chloro-4-methylquinoline, 1-chloroisoquinoline and 2-bromoquinoline. 4-tert-Butylphenyl-boronic acid was used as organic borane. The dopant was synthesized by Noyama reaction. Red dopants were observed with an emission peak at approximately 600nm. Iridium(III) complexes were measured by nuclear magnetic resonance (NMR), UV-visible spectroscopy and photoluminescence (PL). The phosphorescence emission maxima were dependent on the electron density of donor and acceptor moiety of the ligands.

### 9745-51, Poster Session

**Thin films of cyanine J-aggregates doped with silver nanoparticles and their laser-induced modification**

Anton A. Starovoytov, Nikita A. Toropov, Rezida Nabiullina, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Metal-organic hybrid nanostructures attract much attention because of the benefits of novel physical and chemical properties exhibited by certain classes of plasmon nanoparticles or organic molecules. This result from the huge enhancement of the near fields around the nanoparticles provided the incident radiation resonates with the localized plasmon excitations. It is known that the field enhancement leads to modification of optical properties of organic molecules. It can be used for developing the thin-film solar cells, the OLED, etc.

We used the absorption spectroscopy and fluorescence confocal microscopy to study the formation of molecular nanoclusters of cyanine dyes called J-aggregates coated on the island films of Ag nanoparticles, deposited on sapphire substrate. Varying the length of the molecular conjugated chain and the size of the nanoparticles allowed adjusting the position of the absorption maximum of the organic film and the plasmon resonance of the particles. The distancing of molecules from the nanoparticles was provided by PMMA layer. Considerable incensement of the absorption and fluorescence of cyanine dye, especially of J-aggregate, in the presence of nanoparticles was demonstrated. It’s showed that the absorption of J-aggregate band increased after exposure to nanosecond laser on the samples. We can assume that it’s due to photo-induced additional self-organization of J-aggregates.

### 9745-52, Poster Session

**Carrier injection and recombination processes in perovskite CH3NH3PbI3 solar cells studied by electroluminescence spectroscopy**

Taketo Handa, Kyoto Univ. (Japan); Makoto Okano, Keio Univ. (Japan); David Michael Tex, Ai Shimazaki, Tomoko Aharen, Atsushi Wakamiya, Yoshikihiko Kanemitsu, Kyoto Univ. (Japan)

Organic-inorganic hybrid perovskite materials such as CH3NH3PbI3 are considered as promising candidates for emerging thin-film photovoltaics. This new class of solar cells shows high conversion efficiencies of over 20%. However, rapid degradation of performance is a serious problem in CH3NH3PbI3 solar cells. To understand the optical and electronic properties of complicated thin-film solar cells, a combination of different optical methods is useful. In particular, electroluminescence (EL) is a very powerful technique for gaining deeper insights into the photovoltaic conversion processes in solar cells because the EL process is intrinsically related to the photovoltaic process through reciprocity between light absorption and emission. In this work, we studied the time evolution of EL intensities and EL images of CH3NH3PbI3 solar cells in air at room temperature and discuss the charge injection and recombination processes and degradation mechanism of the devices. Under applied voltages of about 1 V, EL is clearly observed from CH3NH3PbI3 solar cells. The EL spectrum is almost identical to the photoluminescence spectrum of the CH3NH3PbI3 layer in the device. Moreover, the high-efficiency solar cells exhibit high EL intensities, making EL intensity an indicator of good material quality. During prolonged exposure to applied bias in air, the EL intensity gradually decreases, which indicates the degradation of the solar cell performance. The rate of degradation can be reduced by introducing time intervals: On-off cycling of applied voltage significantly reduced the EL intensity drop. The degradation mechanism of the perovskite solar cell is discussed in terms of ion migration under applied voltage.

### 9745-53, Poster Session

**Growth directions of C8-BTBT thin films during drop-casting**

Naoki Iizuka, Tomohiko Zanka, Yosuke Onishi, Ichiro Fujieda, Ritsumeikan Univ. (Japan)

Because charge transport in a single crystal is anisotropic, it is desired to control the crystalline orientation for enhancing device performance and reducing its variation among devices. For an organic thin film, a solution process such as inkjet printing offers advantages in throughput. We have proposed to apply an external temperature gradient during drop-casting an organic semiconductor solution in order to control the direction of solidification. In experiments, we generate a temperature gradient in a Si plate bridging two heat stages. A solution of 2,7-dioctyl[1]benzothieno[3,2-b]benzothiophene (C8-BTBT) in toluene is drop-casted on a glass substrate placed on the Si plate. When the two stages are kept at room temperature, evaporation starts at the perimeter of the droplet and ends at the center. The C8-BTBT molecules move outward and a ring-like pattern is formed. This is known as the coffee-stain effect. When a temperature gradient is present by setting one of the stages to 80°C, evaporation starts at the hotter side of the droplet and the remaining liquid moves toward the colder side of the substrate. As a result, the film is formed in an elongated region. Observation by a polarization optical microscope reveals that multiple domains are formed in the film and that their optical axes are mostly along the directions of the solvent evaporation. When the film is rotated between the crossed polarizers, the intensity of the transmitted light varies with the rotation angle just as in the case of a retarder plate.
Effect of UV irradiation on the dynamics of oxygen and water interaction with carbon nanotubes

Eric Muckley, Oak Ridge National Lab. (United States) and The Univ. of Tennessee Knoxville (United States); Tony Nelson, Virginia Polytechnic Institute and State Univ. (United States); Christopher B Jacobs, Oak Ridge National Laboratory (United States); Ilia Ivanov, Oak Ridge National Lab. (United States)

Demand is growing for carbon-based electronics because of their low cost, mechanical flexibility, and compatibility with roll-to-roll processing. Carbon allotropes including metallic and semiconducting carbon nanotubes, fullerenes, and graphene have shown promise for application in a wide range of flexible thin film electronic devices including photovoltaics, LEDs, transistors, biointerfaces, and sensors. While semiconducting carbon allotropes exhibit a wide range of bandgaps, intrinsic and extrinsic dopants allow for further tunability of the bandgap and work function of these materials. However, the environmental stability of doped films in oxygen and humid atmospheres may become a fundamental limitation on the practical application of carbon allotropes for optoelectronic and biomedical applications. The high surface area of carbon-based nanostructured materials allows gas adsorption which makes tuning of the optoelectronic properties of carbon allotropes unpredictable. An effective and popular method of inducing gas desorption from carbon surfaces is UV treatment. Here, we study the effect of UV activation on the electronic properties and sorption kinetics of different carbon nanostructures in humid and oxygen rich environments using in situ quartz crystal microbalance (QCM) and electronic measurements. By correlating electrical measurements with the QCM response, we determine conductivity change as a function of the adsorbed mass of oxygen and water and compare these across different nanostructures in order to investigate the mechanisms behind UV activation of carbon surfaces.

Highly crystalline growth of organic small molecule assisted with biomolecules

Ho Jin Lee, Seokho Kim, Hyeong Tae Kim, Dong Hyuk Park, Inha Univ. (Korea, Republic of); Chunzhi Cui, Yanbian Univ. (China) and Korea Univ. (Korea, Republic of)

We report on the self-assembly growth of organic small molecules using biomaterials containing solutions to fabricate crystalline organic microwires (MWs). When hybridized with biomaterials such as oligonucleotide, aptamer, the organic small molecules could be form hexagonal shaped crystalline MWs. The organic crystal MWs were prepared by a simple recapitulation method. The formation and structure were measured by SEM and HR-TEM experiments, respectively. We measured the nanoscale solid-state PL image and spectra for organic crystal MWs hybridized with biomaterials using a homemade LCM equipment. We observed the strong enhancement of emission efficiency in highly crystalline organic MWs hybridized with biomaterials, compared with that of organic small molecules only. These highly crystalline organic MWs would be extended to applications in developing optoelectronic devices and sensors because of their novel structure and optical characteristics.

Random laser properties changes in rhodamine-B-doped organic/silica hybrid materials using femtosecond laser micromachining

Luís M. G. Abegão, Paulo Henrique D. Ferreira, Univ. Federal de São Carlos (Brazil); Adriano J. G. Otuka, Instituto de Física de São Carlos IFSC-USP (Brazil); Diego S. Manoel, Fábio S. De Vicente, Univ. Estadual Paulista “Júlio de Mesquita Filho” (Brazil); Cleber R. Mendonça, Instituto de Física de São Carlos IFSC-USP (Brazil); Gabriel Herbet Gomes, Univ. Federal de São Carlos (Brazil); Dario A. Donatti, Univ. Estadual Paulista “Júlio de Mesquita Filho” (Brazil); Márcio A. R. Alencar, José J. Rodrigues Jr., Univ. Federal de Sergipe (Brazil)

Organic/Silica hybrid materials have been investigated to several technological applications. These materials can be easily doped with organic chromophores, increasing the interest in the optical and photonic fields. Furthermore, hybrid materials present advantages over fused glasses, such as easiness of processing and low cost of production. On the other hand, femtosecond micromachining allows the fabrication of microstructures inside the volume of a material without damaging its surface. Due to its features, fs-laser micromachining has been used in a broad variety of materials to increased performance in optical and photonic systems. In this work we studied the influence of evenly spread scatters produced by fs-laser micromachining on the random laser properties in monoliths of Rhodamine-B-doped organic/Silica hybrid materials. Rhodamine-B doped GPTS/TEOS-derived organic/Silica were prepared by sol-gel process, starting from the hydrolysis of 3-glycidoxypropyltrimethoxysilane (GPTS) and tetraethylorthosilicate (TEOS), yielding a clear sol doped with Rhodamine-B. Dense and clear monolithic xerogels with 10 mm-diameter and 3 mm-thick were obtained after drying of the sol. The microstructures were produced using extended-cavity femtosecond laser irradiation (50-fs, 800-nm, 5.1 MHz), the luminescence of the samples was observed using pulsed frequency-doubled Nd:YAG pulsed laser (5-nm, 532-nm, 10 Hz), and the signal was analyzed by a CCD-compact spectrophotometer. For lower excitation energy the typical Rhodamine-B luminescence was observed. Further increase of the excitation laser energy showed a distinct emission lineshape for the microstructured sample and a typical random laser emission regime was achieved. Such results open new possibilities to microstructured random laser development using different optically active materials.

Investigation of organolead halide perovskite phototransistors with low-temperature processed gate dielectrics

Youngseo Park, Sang Jin Park, Hui Joon Park, Junseok Heo, Ajou Univ. (Korea, Republic of)

Organolead halide perovskites (CH3NH3PbI3) have been actively researched for photovoltaic applications because of their unrivaled characteristics such as high absorption of broadband light, high carrier mobility, low cost, and ease of fabrication. There were also a few reported works of the perovskite based phototransistors where photo-generated carriers transport within the perovskite or the underlying graphene layer. The perovskite based phototransistors reported up-to-date utilize a thermal oxide (SiO2) as a gate dielectric insulator and a heavily doped silicon substrate as a back-gate. This does not allow to implement the perovskite based phototransistor on a flexible substrate due to a thermal budget. In addition, it has been reported that the hysteresis on current-voltage characteristics were unavoidable due to charge traps at the perovskite-SiO2 interface and the field-induced
drift of methylammonium cations. We have investigated the characteristics of perovskite based phototransistors with various gate dielectrics formed at a low temperature, resulting in a different density of charge traps at the interface. The aluminum oxide (Al2O3) deposited by an atomic layer deposition and the insulating polymers (polyimides, PMMA) spin-casted are applied as a gate dielectrics. This low-temperature processed gate dielectrics enable to implement a flexible perovskite phototransistor for wearable application. The overall characteristics such as current-voltage, transconductance, and light responsivity are experimentally investigated and the phototransistors with different gate dielectrics are compared.

9745-59, Poster Session

Plasmon-enhanced optical waveguide based on organic crystals

Hyeong Tae Kim, Ho Jin Lee, Seokho Kim, Dong Hyuk Park, Inha Univ. (Korea, Republic of)

We demonstrate the fine control and enhancement of the photoluminescence (PL) and optical waveguiding characteristics of light-emitting organic microcrystals (OMs) through incorporated with nanoscale metals. We observed nanoscale laser confocal microscope (LCM) PL intensity and spectra of the OMs drastically varied with silver nanoparticles (NPs).

In optical waveguiding experiments, the propagation characteristics of optical signals along the single OM were dependent on the existence of the metal NPs. For the hybridized with silver NPs, the waveguiding PL signals of OM had relatively higher output, indicating the strong optical energy transfer. Additionally, the waveguiding characteristics such as decay constant along the OM considerably decrease the optical loss in hybrid OMs. It is remarked that the effective surface plasmon resonance (SPR) coupling between organic crystal and nanoscale metals can be significantly activating luminescence propagate without optical loss, since the local excitation may occur optical activation.

9745-60, Poster Session

Low-loss and high-bandwidth graded-index plastic optical fibers for 4K/8K transmissions

Soichi Furukawa, Kotaro Koike, Yasuhiro Koike, Keio Univ. (Japan)

In order to achieve uncompressed 4K/8K video transmissions, development of graded-index plastic optical fibers (GI POFs) with a low attenuation and high bandwidth at 850 nm, where commercial 10 Gb/s VCSELs are available, is demanded. As typical POFs based on PMMA exhibit high attenuations at near-IR due to vibrational absorptions of carbon-hydrogen bonds, we observed large optical nonlinearity and reversible photoinduced anisotropy. We further demonstrated novel photonic applications, including holographic elements, all-optical switching and spatial light modulation. As compared to Retinal proteins, the Retinal/inorganic hybrids may have many advantages for photonic applications including low cost and ease of preparation and optimization. In addition, study on Retinal chromophore and its derivatives is much easier than that of their complex proteins. It may further facilitate understanding the photochemical process of Retinal proteins as well as the mechanism of vision process.

References:


9746-1, Session 1

Terahertz-field-induced ionization effect in a single nano island (Invited Paper)

Minah Seo, Korea Institute of Science and Technology (Korea, Republic of)

In recent years, there has been an increased interest in development of new type of terahertz (THz) high power sources using various techniques. THz plasmonics using metamaterial in nanoscale can be a significant breakthrough offering extreme local field enhancement and implements new capabilities on their use for various applications. Here, we show THz light induced marshmallowing effect as carbon based contaminants by using a novel type of hybrid system of a single gold nano island embedded within a nano slot antenna structure, which works as a launching pad for extremely enhanced THz light. THz radiation is strongly confined at the island-to-slot gap and induces enormous current across the slot antenna that leads to carbon ionization around the gap. THz radiation induced geometrical change in nanostructure is investigated by THz transmittance measurement and the result agrees well with finite-difference time-domain (FDTD) calculation. Our observation can be a unique example of THz light self-stimulated nonlinear effect opening up new avenues of exploration for nonthermal THz induced changes in nano structures, which were hindered by a difficulties to use such high power THz sources thus far and, consequently, a lack of an experimental research verifying the light-matter interaction mechanism at this frequency regime.

9746-2, Session 1

Funneling of electromagnetic waves through angstrom gaps (Invited Paper)

Young-Mi Bahk, Seoul National Univ. (Korea, Republic of); Bong Joo Kang, Ajou Univ. (Korea, Republic of); Yong Seung Kim, Sejong Univ. (Korea, Republic of); Joon-Yeong Kim, Seoul National Univ. (Korea, Republic of); Won Tae Kim, Ajou Univ. (Korea, Republic of); Tae Yun Kim, Taehoon Kang, Ji Yeong Rhee, Sanghoon Han, Cheol-Hwan Park, Seoul National Univ. (Korea, Republic of); Fabian Rotermund, Ajou Univ. (Korea, Republic of); Dai-Sik Kim, Seoul National Univ. (Korea, Republic of)

We manufactured an array of three angstrom-wide and five millimeter-long metallic gaps by inserting a vertically-aligned single layer graphene between two coplanar copper films. Ultra-long subnanometre metallic gap is applicable to broad band spectral domain including millimeter waves as long as the lateral size of the gap is longer than the wavelength of the incoming light. To fabricate angstrom gaps, we utilized van der Waals interaction between copper/graphene/copper interfaces which is sufficiently weak to create atomically sharp interfaces with a region of low electron probability acting as ‘vacuum’. The van der Waals gaps formed by copper-graphene-copper hybrid structure provide the narrowest possible metallic gap of three angstrom where quantum tunneling becomes unavoidable.

We experimentally demonstrate colossal optical nonlinearity of angstrom gaps through which terahertz waves squeeze. The intense terahertz funneling through the angstrom gap induces the large transient voltage across the gap facilitating electron tunneling through the quantum barrier formed by copper-graphene-copper composite. The tunneling electrons induce the gap to become more lossy, limiting terahertz field enhancement itself.

We observed that the self-limiting process of electron tunneling leads to giant nonlinear optical response with 97% decrease of the normalized transmittance.

Our technology for fabrication of infinitely long angstrom gaps enables linear and nonlinear angstrom optics in long wavelength domain.

9746-3, Session 1

Nonlinear quantum plasmonics of terahertz nanoantennas

Joon-Yeon Kim, Seoul National Univ. (Korea, Republic of); Bong Joo Kang, Ajou Univ. (Korea, Republic of); Joohyun Park, Hanyang Park, (Korea, Republic of); Young-Mi Bahk, Seoul National Univ. (Korea, Republic of); Won Tae Kim, Ajou Univ. (Korea, Republic of); Ji Yeong Rhee, Seoul National Univ. (Korea, Republic of); Hyeongtak Jeon, Hanyang Univ. (Korea, Republic of); Fabian Rotermund, Ajou Univ. (Korea, Republic of); Dai-Sik Kim, Seoul National Univ. (Korea, Republic of)

Plasmonic systems in the nanometer scale enter the regime of quantum mechanics as the separation between two metals becomes small enough for electrons to tunnel through the potential barrier of a nanogap. Here, we show that with pulsed terahertz radiation through vertical nanogaps, enhanced electric fields achieve the atomic strengths needed for tunneling of electrons, and tuning the spectra into the low-frequency sub-terahertz and terahertz regime relieves practically demanding issues to study quantum plasmonics in super-nanometer barriers. Gold or silver metal patterns on top of a quartz substrate are coated with aluminium oxide using remote plasma atomic layer deposition followed by a simple adhesive-tape-based planarization to produce an array of ring-shaped nanoantennas. High-power terahertz pulses are generated via optical rectification in a lithium niobate crystal, and an electric field strength of up to 150 kV/cm is reached on the incident surface of the sample. Derived from the Kirchhoff integral formalism, field inside the nanogaps is estimated to be enhanced up to 5 V/nm at the maximum incident field strength. In the presence of this high field, transmittance is largely reduced and the transient voltage induced across the nanogap exhibits a saturating behavior. This nonlinear response can be explained in terms of a steady-state polarization density of tunneling charges which are induced by the terahertz electric field.

In conclusion, our approach of using terahertz spectroscopy enlarges the boundary of the study of quantum effects in plasmonic nanostructures down to frequencies of 0.1 THz, up to field amplitudes of 5 V/nm, and barrier widths as large as 10 nm.

9746-4, Session 1

THz magneto-spectroscopy of superconducting metamaterials in the mK range

Curdin Maisseen, Giacomo Scalari, ETH Zürich (Switzerland); Sara Cibella, Roberto Leoni, CNR-Istituto di Fotonica e Nanotecnologie (Italy); Gianlorenzo Paravicini Bagliani, Mattias Beck, Jérôme Faist, ETH Zürich (Switzerland)

Metamaterials are known for their flexibility and their scalability making them powerful elements for the control of THz beams. They have also
been used as strongly subwavelength resonators for light-matter coupling experiments. Superconducting materials offer a powerful degree of freedom in the engineering of these multifunctional THz metasurfaces. We recently presented a fully switchable, high quality factor complementary THz metasurface based on Niobium thin film. We now present experimental results obtained measuring these metasurfaces at temperatures as low as 20 mK and magnetic fields up to 6 T. A THz-TDS spectrometer is coupled to a cryo-free dilution refrigerator equipped with superconducting magnet. The Nb complementary metasurface displays a narrow transmission resonance at 270 GHz. Impressive narrowing of this LC mode resonance is observed when the sample temperature is varied from 3 K (already in the superconducting state, when the Q factor is 55) down to the mK range. Q factors as high as 85 are measured at 16 mK for strongly subwavelength structures with normalized cavity volumes $V_{\text{cav}}/\lambda^3$ of the order of $10^{-6}$-6. Our measurements highlight the role of the residual normal state electrons at temperatures well below the critical temperature $T_C$. Behavior of the samples as a function of magnetic field applied perpendicularly to the surface and as a function of the temperature will be also discussed. Experimental data will also be presented where the same metasurface is used as a resonator in an ultrastrong light-matter coupling experiment in conjunction with a high-mobility two dimensional electron gas.

9746-5, Session 2

Ultrafast spectroscopy and control from THz through x-rays (Keynote Presentation)

Keith A. Nelson, Massachusetts Institute of Technology (United States)

(This is an abstract for a plenary talk for the symposium “Ultrafast Phenomena and Nanophotonics.”)

9746-6, Session 2

High-harmonic generation in solids (Invited Paper)

Ulrich Huttner, Philipps-Univ. Marburg (Germany); Matthias Hohenleutner, Fabian Langer, Olaf Schubert, Matthias Knorr, Rupert Huber, University of Regensburg (Germany); Stephan W. Koch, Mackillo Kira, Philipps-Univ. Marburg (Germany)

This talk summarizes the results of our microscopic approach to study short-pulse induced high-harmonic generation in semiconductors and in a many atom system. The interaction of a highly off-resonant light pulse with an atomic gas and with a semiconductor is modeled fully microscopically. Whereas we consider optical frequencies in the atomic system, the semiconductors are excited by very strong fields in the terahertz (THz) range of the electromagnetic spectrum. For the atomic gas, the theory systematically includes the light-atom interaction, as well as the electron-electron and electron-ion interaction effects on the distributions and the optically induced coherent polarization. The resulting equations are solved numerically for an atomic model system excited by a strong light pulse. Depending on the field strength and the atomic density, different degrees of high-harmonic generation and atomic ionization are obtained. For very short pulses and low atomic gas pressures, the results of an independent atom model are reproduced. For longer pulses and/or higher atomic pressures the intrapulse Coulomb interaction lead to significant modifications, strongly reducing the anisotropy of the excited state after the pulse. In our semiconductor analysis, we consider extremely strong and ultrashort THz pulses that excited the system to a regime where electrons are transported coherently. Since the bandgap energy in semiconductors is typically much larger than the THz-photon energy, a THz pulse non-resonantly excites coherent interband polarizations, lifting electrons to the conduction bands only if the field is strong enough. Once carriers are created, they are accelerated inside the bands by the THz field simultaneously with the polarization giving rise to intraband currents and high-harmonic emission. We analyze this system by numerically solving the pertinent multi-band semiconductor Bloch equations to study high-harmonic generation in a GaSe sample. By time resolving the high-harmonic emission, we find that the radiation is emitted exclusively during positive crests of the driving THz field because negative crests show a suppressed emission.

9746-7, Session 2

Application of ultrafast electron field emission induced by strong terahertz transient for nonlinear terahertz spectroscopy (Invited Paper)

Krzysztof Iwaszczuk, Abebe T. Tarekegne, Peter Udh Jepsen, DTU Fotonik (Denmark)

High field terahertz (THz) pulses with photon energies in the few meV range and subpicosecond pulse duration are ideal for exploring nonlinear optics in non-perturbative electrostatic regime while maintaining ultrafast time resolution. Recent substantial progress in high power THz sources based on optical rectification of near-infrared laser pulses opened possibility for investigating those elusive processes. Here we investigate ultrafast electron field emission from resonant gold dipole antennas induced by strong THz transients.

We will discuss systems for generation of intense, ultrafast and broadband pulses of THz radiation with focus on tilted pulse front excitation of LiNbO3 crystal, which generates multi-$\mu$J pulses with spectral coverage 0.2 - 5 THz. Furthermore various methods for field enhancement will be discussed and we will show that metal dipole antennas on dielectric substrates fabricated by photolithography can provide significant enhancement.

We will show that strong THz transients enhanced in the near field of resonant dipole antenna can lead to ultrafast electron field emission from metal surface. Liberated electrons acquire substantial kinetic energy in the THz field and by collisions with nitrogen molecules surrounding dipole antennas lead to nitrogen plasma formation. UV emission from nitrogen plasma is a good indicator of the local electric field at the antenna tips. By monitoring UV emission in THz pump-THz probe experiments, resonant properties of antennas fabricated on various dielectric substrates are investigated. We show that ultrafast multiplication of carriers in silicon by impact ionization due to strong terahertz field can be monitored using this technique.

9746-8, Session 3

Broad gain InAs quantum dash nanostuctures on InP: recent progress in material structures and device demonstrations (Invited Paper)

Boon S. Ooi, Mohammed Zahed Mustafa Khan, Tien Khee Ng, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Self-assembled InAs quantum dots on InP substrate has set path to the development of an interesting quantum dash (Qdash) nanostuctures with features combining that of a conventional quantum dot and quantum wire. This new class of quasi-zero dimensional InAs elongated quantum dot has shown superior characteristics and wide wavelength tunability covering important C - L - U telecommunication bands (~1.4 $\mu$m to ~2.0 $\mu$m), and hence is a promising candidate for optoelectronics industry. Furthermore, devices based on self-assembled Qdash active region have demonstrated a
number of unique features viz. ultra-wide gain profile (>300 nm), ultra-broad interband emission under both stimulated (broadband lasers) and amplified spontaneous (superluminescent diodes) emissions regimes. In general, this has been attributed to the carrier localization in non-interacting or spatially isolated dot/dash in a highly inhomogeneous system. Furthermore, the inhomogeneous nature of the Qdash active region has also been exploited in the realization of broadband semiconductor optical amplifiers (SOA), sub-picosecond pulse generation (mode locked lasers, MLL), multi-wavelength sources, comb generation, etc. These novel active region based semiconductor devices are particularly attractive for many practical applications crossing different fields of optical communications, medical imaging, sensing, metrology, etc., due to their small footprint and relatively low energy requirement. In this paper, we will review the recent development of InP-based Qdash lasers. The technology for growing these nanostructures, as well as the technologies for engineering the bandgap of the InP-based Qdash system using epitaxy growth technique and postgrowth intermixing methods will be presented. Improvement of the Qdash broadband lasers and superluminescent diodes characteristics using various active region designs, and Qdash laser modeling, particularly highlighting the effect of the inhomogeneity on laser characteristics, will also be reviewed.

9746-9, Session 3

**Excitonic effects in quantum dot intraband spectroscopy indicating the formation of bound continuum excitons**

Sandra Kuhn, Marten Richter, Technische Univ. Berlin (Germany)

Coulomb induced effects on intraband transitions between bound quantum dot and unbound continuum states of the host material can play a role in a variety of applications. Since bound to continuum transitions are relevant for pumping, dephasing properties of the quantum dot states as well as for bound to continuum intraband spectroscopy.

We present bound to continuum intraband absorption spectra including Coulomb interaction, which are calculated using a theory based on a density matrix formalism.

Different bound to continuum quasi particles such as excitons, biexciton or trions results in characteristic spectral signatures like energy shifts, variations of the line width and splittings for every bound to continuum quasi particle.

Especially, we predict the existence of bound excitons consisting of a localized carrier inside the quantum dot and a delocalized carrier of the continuum.

In addition to intraband absorption spectra, we discuss the bound to continuum exciton wave function to get information about the localization of the unconventional bound continuum exciton. The results show signatures of a Coulomb induced formation of a bound excitonic state, which is spatially localized in the vicinity of the quantum dot.

The spatial extension of the bound excitons can increase up to 100 nm, which is much larger than the quantum dot extension of 10 nm.

This large extension of the exciton wave function opens a way to study new coupling between excitons in different distant quantum dots.

9746-10, Session 3

**Two-photon emission from quantum dot biexcitons**

Dirk Heinze, Dominik Brendermann, Artur Zrenner, Stefan Schumacher, Univ. Paderborn (Germany)

In this work we study the possibilities of cavity enhanced two-photon emission from a quantum dot biexciton. Firstly, a high-Q cavity is used to enhance the spontaneous emission of two degenerate photons with polarization-entanglement that is shown to be insensitive to fine-structure splitting. This mechanism is robust even against phonon-assisted cavity feedings at low temperatures. Secondly, a non-degenerate partly stimulated two-photon process allows us to study triggered single-photon emission. The triggering laser pulse enables the biexciton to relax into the ground state via a virtual state from which a second photon is then spontaneously emitted. The properties of this latter single photon, such as polarization and time of emission, can be controlled all-optically by the laser pulse.

The theoretical model used in this study includes coupling of the quantum dot states to two fully quantized cavity modes of orthogonal polarization and to an external, classical light field (laser pulse) in the case of the triggered single-photon emission. We obtain the system dynamics by solving the Liouville-von Neumann equation directly in the finite-dimensional Fock space spanned by the system's degrees of freedom. All results were obtained for realistic cavity quantum dot parameters and include photon loss and decoherence in the quantum dot.

9746-11, Session 3

**Control of macroscopic quantum interference in an inhomogeneous quantum dot ensemble**

Shota Ichikawa, Yuto Arai, Sayaka Kitazawa, Keio Univ. (Japan); Kouichi Akahane, National Institute of Information and Communications Technology (Japan); Junko Ishi-Hayase, Keio Univ. (Japan)

Quantum coherence and its interference of excitons play important roles in coherent control of semiconductor nanostructures. Quantum interference phenomena such as quantum beats of excitons have been demonstrated in a semiconductor quantum dot (QD), since QD excitons can maintain its coherence for relatively long time (>1 ns). However, in an ensemble of QD, the visibility of quantum interference is degraded, since the inhomogeneous distribution of exciton energies causes the dephasing of macroscopic coherence. Therefore, it is difficult to control quantum interference phenomena in an inhomogeneous QD ensemble. In this presentation, we propose and demonstrate new technique to control quantum interference of exciton fine-structure states in an inhomogeneous QD ensemble using 3-pulse photon echo (PE) technique.

We performed 3-pulse PE in highly-stacked InAs QDs using 1-ps excitation pulses with the central wavelength of 1530 nm. For tilted polarization of excitation pulses, quantum beat attributed to exciton fine-structure states was observed. We found that the amplitude of the exciton fine-structure quantum beat can be changed depending on the time delay of excitation pulses as well as the polarization direction of excitation pulses with respect to the crystal axes. We clarify that the anomalous behavior of quantum beat is caused by the difference of time evolution of two PE processes due to the inhomogeneity of QDs. Our results provide a new tool to control quantum interference of excitons which is useful even in an inhomogeneous system.

9746-12, Session 3

**On-chip broadband sources of correlated photon pairs in AlGaAs nanowaveguides**

Pisek Kultavewuti, Eric Y. Zhu, Qian Li, Univ. of Toronto (Canada); Vincenzo Pusino, Marc Sorel, Univ. of Glasgow (United Kingdom); J. Stewart Aitchison, Univ. of Toronto (Canada)

On-chip correlated photon pair sources are one of the key components of scalable, integrated quantum photonic circuits for applications such as quantum computing. We demonstrate correlated photon pair generation in a deeply-etched 700-nm-wide AlGaAs nanowaveguide via spontaneous four-wave mixing (SFWM). We design the nanowaveguide for a broadband
An investigation of semiconductor nanoparticles for application to all-optical switching

Brandon Born, Simon Geoffroy-Gagnon, Jonathan F. Holzman, UBC Okanagan (Canada)

The realization of a practical all-optical switch, for terabit-per-second processing of optical fibre signals, is necessary to alleviate the disparity between electronic and fibre optic data rates. Efficient all-optical switching is achievable with non-linear semiconductor mediums to cause interaction between the signal and control beams. Efficient operation is quantified by the switching energy (with a goal of femt joule energies) and the switching time (with a goal of femtosecond times). This work demonstrates these requirements with a new all-optical switching architecture. Dielectric spheres, with a diameter of 40 µm, are used to direct high-intensity photonic nanojets into peripheral coatings of semiconductor nanoparticles, with diameters of 20-200 nm. It is shown that localized photo injection from the photonic nanojet enables femtojoule switching energies, and localized recombination within the semiconductor nanoparticles enables femtosecond switching times. A variety of semiconductor nanoparticles with bandgap energies above the photon energy of the 1550 nm telecom wavelength are tested experimentally and analyzed theoretically, according to a coupled Drude theory and charge-carrier dynamical model. It is found that localized photo injection and recombination within the semiconductor nanoparticles enables surface recombination, leading to rapid switching times. Semiconductor nanoparticle coatings of Si, CdTe, CuO, InP and SiC are investigated and found to yield switching energies of approximately 1 fJ, 500 fJ, 500 fJ, 400 fJ and 20 fJ, with switching times of 2 ps, 2.3 ps, 450 fs, 900 fs and 270 fs, respectively.

Theory of coupled hybrid inorganic/organic systems: Excitation transfer at semiconductor/molecule interfaces

Judith F. Specht, Eike Verdenhalven, T. Sverre Theuerholz, Andreas Knorr, Marten Richter, Technische Univ. Berlin (Germany)

Hybrid inorganic/organic systems combine the optoelectronic properties of their individual constituents to exhibit novel device functionality. A detailed theoretical understanding of the temporal dynamics of the excitation transfer processes across the semiconductor/molecule interface is crucial for optimizing the performance of future hybrid optoelectronic devices.
9746-16, Session 4

Theory of photo-induced Floquet topological states in graphene and beyond (Invited Paper)

Michael A. Sentef, Max-Planck-Institut für Struktur und Dynamik der Materie (Germany)

Ultrafast materials science holds the promise to revolutionize materials design by including the photon field coupling to a solid beyond linear response. Here we examine in detail theoretical possibilities of nonlinear effects of light-matter coupling. For continuous-wave laser driving with a time-periodic electric field, the concept of Floquet theory can be applied to a many-body Hamiltonian, with intriguing consequences. As an example, the concept of Floquet topological insulators was recently introduced. In essence, it describes a photo-induced electronic band structure with tunable energy gaps and quantum geometry (Berry curvature) that determines the topology of the band structure.

In our work, we employ Floquet theory and the nonequilibrium Keldysh Green function formalism to numerically explore what can be achieved with realistic pump-probe spectroscopy setups. Specifically for graphene, we predict sizeable energy gaps at the Dirac points and nontrivial local Berry curvatures at realistic pump photon frequencies [1]. Importantly, the specifics of the pump laser pulse (polarization, frequency, pulse duration, intensity) play important roles in shaping the achieved state of matter. We make quantitative predictions that can be tested experimentally and used as clear-cut evidence of the Floquet nature of the measured results.

Finally, I will also show new results for topologically interesting materials beyond graphene, with a comparison of model calculations and ab-initio time-dependent density functional theory.


9746-17, Session 4

Buckled graphene-like materials in ultrashort and strong optical fields

Hamed Koochaki Kelardeh, Vadym Apalkov, Mark I. Stockman, Georgia State Univ. (United States)

This paper investigates the interaction of buckled Dirac materials (silicene and germanene) with ultrashort and ultrastong optical pulses. Highly intensive few-cycle pulses strongly modify the electronic and optical properties of these two dimensional materials. Electron dynamics in such a short optical pulse is coherent and can be robustly controlled by altering the propagation direction, as well as the polarization angle of the pulse. The strong nonlinearity of the system for fields applied (~ V/Å) causes the violation of the charge (C) and parity (P) symmetries, effectively reducing the system's symmetry from hexagonal to triangular. Such symmetry violations are related to the electron transfer between the sublattices caused by the normal field component and result in nonreciprocity, optical rectification and the appearance of a cross current.

The finite transferred charge through the system also illustrates a significant violation of the time reversal symmetry in the system. We attributed this phenomena to the so-called Landau damping which is inherent in all Dirac materials due to the absence of a significant band gap. Finally, we note a direct resemblance between silicene and field-effect transistors (FET). In FETs, the (perpendicular) gate field changes the carrier concentration and thereby, controls its conductance. Anologously, in silicene, the normal field component of the pulse, transfers carriers between two sublattices, and consequently modulates the response function of silicene to the in-plane field. Our findings open a new horizon for various applications employing silicene and are promising for petahertz signal processing.

9746-18, Session 4

Broadband ultrafast saturable absorption of black phosphorus nanosheets over near-to middle-infrared region

Kangpeng Wang, Beata M. Szydlovksa, Gaozhong Wang, Johnathan N. Coleman, Werner J. Blau, Trinity College Dublin (Ireland)

The recent increasing demands of high power ultrafast mid-infrared fiber laser call for broadband saturable absorbers as mode-lockers. 2D nanomaterials, such as graphene and MoS2, are considered as candidates because of their broadband response and easy fabrication, but their inherent limitations drive researchers to explore alternative materials with better nonlinear optical properties.

In this report, we investigate the ultrafast nonlinear optical properties of 2D black phosphorus (BP) nanosheets with 1420, 1550 and 1972 nm femtosecond pulses. The BP crystal is exfoliated in CHP (1-Cyclohexyl-2-pyrrolidone) to obtain dispersions by ultrasonic liquid phase exfoliation. The characterizations including UV-Vis absorption, Raman and APM confirm effective exfoliations of BP crystal to high quality nanosheets. The ultrafast nonlinear optical responses of BP dispersions are investigated by open-aperture Z-scan. All experiments are performed using wavelength tunable 100 fs 100 KHz laser from an optical parametric amplifier pumped by 800 nm Ti:Sapphire femtosecond laser. Ovious saturable absorption of BP dispersions are observed at all the three wavelengths which correspond the emissions of Nd, Er and Tm ions. The saturable absorption of BP nanosheets can be explained by the free-carrier absorption of multi-layer BP nanosheets for its narrow bandgap (0.3 eV, ~4.1 um). Although many reports shows the instability of BP nanosheets in ambient air, the saturable absorption of BP dispersions seems to be quite stable for at least one month without any extra protection in our experiments. Our results reveal the promising potentials of BP to nanosheets as nanophotonic devices, especially as mode-lockers for mid-infrared fiber lasers.

9746-19, Session 4

Carbon nanotubes for ultrafast switching: nonlinear polarization

Hanieh Afkhamiardakani, Jean Claude M. Diels, Ladan Arissian, The Univ. of New Mexico (United States)

Carbon nanotubes (CNT) have become a preferred switch for fs pulse generation in fibers for their fast recovery time and a relatively high damage threshold. Femtosecond pulses in fiber lasers were previously achieved by mode-locking through nonlinear polarization rotation. This mechanism can only be used with single mode fibers, making the laser extremely sensitive to manipulation. CNT in addition can be used with polarization maintaining fibers, a considerable improvement in stability. Another advantage is the possibility to create a mode-locked laser with two pulses circulating in its cavity, along the slow and fast axis, leading to sensors of unprecedented sensitivity (Intracavity Phase Interferometry).

We investigate the third order nonlinearity of the CNT, which can couple the pulses in the fast and slow axis. A PM fiber was tapered down to a diameter of 20 micron, leading to a transmission of 40%. A solution of carbon nanotube dissolved in polydimethylsiloxane is deposited on the tapered section. The CNT attach tangentialy along the perimeter of the fiber, providing an azimuthal symmetry. The polarization in transmission is analyzed for an initially elliptically polarized (ellipticity in field 0.25) 980 nm beam. The polarization ellipse is seen to rotate by 5.8 degree/mW of input, in the range of input power between 16 and 75 mW. The saturation intensity corresponds to an input power of 45 mW. There is an ellipticity change as well. The results resembles similar measurements performed with filaments in air, and the mechanism (under investigation) may involve similar molecular re-orientation.
Electrically-driven carbon-based plasmonic laser on silicon for ultrafast modulation

Ke Liu, Volker J. Sorger, The George Washington Univ. (United States)

Photonic signal processing requires efficient on-chip light sources with higher modulation bandwidths. Today's conventional fastest semiconductor diode lasers exhibit modulation speeds only on the order of a few tens of GHz due to gain compression effects and parasitic electrical capacitances. Here we show an electrically-driven Carbon nanotubes-based laser utilizing strong light-matter-interactions via monolithic integration into Silicon photonic crystal nanobeam cavities. This device is formed by single-wall CNTs inside a combo-cavity consisting of both a plasmonic metal-oxide-semiconductor hybrid mode embedded in the one dimensional photonic crystal cavity. The Carbon-based plasmonic laser operates at telecom frequencies resulting in a power output >10 W and 100's GHz modulation speed, showing an alternative promising approach for future photonic integrated circuits.

Structure-function relationship of perovskite film morphology and charge dynamics

Swee Sien Lim, Nanyang Technological Univ. (Singapore); Wee Kiang Chong, Nanyang Technological Univ. (Singapore) and Interdisciplinary Graduate School (Singapore); Herlina Dewi, Nripan Mathews, Subodh G. Mhaisalkar, Tze Chien Sum, Nanyang Technological Univ. (Singapore)

The low-temperature solution processed organic-inorganic lead halide perovskite has attracted the interest of many researchers, in particular, the 3D perovskite, CH3NH3PbI3. It has demonstrated high solar-to-power conversion efficiencies, but the underlying photophysical mechanisms are still not understood. As such, recent efforts to study the effects of different growth procedures were carried out. In this work, we performed a structure-functional study using steady-state and femtosecond time-resolved spectroscopy to determine the effects of substrate and film treatments. We found that the carrier lifetimes, trap densities, and ASE thresholds were modulated. In order to ascertain possible factors, complementary physical characterisation methods such as X-Ray diffraction and scanning electron microscopy were performed. This allowed us to determine the crystallographic phases present in the different thin films prepared and its associated morphology. By studying how these processing methods affect the intrinsic properties of the perovskite can help improve device performances even further, surpassing commercial silicon solar cells and lasers.

Ultrafast spin dynamics and ultra-large Faraday rotation in methylammonium lead iodide perovskite thin films

David Giovanni, Nanyang Technological Univ. (Singapore); Hong Ma, Shandong Normal Univ. (China); Julianto Chua, Nanyang Technological Univ. (Singapore); Michael Grätzel, Ecole Polytechnique Fédérale de Lausanne (Switzerland) and Nanyang Technological Univ. (Singapore); Ramamoorthy Ramesh, Univ. of California, Berkeley (United States); Subodh G. Mhaisalkar, Nripan Mathews, Tze Chien Sum, Nanyang Technological Univ. (Singapore)

Low-temperature solution-processed organic-inorganic hybrid metal halide perovskite, especially methylammonium lead iodide (CH3NH3PbI3), has demonstrated to possess great potential for photovoltaics and light-emitting devices. Recent discoveries of long ambipolar carrier diffusion lengths and the prediction of the Rashba effect in CH3NH3PbI3, that possesses large spin-orbit coupling, also point to a novel semiconductor system with highly promising properties for spin-based applications. Here we present the first study of ultrafast spin dynamics in CH3NH3PbI3 -70 nm-thick film. Its strongly reshaped band structure by spin-orbit coupling results in J ~1/2 at conduction and valence band-edge, allowing spin-polarized carriers to be generated by circularly polarized light. Experimentally, we observed ~90% J-polarized photoinduced carriers at band-edge, which produce magnetization corresponds to strikingly large Faraday rotation up to 10°/μm depending on temperature, which decays within 10 ps. This dynamic is well described by simple two-level model with intraband carrier spin-flip. Temperature dependent study reveals weak spin-phonon interaction in the system, from which we assign the spin-relaxation mechanism to be Elliott-Yafet mechanism through impurities and grain boundaries scattering. This work highlights organic-inorganic hybrid perovskites as excellent candidates for opto-spintronics applications, especially for optical spin switches.

Factors affecting amplified spontaneous emission in (C6H5C2H4NH3)2PbI4 perovskite

Wee Kiang Chong, David Giovanni, Teck Wee Goh, Krishnamoorthy Thirumal, Nanyang Technological Univ. (Singapore); Xinfeng Liu, Nanyang Technological Univ. (Singapore); Nripan Mathews, Subodh G. Mhaisalkar, Tze Chien Sum, Nanyang Technological Univ. (Singapore)

Two dimensional (2-D) lead halide perovskite is a class of material that possesses strong excitonic properties. The excitonic recombination in these materials gives rise to bright spontaneous emission desired for light emitting applications. Till date, there have been many demonstrations of bright LEDs from this material. However, amplified spontaneous emission (ASE) gain in this material is not especially successful and only one instance on low temperature biexciton lasing has been reported. This necessitates a study to reveal ASE challenges ASE from 2D perovskite and (C6H5C2H4NH3)2PbI4 will be used as a representative system for our study. Both experimental and theoretical approaches will be employed to identify these challenges. Low temperature (~10 K) steady-state PL revealed significant amount of traps and biexciton formation at high laser fluence with no ASE onset. Low temperature time-resolved photoluminescence (TRPL) also revealed...
short lived (tens of ps) emission. We model the exciton decay dynamics using a set of rate equations based on 7 physical processes within a 4-level electronic system. The exciton-exciton annihilation coefficient (\( \gamma \)) and non-radiative trapping rate (\( k_T \)) were found to be 0.15 ps^{-1} and 0.05 ps^{-1}. Consistent with our experimental observation, our calculations based on these two values showed no super linear light intensity increase at higher laser fluence. Our calculations also show ASE occurrence when \( \gamma \) and \( k_T \) is increased and decreased respectively. This work highlights the intrinsic challenges in obtaining ASE in 2D perovskite and suggests more effort must be introduced to realize high gain in this material.

9746-25, Session 6

Ultrafast terahertz scanning tunneling microscopy (Invited Paper)

Vedran Jelic, Peter H. Nguyen, Graham J. Hornig, Haille M. Sharum, James R. Hoffman, Univ. of Alberta (Canada); Christopher Rathje, Univ. of Göttingen (Germany); Claus Ropers, Georg-August-Univ. Göttingen (Germany); Frank A. Hegmann, Univ. of Alberta (Canada)

Terahertz-pulse-coupled scanning tunneling microscopy (THz-STM) is an emerging technique for ultrafast imaging of surfaces at the nanometer scale. A spatial resolution of 2 nm and temporal resolution of 500 fs has been demonstrated under ambient conditions. We are currently developing THz-STM for operation in ultrahigh vacuum. The challenges involved with operating in an ultrahigh vacuum environment, simulations of a THz pulse coupling to an STM tip, and progress towards atomic resolution with the THz-STM will be discussed.

9746-26, Session 6

Nonperturbative THz Nonlinearities for Many-Body Quantum Control in Semiconductors (Invited Paper)

Christoph Lange, Thomas Maag, Univ. Regensburg (Germany); Andreas Bauer, Univ. of Regensburg (Germany); Matthias Hohenleutner, Sebastian Baierl, Dominique Bougard, Univ. Regensburg (Germany); Martin Mootz, Stephan W. Koch, Mackillo Kira, Philippus-Univers. Marburg (Germany); Rupert Huber, Univ. Regensburg (Germany)

Quantum computing and ultrafast quantum electronics constitute pivotal technologies of the 21st century and revolutionize the way we process information. Successful implementations require controlling superpositions of states and coherence in matter, and exploit nonlinear effects for elementary logic operations. In the THz frequency range between optics and electronics, solid state systems offer a rich spectrum of collective excitations, such as excitons, phonons, magnons, or Landau electrons. We pursue two experiments towards THz quantum electronics.

First, single-cycle THz transients of 8.7 kV/cm amplitude centered at 1 THz strongly excite a cyclotronic GaAs quantum well system, drive coherent Landau ladder climbing by more than six rungs leading to population inversion, and facilitate coherent polarization control. Highly nonlinear four- and six-wave mixing signals, entirely unexpected for this paradigm of the harmonic oscillator, are revealed through two-time THz spectroscopy. In this scenario of nonperturbative polarization dynamics, our microscopic theory shows how the protective limits of Kohn's theorem are ultimately surpassed by dynamically enhanced Coulomb interactions.

In a second experiment we exploit the near-field in gold metamaterials to increase the THz amplitude beyond 10 MV/cm and explore high-field interband charge dynamics in undoped GaAs, at 1 THz. At a Keldysh parameter of 0.02 and keV-scale ponderomotive energies, interband Zener tunneling exceeding previously reported rates by 10 orders of magnitude injects more than 10^19 cm^{-3} carriers during a single cycle of the THz field, evoking strong luminescence.

Our experiments show how coherent THz quantum control and THz interband carrier generation lead the way towards future THz quantum electronics.

9746-27, Session 6

Strong sub-terahertz surface waves generated by relativistic laser pulses (Invited Paper)

Shigeki Tokita, Osaka Univ. (Japan); Shunsuke Inoue, Kyoto Univ. (Japan); Ryo Yasuhara, National Institute for Fusion Science (Japan); Kensuke Teramoto, Kyoto Univ. (Japan); Takeshi Nagashima, Setsunan Univ. (Japan); Masaki Hashida, Shuji Sakabe, Kyoto Univ. (Japan)

We report high-time-resolution measurements of the temporal waveform of an electromagnetic field, induced by a femtosecond laser pulse with an intensity of 10 to power of 18 watt per square centimeter, propagating along the surface of a metal wire. The measurement is realized by a new technique for ultrafast field measurement based on femtosecond electron deflectometry using laser-accelerated and recompressed electron pulses. We observe a strong pulse signal propagating at the speed of light, even though there is no significant number of high-energy fast electrons propagating at that speed. Experimental results show that the pulse signal is due to a surface wave rather than fast electrons. Numerical simulations indicate that a sub-terahertz TM surface wave was efficiently excited by laser-plasma interaction in the metal wire targets.

9746-28, Session 6

Terahertz cyclotron spectroscopy of spin-split holes in Ge quantum wells and polarons in ZnO heterostructures (Invited Paper)

James Lloyd-Hughes, The Univ. of Warwick (United Kingdom)

The cyclotron resonances of two 2D quantum-confined materials of potential interest in spintronics were examined using terahertz time-domain spectroscopy. Oxide heterostructures can display exotic ground states, such as fractional quantum Hall states and weak ferromagnetism. A single cyclotron resonance was found for 2D electrons in Zn(1-x)Mg(x)O/ZnO heterostructures (with x=0.2). Low-temperature complex magnetococonductivity spectra allowed important material parameters to be determined. The polaronic mass measured was observed to reduce at lower applied magnetic fields. We discuss this finding in relation to polaron mass renormalization effects that can be created by the electron-LO phonon and electron-acoustic phonon interactions.

In contrast, for high-mobility 2D heavy-hole gases in Ge quantum wells with structural inversion asymmetry we find multiple cyclotron resonances. This can be ascribed to the spin-splitting driven by the Rashba spin-orbit interaction (at low magnetic fields) and to the Zeeman effect in a nonparabolic band (at high magnetic fields). The cubic spin-orbit interaction strength was determined in a non-contact fashion from the cyclotron resonances, and agreed with results from device magnetotransport. Importantly, an enhanced spin-orbit interaction was found to be concomitant with a high mobility, suggesting the promise of this system for CMOS-compatible spintronics.
9746-29, Session 7

Optically-induced currents in dielectrics and semiconductors: a new ultrafast nonlinear optical effect (Invited Paper)

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

We demonstrate theoretically that when well-below-the-bandgap femtosecond optical pulses propagate through a dielectric or semiconductor, DC current and charges are produced even though no real carriers are excited in the bands. The photo-induced current is a new ultra-fast nonlinear optical effect based on multi-photon quantum interference and creation of an asymmetric distribution of virtual carriers in the conduction and valence bands. We establish an unambiguous connection between the nonlinear optical conductivity responsible for the photo-induced DC currents and charges and the odd-order nonlinear optical susceptibilities of the material. We then apply our results to the recent experiments [1] in which photo-induced charges have been observed in SiO2 irradiated by below-the-gap ultra-short optical pulses. Using a single well known measured value of the third order susceptibility (nonlinear index) of SiO2 we obtain excellent agreement with all the experimental data of [1]. A clear physical picture of the origin of the photo-induced currents and charges shows that the versatility of ultrafast (virtual) nonlinear optical phenomena extends even further than had been previously thought.


9746-30, Session 7

Investigation of coupled optical parametric oscillators for novel applications (Invited Paper)

Yuuie J. Ding, Lehigh Univ. (United States)

During this presentation, we review the progress made by us on the coupled optical parametric oscillators and their applications. In a conventional optical parametric oscillator, a pump beam generates a pair of signal and idler waves in a nonlinear medium being placed in an optical resonator. In our novel scheme, each pump wave generates a pair of signals and a pair of idlers from a composite consisting alternating nonlinear plates. These signal twins (also idler twins) exhibit ultrastability, i.e. their relative phase difference and frequency separation are insensitive to the temperature fluctuation and the phase variation of the pump beam. As a result, these twins can be used to realize variety of the applications. For example, when using them for THz generation, the THz output power is greatly enhanced compared with that generated by the pair of signal and idler waves in the conventional optical parametric oscillator. Moreover, the linewidth and noise of the THz output are greatly reduced using the twins. These coupled parametric processes can be also used to compensate for the effect induced by the atmospheric turbulence which makes images lose their original resolutions and generates additional noises for the electromagnetic waves propagating through atmosphere. Other applications include quantum communications and imaging.

9746-31, Session 7

Photocurrents in semiconductors and semiconductor quantum wells analyzed by k.p-based Bloch equations

Reinold Podzimski, Torsten Meier, Univ. Paderborn (Germany); Huynh Thanh Duc, Vietnamese Academy of Science and Technology (Viet Nam); Shekhar Priyadarshi, Christian Schmidt, Mark Bieler, Physikalisch-Technische Bundesananstalt (Germany)

Using a microscopic theory that combines k.p band structure calculations with multisubband semiconductor Bloch equations [1,2,3] we are capable of computing coherent optically-induced rectification, injection, and shift currents in semiconductors and semiconductor nanostructures. A 14-band k.p theory have been employed to microscopically compute electron states in non-centrosymmetric semiconductor systems. Numerical solutions of the multisubband Bloch equations provide a detailed and transparent description of the dynamics of the material excitations in terms of interband and intersubband polarizations/coherences and occupations. Our approach allows us to calculate and analyze the photocurrents in the time and the frequency domains for bulk as well as quantum well and quantum wire systems with various growth directions. As examples, we present results on the rectification, injection, and shift currents in GaAs bulk and GaAs based quantum well systems and compare our results with experiments on shift and injection currents. In the experiments the THz radiation emitted from the currents is detected via electro-optic sampling. We find a very good agreement between theory and experiments.


9746-32, Session 7

All-optical field-induced second-harmonic generation

Roderick B. Davidson II, Vanderbult Univ. (United States); Anna Yanchenko, Univ. of Virginia (United States); Jed I. Ziegler, Sergey M. Avanesyan, Vanderbult Univ. (United States); Benjamin J. Lawrie, Oak Ridge National Lab. (United States); Richard F. Haglund Jr., Vanderbult Univ. (United States)

Efficient frequency modulation is crucial to the development of plasmonic metasurfaces for information processing and energy conversion. This paper describes an experimental realization of all-optical field-induced second-harmonic generation (SHG) enhanced by an asymmetric plasmonic nanostructure, a serrated nanogap (SNG). The lithographically fabricated SNG creates a series of electric-field ‘hotspots’ in a planar capacitor-like geometry. By taking advantage of the short lifetime and polarization sensitivity of a plasmon resonance in this high-aspect-ratio geometry, we distinguish second-order plasmonic SHG from plasmon-induced SHG generated in a polymer embedded in the SNG. We employ second-harmonic interferometric pump-probe interferometric pump-probe (SHIP) spectroscopy with sub-femtosecond temporal resolution to isolate the sources of the observed SHG. When the nanostructure is excited by a control laser pulse (800 nm wavelength, 30 fs pulse duration) polarized perpendicular to the gap, regions of high electric field form at the teeth of the serrations, creating steep electric field gradients within the nanogap. When the nanogap is filled by spin-coating the sample with poly(methyl methacrylate) (PMMA) and the plasmon is excited using an ultrafast laser pulse, intense electric fields within the dielectric oscillate with a period of approximately 2.7 fs. These oscillations rapidly polarize the electronic structure of the PMMA, causing large changes in its effective nonlinear susceptibility. This technique points the way to creating novel families of plasmonic devices, as well as a new way to interrogate the nanoscale response of bulk materials to THz electric fields.

9746-33, Session 7

Phase manipulation of nonlinear processes by metasurfaces (Invited Paper)

Thomas Zentgraf, Univ. Paderborn (Germany); Guixin Li, Univ. of Birmingham (United Kingdom) and Hong Kong
Engineering the nonlinear optical properties of media is a crucial process in nonlinear optics. The most well-known technique for spatially engineering the nonlinear properties is quasi-phase matching for second-order processes like SHG. The quasi-phase matching leads to efficient frequency conversion compared to a homogeneous nonlinear medium by providing the extra momentum to compensate the phase mismatch between the fundamental and harmonic waves. The so-called ‘poling’ is the most widely employed technique for achieving quasi-phase matching. By periodically reversing the crystalline orientation of ferroelectric materials, the sign of the chi(2) nonlinear susceptibility can be spatially modulated along the propagation direction. However, such a poling only leads to a binary state for the nonlinear material polarization, which is equivalent to a discrete phase change of π of the nonlinear polarization.

Here we will demonstrate a novel nonlinear metamaterial with homogeneous linear optical properties but continuously controllable phase of the local effective nonlinear polarizability. The controllable nonlinearity phase results from the phase accumulation due to the polarization change along the polarization path on the Poincare Sphere (Pancharatnam-Berry phase) and depends therefore only on the spatial geometry of the metasurface. In contrast to the quasi-phase matching the continuous phase engineering of the effective nonlinear polarizability enables complete control of the propagation of harmonic generation signals, and therefore, it seamlessly combines the generation and manipulation of the harmonic waves for highly compact nonlinear nanophotonic devices. We will demonstrate the concept of phase engineering for the manipulation of the SHG and THG from metasurfaces.

9746-35, Session 8
Long-range energy transfer mechanism between two coupled plasmonic nanoantennas (Invited Paper)
Martin Aeschlimann, Technische Univ. Kaiserslautern (Germany); Tobias Brixner, Julius-Maximilians-Univ. Würzburg (Germany); Benjamin Frisch, Technische Univ. Kaiserslautern (Germany); Bert Hecht, Bernhard Huber, Julius-Maximilians-Univ. Würzburg (Germany); Matthias Hensen, Univ. Bielefeld (Germany); Christian Kramer, Enno Krauss, Julius-Maximilians-Univ. Würzburg (Germany); Walter Pfieffer, Univ. Bielefeld (Germany); Christian Strüder, Imperial College London (United Kingdom); Philip Thielen, Technische Univ. Kaiserslautern (Germany)

Short-range coherent energy transfer dynamics e.g. in light harvesting complexes and their implications from a control systems perspective has been discussed vividly. Here, the long-range energy transfer mechanism between two coupled plasmonic whispering gallery nanoantennas in an elliptical cavity is investigated by optical excitation with shaped sequences of ultrashort pulses centered at 800nm. Upon illumination in a shallow angle geometry only one gold antenna is excited selectively. Plasmon-enhanced time-resolved photoemission microscopy [1] detected at both nanoantennas reveals periodic energy transfer on a micrometer length scale in the hybridized antenna cavity system. Exploiting single quantum emitters to the antenna induced field enhancement these systems might serve for future applications involving strong and ultrafast interaction of well-separated single quantum systems.

9746-38, Session 8

**Design of integrated YIG-based isolators and high-speed modulators**

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

A novel method for manipulation of integrated optical modes involves the use of magneto-optic materials. The application of a transverse static magnetic field over these materials can induce nonreciprocal phenomenon such as the nonreciprocal phase shift. Here, our fully vectorial finite-difference-time-domain (FDTD) simulations demonstrate the occurrence of magneto-optical effects into integrated Mach-Zehnder interferometers (MZIs), constructed with layers of either bismuth- or cerium-substituted yttrium iron garnets (Bi/YIG or Ce/YIG). Applying transverse static magnetic fields of opposite polarity to each arm, one can induce nonreciprocal phase shifts and influence the interference observed at the MZI output. As such, we show that devices constructed with Ce/YIG, known for its high specific Faraday rotation and magneto-optic properties, can be used to implement compact and efficient optical isolators. Conversely, incorporation of Bi/YIG, which is well known for its ultrafast switching speed, facilitates the development of high-speed optical modulators. Modulation of the Bi/YIG magnetization, and hence the applied phase shift in each arm, is achieved through an integrated serpentine transmission line structure generating transient magnetic field pulses. The Landau-Lifshitz-Gilbert model of magnetization dynamics is combined with the fully vectorial FDTD solution of Maxwell’s equations to study this phenomenon. We examine the effects of sub-nanosecond super-Gaussian magnetic field transients on the system to develop a series of modulators. Such devices are fundamental building blocks for nanoscale integrated optics.

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9746-41, Session 9

**Ultrafast all-optical switching with photonic nanojets and semiconductor nanoparticles**

Brandon Born, Jeffrey D. Krupa, Simon Geoffroy-Gagnon, Jonathan F. Holzman, UBC Okanagan (Canada)

Terabit-per-second communication systems can be enabled by emerging all-optical networks and processors employing all-optical switching. To be effective, all-optical switching must support operations with femtosecond switching energies and femtosecond switching times. With this in mind, this work studies the geometrical and material characteristics for all-optical switching and a new all-optical switching architecture is developed, following a guiding principle of localization. A nanojet focal geometry is applied, in the form of dielectric spheres, to direct high-intensity photonic nanojets into peripheral semiconductors. It is shown that a nanojet focal geometry, promotes localized photo-injection of charge-carriers at the semiconductor (GaAs) surface—yielding high charge-carrier densities (for switching energies down to 10 fJ) and surface-assisted recombination (for switching times down to 10 ps). A nanoparticle material system is added to further promote localized recombination, with 20 nm (Si) and 50 nm (SiC) semiconductor nanoparticles embedded into the sphere surface. It is shown that an all-optical switching architecture integrating high-intensity photonic nanojets and semiconductor nanoparticles together achieves 200 fJ (Si) and 100 fJ (SiC) switching energies with 10 ps and 350 fs switching times, respectively, in an all-optical switching architecture that meets practical considerations for coupling and stability.

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9746-39, Session 9

**Sub-one nanometer gap (SONG) for SERS (Invited Paper)**

Yung Doug Suh, Korea Research Institute of Chemical Technology (Korea, Republic of)

Gap Plasmon dominates thus governs the enhancement factor of Surface-Enhanced Raman Scattering(SERS), and it allows SERS sensitivity even down to the single molecule level. Single Molecule SERS(smSERS) is now quite an established field after long and tiring debates since its first phenomenological independent discoveries by S. Nie’s and K. Kneipp’s group published with only two weeks interval in 1997. smSERS can provide a wealth of molecular chemical information from the single molecule probed, thus possesses tremendous amount of potentials if we remind current status of overwhelming biomedical applications based on the Single Molecule Fluorescence(sm Fluorescence) and the Surface Plasmon Resonance(SPR) including DNA sequencing technologies and drug discovery research.

In this talk, I would like to attempt to rationalize and generalize, 1. gap-mode AFM-TERS consisting of a metalized AFM probe and a noble metal substrate, 2. STM-TERS consisting of noble metal tip and noble metal substrate, 3. Au or Ag nanoparticle(NP) dimer junction with sub-one-nanometer-gap where one NP can be viewed as a tip and another as a substrate. 4. SERS sensor array fabricated by E-beam lithography as well as by other fabrication techniques, sharing basically same physics of gap-plasmonics and near-field optics. Maximum near-field enhancement for SERS can be achieved when the nanogap becomes narrower down to sub-one-nanometer peaking at around 0.3-nm gap, just before the quantum tunneling sets in through the nanogap. In the quantum regime of gap plasmon at the nanogap junction, where the nanogap between the particles is smaller than 0.3 nm, new charge-transfer modes arises in dark-field scattering spectrum.

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9746-42, Session 9

**Quantification of electric field enhancement factors of nanogaps in visible - near IR frequencies**

Taehee Kang, Ji Yeah Rhie, Seoul National Univ. (Korea, Republic of); Joohyun Park, Hanyang Univ. (Korea, Republic of); Young-Mi Bahk, Jae Sung Ahn, Seoul National Univ. (Korea, Republic of); Hyeongtae Jeon, Hanyang Univ. (Korea, Republic of); Dai-Sik Kim, Seoul National Univ. (Korea, Republic of)

Strong electric field on nanometer scale metal structure is the key factor for its possible applications in surface enhanced Raman scattering, enhanced fluorescence spectroscopy and single molecule detection. Various metallic nanostructures have been investigated to efficiently generate the strong electric field and to quantify the field enhancement factor, which represent the performance of the metal structure. To determine the enhancement factor, however, most of the previous works relied on the numerical method to characterize the electric field enhancement, which inevitably lacks the real experimental conditions. Therefore, direct experimental verification of enhancement factor is much needed to fully reflect the experimental situations. In this work, we demonstrated the measurement of electric field enhancement factor on the nanometer-sized metal gaps in visible - near infrared frequencies. Experimental estimation of field enhancement was possible by applying the Kirchhoff integral formalism on the measured far-field transmission of nanogap samples. Due to the Fabry-Perot-like resonant feature of the nanogap transmission, electric near-fields on the gap also resonantly enhanced, reaching its maximum enhancement factor up to 40 at the smallest gap size of 1.5 nm. To test the validity of the measured enhancement factor, we theoretically calculated the electric near-fields on the nanogap by mode expansion method. We found that the calculation and experiment data were in good qualitative agreement.
Record high normalized light-matter-coupling strength surpassing unity

Curdin Maisen, Giacomo Scalari, Jérôme Faist, Matthias Beck, Christian Reichl, Werner Wegscheider, ETH Zürich (Switzerland)

We realized a physical system showing a normalized ultrastong light-matter coupling larger than unity. The LC-mode of a THz-metamaterial at $\omega_c/\omega_m?_{2DEG}=4.5*10^{-11}$ cm$^{-2}$, leading to a total thickness of 2.8 nm. The THz-metamaterial unit cell consists of one complementary split ring resonator (SRR). The near field of every SRR forms a strongly subwavelength cavity for the THz radiation. The effective volume is on the order of $V_\text{eff}=7*10^{-5}$ cm$^3$, leading to a strong enhancement of the vacuum electromagnetic field and of the light-matter interaction. We were able to achieve this high coupling by working at increased filling factors $?_{2DEG}/?_{c h/m}^3=10^5$, leading to a strong enhancement of the vacuum electromagnetic field and of the light-matter interaction. The properties of the coupled system were determined by transmission measurements with a THz time domain spectrometer. These results form a further step into the quantum optical regime of ultrastrong light-matter coupling. The control of the semiconductor heterostructure can facilitate the exploration of phenomena in this regime where the energy exchange between the light and matter constituents occurs on time scales faster than the oscillation periods of the constituent resonances.

SPASER as a complex system: femtosecond dynamics traced by ab-initio simulations

Juan Sebastian Totero Gongora, King Abdullah Univ. of Science and Technology (Saudi Arabia); Andrey E. Miroshnichenko, Yuri S. Kivshar, The Australian National Univ. (Australia); Andrea Fratalocchi, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Integrating coherent light sources at the nanoscale with spasers is one of the most promising applications of plasmonics. A spaser is a nano-plasmonic counterpart of a laser, with photons replaced by surface plasmon polaritons and the resonant cavity replaced by a nanoparticle supporting localized plasmonic modes. Despite the large body of experimental and theoretical studies, the understanding of the fundamental properties of the spaser emission is still challenging. In this work, we investigated the ultrafast dynamics of the emission from a core-shell spaser by developing a rigorous first-principle numerical model. Our results show that the spaser is a highly nonlinear system with many interacting degrees of freedom, whose emission sustain a rich manifold of different spatial phases. In the regime of strong interaction we observed that the spaser emission manifests an irreversible ergodic evolution, where energy is equally shared among all the available degrees of freedom. Under this condition, the spaser generates ultrafast vortex lasing modes that are spinning on the femtosecond scale, acquiring the character of a nanoparticle with an “effective” spin. Interestingly, the spin orientation is defined by spontaneous symmetry breaking induced by quantum noise, which is a fundamental component of our ab-initio model. This opens up interesting possibilities of achieving unidirectional emission from a perfectly spherical nanoparticle, stimulating a broad range of applications for nano-plasmonic lasers as unidirectional couplers, random information sources and novel form of photonics neural-networks.
Terahertz (THz) frequencies are particularly interesting for investigating vibrational dynamics in organic crystalline materials since this frequency range corresponds to the lowest vibrational modes of the crystal. These modes are typically of intra- as well as intermolecular character, and thus offer useful information about the chemical composition of molecules as well as their environment. At the same time the single-cycle, sub-picosecond THz pulses are ideal for idealizing ultrafast phenomena on a molecular scale.

2D spectroscopy is a multi-pulse technique which has been widely used for investigating molecular dynamics and nonlinear phenomena in the IR range. But only a few 2D experiments have been reported in the THz range with focus on semiconductor systems, where the nonlinear response is determined by incoherent electronic dynamics, and thus coherence is only preserved within the scattering time of the charges.

Multidimensional coherent spectroscopy of a semiconductor microcavity

Brian Wilmer, West Virginia Univ. (United States); Felix Passmann, Technische Univ. Dortmund (Germany) and West Virginia Univ. (United States); Michael R. Gehl, College of Optical Sciences, The Univ. of Arizona (United States); Galina Khitrova, The Univ. of Arizona (United States) and The Univ. of Arizona, College of Optical Sciences (United States); Alan D. Bristow, West Virginia Univ. (United States)

Semiconductor microcavities are used in optoelectronic applications and provide a platform for exploring exotic coherent phenomena. Normal-mode coupling between cavity mode and exciton resonance enhances the light-matter interactions. Despite extensive studies of microcavity exciton-polaritons, the anti-crossing has not been systematically mapped using two-dimensional coherent spectroscopy (2DCS). In this abstract, the exciton-polariton branches are mapped using rephasing and non-rephasing 2DCS. The microcavity is wedged, allowing detuning of the cavity mode with respect to the bare exciton simply by translating the sample in the laser focus. Three 100-fs phase-locked pulses arranged in the box geometry generate four-wave mixing spectra, which are recorded while incrementing the relative delays between the first and second pulses. The resulting data are transformed numerically to generate the two-dimensional spectrum. Measurements are recorded in the limit of third-order perturbation and the time delay between the second and third pulses is non-zero, ensuring the fewest possible quantum pathways per spectrum. These quantum pathways are analyzed as a function of detuning, showing the expected anti-crossing behavior, an increase in the amplitude of all spectral features close to zero detuning. The line shapes of the features also becomes similar at zero detuning, whereas they take on more exciton- or cavity like properties at the extremes of the detuning range. The spectra also reveal a contribution from a bound biexciton at negative detuning, which is then convolved with the inter-polariton coupling (off-diagonal) features at positive detuning. Two quantum 2DCS confirms that two-quantum states play an important role in modifying the one-quantum emission.

Persistent coherence in nonlinear 2D vibrational THz spectroscopy of sucrose

Pernille Klarskov Pedersen, Brown Univ. (United States); Peter Uhde Jepsen, DTU Fotonik (Denmark)

Mid-infrared (MIR) and THz spectroscopy is a powerful tool for investigating molecular dynamics and nonlinear phenomena in the IR range. But only a few 2D experiments have been published in the THz range with focus on semiconductor systems and DSTMS THz sources for performing collinear 2D spectroscopy in the frequency range from 1 to 5 THz, which is ideal for investigating the lowest phonons in organic materials such as sucrose single-crystals. Using intense pulses with several µJ energy and field strength in the MV/cm range, we have observed nonlinear absorption features from single-crystal sucrose at cryogenic temperature. This enables us to study phonon coupling between the low-frequency vibrational resonances, and it is observed that the nonlinear vibrational coherence is preserved for several picoseconds. This is in contrast to semiconductor systems, where the nonlinear response is determined by incoherent electronic dynamics, and thus coherence is only preserved within the scattering time of the charges.

Efficient numerical method for calculating Coulomb coupling elements and its application to two-dimensional spectroscopy

Anke Zimmermann, Sandra Kuhn, Marten Richter, Technische Univ. Berlin (Germany)

Coulomb coupled quantum systems provide a great flexibility for controlling their optical properties. Due to the Coulomb interaction between nanostructures, new delocalized states can be formed and the individual spectra of coupled quantum systems are modified. If the system requires the calculation of a high number of coupling elements, e.g., if many states are involved, parameters are varied, an efficient numerical method for a fast numerical calculation of the Coulomb interaction is needed.

Typically, to calculate the two-particle Coulomb interaction a six dimensional spatial integral appears. For increasing size or complexity of the system, the calculation of the Coulomb coupling elements presents a significant limiting factor for simulations. Using a Green’s function formulation of a generalized Poisson equation, the number of integrals, necessary for the calculation of the Coulomb interaction in real space, can be reduced. Without being restricted to specific symmetries, the efficient numerical method enables an inclusion of an arbitrary spatial dependent dielectric function.

The Coulomb interaction of two coupled quantum dots (QDs), including monopole-monopole interaction and Förster induced excitation transfer, depends on the spatial distance and the relative dipole orientation of the QDs. For different spatial arrangements of the QDs, the Coulomb coupling under the influence of an inhomogeneous dielectric medium is calculated. To identify the effects of the spatially dependent Coulomb coupling on single excitons and biexcitons, multidimensional coherent spectroscopy can be used. The characteristic two dimensional optical signatures of different spatial arrangements of the Coulomb coupled QDs are calculated and discussed.

Heat-induced and coherent effects in the magnetization dynamics of ferromagnets and ferrimagnets (Invited Paper)

Hans Christian Schneider, Technische Univ. Kaiserslautern (Germany)

This talk reviews experimental results and models on demagnetization dynamics in ferromagnets and optically induced magnetization switching in ferrimagnets. For a theoretical understanding of these effects it discusses a simple dynamical s-d model, i.e., a model that contains itinerant carriers and local spins that is patterned after ferromagnetic semiconductors. This model includes, in a microscopic fashion, the most important contributions: (mean-field) magnetic coupling, spin-orbit interaction, and electron-phonon coupling. In the framework of this model, it is shown how demagnetization and optically induced switching can be understood. A simplified treatment of electron-electron scattering in itinerant magnets is also presented.
Analyzing ultrafast laser-induced demagnetization in Co/Cu(001) via the depth sensitivity of the time-resolved transversal magneto-optical Kerr effect

Andrea Eschenloehr, Jens Wieczorek, Jinghao Chen, Boris Weidtmann, Univ. Duisburg-Essen (Germany); Malte Roesner, Univ. Bremen (Germany); Nicolas Bergeard, Alexander Tarasevitch, Univ. Duisburg-Essen (Germany); Tim O. Wehling, Univ. Bremen (Germany); Uwe Bovensiepen, Univ. Duisburg-Essen (Germany)

Ultrafast spin transport and spin transfer offer new possibilities to manipulate magnetization on femtosecond timescales. In particular, fs spin currents generated in a ferromagnetic layer and propagating through a normal metal contact are potentially relevant for ultrafast spintronics applications. Here, we show how to identify such laser-induced spin currents in a ferromagnet/normal metal heterostructure and separate them from competing phonon-mediated spin-flip scattering in pump-probe experiments. We employ epitaxial Co/Cu(001) as a model system and measure transient spatial profiles of the magnetization in Co via the inherent depth sensitivity of the complex magneto-optical Kerr effect, i.e. the polarization rotation and ellipticity of the reflected light. From a faster response of the ellipticity, which preferentially probes the region near the Co/Cu interface, we find that spin transport into Cu dominates the magnetization dynamics as long as the electronic system is in a non-equilibrium state. After about 100 fs, the magnetization profile redistributes towards one linked to spin-flip scattering, which leads to a stronger demagnetization in the surface-near region preferentially probed by the rotation. Furthermore, first results on ultrafast spin dynamics in metal-organic molecules adsorbed on a ferromagnetic surface will be presented. We analyze spin transfer across a hybrid interface consisting of Fe-porphyrin molecules adsorbed on Co/Cu(001) with magnetization-induced optical second harmonic generation.

Femtosecond modulations based on periodic patterns of excited free-carriers in semiconductors

Yonatan Sivan, Ben-Gurion Univ. of the Negev (Israel); Georgios Ctistis, Emre Yüce, Allard P. Mosk, Univ. Twente (Netherlands)

Ultrafast switching is one of the oldest and most important applications of nonlinear optics. Traditionally, it is based either on Kerr nonlinearity, which is instantaneous, but weak, or on free carrier nonlinearity, which could be much stronger, but comes at the cost of a substantially slower turn-off time. Here, we demonstrate a simple scheme that enables to enjoy the best of the two worlds - to have an ultrafast and strong switching, based on free-carrier generation. Specifically, we describe a novel switching scheme operating on femtosecond time scales, which is based on a periodic pattern of free-carriers (FCs) which serves as a transient Bragg grating. In the first realization, we rely on diffusion to erase the initial FC pattern, hence, to remove the reflectivity of the system. In the second realization, we erase the FC pattern by launching a second, delayed pump pulse. We discuss the advantages and limitations of the proposed approach and demonstrate it for switching ultrashort pulses propagating in silicon waveguides. We show reflection efficiencies of up to 50% for 100 fs pump pulses, which is an unusually high level of efficiency for such a short interaction time, a result of the use of the strong FC nonlinearity. Due to limitations of saturation and pattern effects, the scheme can be employed for switching applications requiring femtosecond features but standard repetition rates. Such applications include switching and modulations of ultrashort pulses, femtosecond spectroscopy (gating) and time-reversal of short pulses for aberration compensation.

Universal ultrafast dynamics of the phase transition in vanadium dioxide thin films

Nathaniel Brady, The Univ. of Alabama at Birmingham (United States); Kannatassen Appavoo, Vanderbilt Univ. (United States); Minah Seo, Los Alamos National Lab. (United States); Joyeeta Nag, Vanderbilt Univ. (United States); Rohit P. Prasankumar, Los Alamos National Lab. (United States); Richard F. Haglund Jr., Vanderbilt Univ. (United States); David J. Hilton, The Univ. of Alabama at Birmingham (United States)

Vanadium dioxide undergoes a first-order insulator-to-metal phase transition at a critical temperature of 340 K at ambient pressure, and for the half century since its discovery, has been explored as a model system for insulator-to-metal phase transitions in strongly correlated materials. The conductivity difference between the two phases can be as large as five orders of magnitude, with concomitant large changes in optical contrast. A structural distortion from a monoclinic to a rutile crystallographic phase accompanies, but is not necessarily congruent with, the conductivity increase. Here we study the optically-induced insulator-to-metal phase transition in vanadium dioxide using femtosecond pump-probe spectroscopy. We compare near-threshold dynamics in thin films grown with varying degrees of substrate-mediated strain, and with morphology-dependent differences in the nucleation and growth of metallic precursors in the mixed phase regime that result from differences in defect density. Remarkably, we find a universal dynamical response above the threshold fluence for the nucleation and growth of the rutile phase characterized by a 40 ps rise time, similar to recent reports of the transient crystalline structure changes after photoexcitation of monoclinic VO2. These studies of differing sample morphologies highlight the role that the crystallographic and electronic phases have on the optical properties of bulk samples. Furthermore and more importantly, they disentangle those parameters – in particular lifetimes – that are independent of disorder by virtue of the common temporal dynamics displayed in three varieties of heteroepitaxy as well as growth on an amorphous substrate.

Upconversion fluorescence engineering on nanopatterned metasurface

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Upconversion materials like rare earth doped upconversion nanocrystals, the low quantum efficiency intrinsically limits its further implementation. Various methods such as plasmonic materials with various structures, geometries and materials have been adopted to enhance the upconversion fluorescence efficiency, by tuning the overlap between the frequency of the excited surface plasmon mode and the absorption or emission band of the fluorophores. We proposed a coherent metasurface with periodic arrays of asymmetric split-ring slits, which was designed according to the optical properties and the compatibility of film growth. The formed coherent state within this metasurface could narrow the absorption band and hence increase the Q factor significantly, which is very critical to enhance the upconversion
fluorescence. The metasurface with different periods were fabricated by focus ion beam milling in a multilayered Au-SiO2-Au film on a glass substrate. The SiO2 coated NaYF4:Er3+upconversion nanocrystals was then spin coated on the metasurface. The results show that the fluorescence intensity are strongly affected by the characteristics of the nanopatterned metasurface. As the period of the arrays shrinks, the Q factor of the absorption peak increases, resulting as much as 8 fold enhancement of the fluorescence comparing with that on the bare glass substrate.

9746-71, Poster Session

On the problems of stability and durability of field-emission current sources for electrovacuum devices

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The paper studied the possibility of using photoemission phenomenon as an important factor of stabilization of a planar field emission cathode with advanced surface based nanoscale film DLC. The main drawback of field-emitter is the low durability at an average current density of the order of several kiloamperes per square meter. It rarely exceeds few hours due to the degradation of the emitting surface. It is caused by a very steep current-voltage characteristic. Slight increase in operating voltage leads to an transition from the stable field emission mode to explosive emission. This is accompanied by the destruction of emission centers and local degradation of the cathode surface. The authors investigated the effect of the injection of nonequilibrium electrons by irradiating the surface of the cathode laser beam. Also previously it was found that photoemission occurs in a broad band of frequencies (it includes visible and near-infrared regions 405-1550 nm) if field emission cathode is operated in the mode of prebreakdown.

A phenomenological model is constructed that describes the tunneling of both equilibrium and nonequilibrium electrons in a vacuum from the zone of concentration of the electrostatic field. Conditions are discussed as the resulting increase in the emission current due to the connection mechanism of the photoelectric effect is thermodynamically favorable, that is not accompanied by an undesirable increase in the temperature of the local emission zone. It is shown that to ensure stability and durability of the cathode is also important to limit the concentration of equilibrium carriers through the use of composite structures «DLC film on the Mo substrate.» This helps to reduce the criticality of the CVC. A possible alternative is to use a restrictive resistance in the cathode. However, this substantially increases the heat losses and thus decreases assembly efficiency.

The results of experimental studies of the structure showing the saturation of the photoemission current component with an increase in the operating voltage. This fact suggests the existence of an effective mechanism for control of the emitter current at a constant operating voltage. This is fundamentally important for the stabilization of field emission cathode, providing a reliability and durability. The single-photon processes and the small thickness DLC films (15-20 nm) provide high speed process of control.

9746-54, Session 12

Ultrafast transmission electron microscopy with highly-coherent electron sources (Invited Paper)

Armin Feist, Katharina Echtelnkamp, Nara Rubiano, Marcel Möller, Sergey Y. Yalunin, Sascha Schäfer, Claus Ropers, Georg-August-Univ. Göttingen (Germany)

Ultrafast transmission electron microscopy (UTEM) with sub-picosecond temporal resolution is a promising laser-pump/electron-probe approach to study structural and electronic dynamics at nanometer length scales [1]. However, its applicability was previously limited by the coherence properties of available pulsed electron sources. Here, we report on first UTEM experiments with highly coherent, laser-driven electron emitters. Specifically, we utilize localized photoemission from the nanoscale front facet of a single crystalline (100)-oriented tungsten tip implemented into a modified transmission electron microscope. At the sample position, electron pulses with 300 fs (FWHM) pulse duration are obtained, which can be focused down to spot diameters of about 3 nm (normalized emittance of 4 nm·mrad). Such ultrashort, highly coherent electron pulses open up numerous possibilities in time-resolved electron microscopy, and we show applications in ultrafast nanoscale probing and phase-contrast imaging.

UTEM not only equips traditional electron microscopy techniques with ultrafast temporal resolution, but also allows for the fundamental investigation of electron light interactions. In a first proof-of-principle experiment, we employ tightly focused electron pulses which are traversing an optical near-field [2]. Considering photon-sidebands in the electron energy spectrum, we demonstrate coherent optical phase modulation of the high-energy electron wave packets with implications for attosecond pulse shaping and electron imaging of charge dynamics within an optical cycle.


9746-55, Session 12

Electro-phononics for modulating acoustic pulses (Invited Paper)

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Restructuring materials below the acoustic (AC) phonon mean free path or implementing variations in their elastic properties suggested new perspectives regarding the controllability of the AC and thermal properties of crystals. In this work, we report on electrical switching and modulating the wavy properties of the coherent AC phonons in various nanoscale quantum structures with piezoelectricity. The fundamental idea is to design the devices so that a combined use of lateral and vertical electric fields along the symmetry axis can be used to control both the carrier distributions and strain tensor components. This allows us to electrically control features of AC phonons such as the mode, amplitude, phase, and detection sensitivities. The capability to control and manipulate the phononic functionalities with external electric fields is analogous to that for manipulating photons and electrons in major technological devices such as transistor switches and amplifiers and can be an essential step in foreshadowing integrated phononic circuitry.

9746-56, Session 12

Tuning coherent acoustic phonon dynamics by strain engineering of ultrathin suspended nanostructures

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The capability to tune the acoustic phonon dynamics in technologically relevant group IV nanostructures provides a promising prospect to control the propagation of acoustic and thermal phonons with great implications on nanoscale hyperson and thermal transport. Despite their fundamental importance, accurate measurements of acoustic phonon lifetimes are challenging and their values are still unknown for most materials. Even in the case of the extensively studied group IV semiconductors, measurements of phonon lifetimes are scarce [1, 2] and the impact of strain engineering is not well understood.

In this contribution we address the influence of tensile strain on the thermo-mechanical properties of suspended group IV nanostructures with thicknesses below 100 nm. The influence of strain on the acoustic phonon lifetimes was measured using ultra-fast pump-and-probe reflectivity measurements based on an asynchronous optical sampling (ASOPS) technique. The coherent acoustic phonon lifetimes are obtained from the dynamical variations of the reflectivity with a sensitivity of 10-6 and a time resolution of 50 fs. It is shown that the acoustic phonon lifetimes can be tuned both by strain engineering of the suspended structures and strain modification by temperature variation in addition to a strong dependence on the thickness of the suspended structures [2]. The combination of temperature dependent µRaman and ultrafast reflectivity measurements allows for a complete decoupling of the effects of temperature, geometry, and strain on the acoustic phonon dynamics.


9746-57, Session 12

Modified vibrational dynamics via coupling to optical microcavities

Adam D. Dunkelberger, Bryan T. Spann, Kenan P. Fears, James P. Long, Blake S. Simpkins, Jeff C. Owtrutsky, U.S. Naval Research Lab. (United States)

While coupling to microcavities has been extensively studied for electronic transitions, it has only recently been reported for molecular vibrations coupled to Fabry-Perot cavities. Coupling to the cavity splits the etalon fringe transmission into two polariton modes separated by the Rabi splitting. The first such experiments involved coupling strongly absorbing infrared modes (carbonyl bands) of molecular polymers to first-order cavity modes. Here we present results of experiments that demonstrate strong coupling in systems comprised of solutions of strongly infrared-absorbing compounds, W(CO)6 and Mo(CO)6 in organic solvents and aqueous NCS-, contained in optical cavities. The studies have been extended to examine how microcavity coupling to vibrations modifies the transient behavior including effects on transient spectra and vibrational relaxation.

We report the first ultrafast infrared pump-probe measurements for a cavity-coupled molecular vibration. After excising the CO band of synthesized silver nanocubes and a metal film. Utilizing dye molecules with an intrinsic long lifetime, and cavities resonant with the emission, reveals spontaneous emission rate enhancements exceeding a factor of 1,000 while maintaining directional and emission efficiency [Askelöf et al., Nature Photonics 8, 835 (2014)]. Incorporating colloidal CdSe/ZnS semiconductor quantum dots into the nanocavities enables experimental demonstration of an ultrafast (<11 ps) yet efficient source of spontaneous emission, corresponding to an emission rate exceeding 90 GHz [Hoang et al., Nature Communications 6, 7788 (2015)]. We show an increase in the spontaneous emission rate of a factor of 880 and simultaneously a 2,300-fold enhancement in the total fluorescence intensity, which indicates a high radiative quantum efficiency of ~50%. Finally, by also utilizing the second order mode of the cavity, optical processes at multiple energies can be optimized simultaneously. We demonstrate this by enhancing both

9746-58, Session 13

Ultrafast spontaneous emission from semiconductor quantum dots coupled to plasmonic nanoantennas (Invited Paper)

Maiken H. Mikkelsen, Duke Univ. (United States)

Metal-dielectric nanocavities have the ability to tightly confine light in small mode volumes resulting in strongly increased local density of states. Placing fluorescing molecules or semiconductor materials in this region enables wide control of radiative processes including absorption and spontaneous emission rates, quantum efficiency, and emission directionality. Here, I will describe our recent experiments utilizing a tunable plasmonic platform where emitters are sandwiched in a sub-10-nm gap between colloidal synthesized silver nanocubes and a metal film. Utilizing dye molecules with an intrinsic long lifetime, and cavities resonant with the emission, reveals spontaneous emission rate enhancements exceeding a factor of 1,000 while maintaining directional and emission efficiency [Askelöf et al., Nature Photonics 8, 835 (2014)]. Incorporating colloidal CdSe/ZnS semiconductor quantum dots into the nanocavities enables experimental demonstration of an ultrafast (<11 ps) yet efficient source of spontaneous emission, corresponding to an emission rate exceeding 90 GHz [Hoang et al., Nature Communications 6, 7788 (2015)]. We show an increase in the spontaneous emission rate of a factor of 880 and simultaneously a 2,300-fold enhancement in the total fluorescence intensity, which indicates a high radiative quantum efficiency of ~50%. Finally, by also utilizing the second order mode of the cavity, optical processes at multiple energies can be optimized simultaneously. We demonstrate this by enhancing both
the absorption and the quantum yield in monolayer MoS2 resulting in a 2,000-fold enhancement in the overall fluorescence [Akselrod et al., Nano Letters 15, 3578 (2015)]. Additionally, the colloidal assembly enables quick, large-area nanofabrication.

9746-59, Session 13

**Time-resolved near-field imaging of plasmonic vortices (Invited Paper)**

Deirdre Kilbane, Anna-Katharina Mahro, Technische Univ. Kaiserslautern (Germany); Grisha Spektor, Meir Orenstein, Technion-Israel Institute of Technology (Israel); Stefan Mathias, Martin Aeschlimann, Technische Univ. Kaiserslautern (Germany)

Nanoplasmonic functional devices can be devised with suitable choice of the nanostructure’s material, geometry and environment. We can also control the shape and position of surface plasmon polaritons (SPPs) by varying the polarization of the exciting light. Depending on the handedness of circularly polarized light, plasmonic near fields can be designed to form a vortex - a rotational flow around a phase singularity.1

We perform near-field imaging of plasmonic vortices by combining interferometric time-resolved two photon photoemission and photoemission electron microscopy (I-TR-2PPE PEEM).2,3 A broadband ultrashort pulse laser excites and probes the plasmonic dynamics with 100 as time step and 40 nm spatial resolution. Here we observe the spatiotemporal evolution of vortices in plasmonic Archimedes spirals (PAS) and vortex lattices (PVL). The generation of plasmonic vortices has huge potential in nanofocusing and optical trapping.4

9746-60, Session 13

**A remotely driven ultrafast electron source**

Jan Vogels, Jörg Robin, Carl von Ossietzky Univ. Oldenburg (Germany); Benedek J. Nagy, Wigner Research Ctr. for Physics of the H.A.S. (Hungary) and Univ. of Pécs (Hungary); Péter Dombi, Wigner Research Ctr. for Physics of the H.A.S. (Hungary); Daniel Rosenkranz, Manuela Schiek, Petra Gross, Christoph Lienau, Carl von Ossietzky Univ. Oldenburg (Germany)

For three decades, scientists pursue the combination of high spatial resolution electron microscopes and high temporal resolution laser spectroscopy. This approach promises experiments in today unexplored spatio-temporal regimes. However, in modern ultrafast electron microscopes the time resolution is so far limited to -100 fs. Yet, many fundamental photoinduced processes such as ultrafast, coherent charge and energy transport phenomena, e.g. in solar cells, occur on much faster time scales. Hence, these processes necessarily remain hidden.

Our experiment is based on laser-driven electron emission from sharp gold tapers. Temporal broadening is fundamentally suppressed by reducing the propagation distance from the emission site to the sample. This is made possible by adiabatic nanofocusing of surface plasmons (ACS Nano 6, 6040) followed by plasmon-assisted electron emission from the taper apex. 16-fs laser pulses with a central wavelength of 1.6 μm illuminate a grating on the taper shaft and create plasmons in a mesoscopic distance of -50 μm from the apex (Nano Lett. 15, 4685).

We observe a more than fifty-fold increase of electron yield compared to direct apex illumination for an exceedingly low pulse energy of 160 pJ. The increased efficiency reduces heating of the taper and might pave the way for an ultrafast scanning tunneling microscope. We verify high spatial localization of multiphoton electron emission from the apex by recording shadow images of Ag-nanowires in an electron point-projection microscope set-up.

Our current efforts aim at temporally resolving plasmon motion on metallic nanostructures. This should result in a major improvement of time resolution in ultrafast electron microscopy.

9746-61, Session 13

**High-energy attosecond nanoplasmonic-based electron gun**

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

We present a detailed investigation of a nanoplasmonic based electron gun capable of generating ultrashort electron pulses. The electron gun consists of a silica axicon lens coated with an Ag film. A traveling surface plasmon (SP) wave is excited at the Ag-vacuum interface by a 5 fs radially polarized laser pulse with a central wavelength of 800 nm. Electrons generated through multi-photon absorption of the SP wave are ponderomotively accelerated away from the axicon tip. Owing to the fact that a radially polarized laser pulse will be p-polarized with respect to the Ag film along the entire circumference of the axicon lens, SP waves will be excited along each transverse plane of the axicon. As such, a large electric field enhancement will occur at the tip leading to increased ponderomotive acceleration and higher kinetic energies of the resulting electron pulse.

Through application of a static magnetic field, the electrons from the tip can be filtered based on their kinetic energy and will become spread out along a detector located to the side of the tip. By introducing a thin film with a properly selected opening in front of the detector, the kinetic energy and ultimately the duration of the electron pulse arriving at the detector can be tuned. Remarkably, electron pulses with energies up to 1keV and with durations as short as 140 as can be achieved.

9746-62, Session 13

**Control and mapping ultrafast plasmonic field with PEEM**

Boyu Ji, Jiang Qin, Alemayehu Nana, Zuoqiang Hao, Toshihisa Tomie, Jingquan Lin, Changchun Univ. of Science and Technology (China)

Extinction spectrum, local electric field intensity and temporal response of the local electric field on asymmetric nanocross and a coupled ring dimerrated nanosystem under ultrashort laser illumination are firstly theoretically investigated in this work. Based on the simulation work on ultrafast plasmonic properties, we further perform the direct imaging of ultrafast plasmon with photoemission electron microscopy (PEEM). We take image of local optical field of the nano-prisms in bowtie structure when excited by 7 fs laser pulses, and coherent control ultrafast plasmon field distribution on the nano-prism by a pair of 7 femtosecond laser pulses. The results show that different photoemission patterns induced by plasmon effect are observed when the bowties are excited by s- and p-polarized femtosecond laser pulses, and the optical near field can be controlled following the user’s design. Furthermore, by combining the pump-probe technology with PEEM, a series of images of local surface plasmon modes temporal evolution on different tips of the bowtie are obtained by time-resolved three-photon photoemission electron microscopy, and the result discloses that plasmon excitation is dominated by interference of the pump and probe pulses within the first 13 fs of the delay time, and thereafter individual plasmon starts to oscillate on its own characteristic resonant frequencies. These works opens
the way for the applications of ultrafast plasmon such as in the field of ultrafast optical switching.

9746-63, Session 14

Unraveling functionality in two-dimensional quantum materials using ultrafast optical and terahertz spectroscopy (Invited Paper)

Rohit P. Prasankumar, Natarajan Kamaraju, Yaomin Dai, Los Alamos National Lab. (United States); Rolando Valdes Aguilar, Los Alamos National Lab. (United States) and Ohio State Univ. (United States); Dmitry A. Yarotski, Antoinette J. Taylor, Los Alamos National Lab. (United States)

Reduced dimensionality, combined with structuring on appropriate length scales, enables tailoring of materials functionality. Ultrafast optical and terahertz (THz) spectroscopy can provide insight into the interplay and coupling between the degrees of freedom in these materials, facilitating the optimization of their design. Here, we will present recent examples where we have used ultrafast optical and THz techniques to unravel carrier dynamics in two-dimensional nanosystems. This will include the use of optical pump, THz-probe spectroscopy to decouple the dynamics of surface and bulk carriers in topological insulators and reveal the nonlinear scaling of the cyclotron resonance frequency with magnetic field in a two-dimensional hole gas. We will also describe the use of ultrafast optical pump-probe spectroscopy to unravel carrier dynamics in the large magnetoresistance material WTe2. These results shed new light on the intrinsic static and dynamic properties of these hotly studied materials.

9746-64, Session 14

Coherent quantum dynamics of excitons in monolayer transition metal dichalcogenides (Invited Paper)

Galan Moody, The Univ. of Texas at Austin (United States) and National Institute of Standards & Technology (United States); Kai Hao, Chandriker K Dass, Akshay Singh, Lixiang Xu, K Tran, The Univ. of Texas at Austin (United States); Chang-Hsiao Chen, Feng Chia University (Taiwan); Ming-Yang Li, Lain-Jong Li, King Abdullah University of Science & Technology (KAUST) (Saudi Arabia); Genevieve Clark, University of Washington (United States); Gunnar Berghauser, Technical University of Berlin (Germany); Ermin Malic, Chalmers University of Technology (Sweden); Andreas Knorr, Technical University of Berlin (Germany); Xiaodong Xu, University of Washington (United States); Xiaqin Li, The Univ. of Texas at Austin (United States)

Transition metal dichalcogenides (TMDs) are an emerging class of semiconductors that have garnered considerable interest in recent years owing to their layer thickness-dependent optoelectronic properties. In monolayer TMDs, the large carrier effective masses, strong quantum confinement, and reduced dielectric screening lead to pronounced exciton resonances with remarkably large binding energy and coupled spin and valley degrees of freedom (valley excitons). Coherent control of valley excitons for atomically-thin optoelectronics and valleytronics requires understanding and quantifying the sources of exciton decoherence. In this work, we reveal how exciton-exciton and exciton-phonon interactions and momentum scattering influence the coherent quantum dynamics of valley excitons in monolayer TMDs, specifically tungsten diselenide (WSe2), using optical two-dimensional coherent spectroscopy (2DCS), which is an enhanced version of three-pulse four-wave mixing. Optical 2DCS enables unambiguous and simultaneous determination of the exciton inhomogeneous and homogeneous linewidths, the latter inversely proportional to the coherence time. Excitation density-dependent measurements of the homogeneous linewidth reveal that exciton-exciton interactions are significantly stronger compared to quasi-2D quantum wells and 3D bulk semiconductors. The role of acoustic-phonon scattering on exciton decoherence is investigated through linewidth measurements for temperatures ranging from 6K to 50K. The residual homogeneous linewidth extrapolated to zero excitation density and temperature is ~1.6 meV (equivalent to a coherence time of 0.4 ps), which we show is limited only by the population recombination lifetime in this sample. Additional experiments are performed using specific combinations of excitation pulse polarizations to resonantly generate and probe exciton valley coherence, providing insight into valley decoherence mechanisms.

9746-65, Session 14

Carrier-phonon interaction in transition-metal-dichalcogenides

Michael Lorke, Univ. Bremen (Germany); Alexander Steinhoff-List, Malte Roesner, Univ. of Bremen (Germany); Matthias Florian, Christopher Gies, Univ. Bremen (Germany); Tim O. Wehling, Univ. of Bremen (Germany); Frank Jahnke, Univ. Bremen (Germany)

Atomically thin two-dimensional semiconductors are of strong current interest for applications as well as for fundamental studies. For optoelectronic applications like displays and photovoltaics, transition-metal-dichalcogenides (TMDs) are an appealing system, as they combine great physical strength with high carrier mobility and an direct optical band gap. To determine the opto-electronic properties under device operation conditions, it is important to consider the relaxation dynamics of excited carriers.

A main source of carrier kinetics is the interaction of the excited carriers with phonons, that has been shown experimentally to cause efficient carrier scattering in TMDs. To analyze carrier-phonon scattering processes of electrons and holes on a microscopic footing, we use a quantum-kinetic description based on non-equilibrium Green’s function techniques. This allows, in a first step, for the description of polarons, which are quasi-particles of the carrier-phonon interaction.

In a second step, the quasi-particles are used for the determination of the carrier kinetics. Such quantum-kinetic models can also incorporate non-Markovian effects, i.e. dependences of the time evolution at the actual time on integrals over the past of the time evolution, that are often important on ultra-short timescales.

We analyze the carrier dynamics for electrons and holes for MoS2 due to the interaction with different types of phonons and discuss the influence both of polaronic quasi-particle effects as well as of non-Markovian effects. Ultrafast carrier relaxation on a timescale faster than 100fs is demonstrated. The excitation density and temperature dependence of the scattering rates is discussed.

9746-66, Session 15

Linear and non-linear optical spectroscopy in binary and ternary transition metal dichalcogenide monolayers (Invited Paper)

Bernhard Urbaszek, Cédric Robert, Lab. de Physique et Chimie des Nano-objets (France)
Transition metal dichalcogenide (TMDC) monolayers are newly discovered semiconductors for a wide range of applications in electronics and optoelectronics. Most studies have focused on binary monolayers that share common properties such as direct optical bandgap in the visible, spin-orbit (SO) splittings of hundreds of meV, light-matter interaction dominated by robust excitons and coupled spin-valley states of electrons.

Here we will present our experimental results on the carrier and polarization dynamics in monolayer WSe2 and MoSe2 on the picosecond time scale [1], the role of multi-phonon resonances in the exciton spectrum for efficient valley coherence generation will be discussed [2]. Studies on alloy-based ternary monolayers are more recent, yet they may not only extend the possibilities for TMDC applications through specific engineering but also help understanding the differences between each binary material. We investigate highly crystalline Mo(1-x)W(x)Se2 to show engineering of the direct optical bandgap and the SO coupling in ternary alloy monolayers. As the tungsten (W) composition is increased, we find a non-linear increase of the optically generated valley polarization degree and a strong impact on the temperature evolution of the photoluminescence (PL) emission intensity [3]. Introducing Mo(1-x)W(x)Se2 monolayers as versatile building blocks for SO-engineered Van der Waals heterostructures.


9746-67, Session 15
Efficient excitonic photoluminescence from atomically thin MoS2

Alexander Steinhoff-List, Univ. of Bremen (Germany); Ji-Hee Kim, Sungkyunkwan Univ. (Korea, Republic of); Frank Jahnke, Univ. of Bremen (Germany); Malte Rössner, Univ. of Bremen (Germany); D.S. Kim, Institute for Basic Science (Korea, Republic of); C. Lee, Gang Hee Han, Sungkyunkwan Univ. (Korea, Republic of); Mun Seok Jeong, Institute for Basic Science (Korea, Republic of) and Sungkyunkwan Univ. (Korea, Republic of); Tim O Wehling, Christopher Gies, Univ. Bremen (Germany)

Atomically thin layers of transition-metal dichalcogenides have emerged in the wake of graphene as new class of optically active materials. We discuss the photoluminescence (PL) of semiconductor transition metal dichalcogenides on the basis of experiments and a microscopic theory.

Our approach combines ab-initio electronic properties with semiconductor many-body calculations of optical transitions [1,2] beyond the reach of typical GW/BSE methods.

Optical recombination at the A and B exciton resonances relies on the presence of carriers in the corresponding K-valleys of the band structure. We discuss two different excitation scenarios: Above-band gap excitation leads to a quasi-equilibrium distribution of carriers in the Brillouin zone. Strain can make the band gap indirect or more direct at K, and for the resulting carrier distributions, we find quenching or enhancement of the light output by an order of magnitude, a trend that has also been observed in a recent experiment [3].

The second scheme is quasi-resonant excitation, which takes place within the single-particle band gap and is only possible due to the existence of bound excitonic states. Here, carriers are created according to the corresponding position of the bound-state wave function in reciprocal space. This excitation scenario enables enhanced B-peak emission in agreement with PL measurements performed at excitation wavelengths of 405 nm (above) and 473, 532 and 633 nm (below the band gap). Further, we observe efficient PL even in case of an indirect band gap, providing a possible explanation for significant photoluminescence observed in bilayer MoS2, which is an indirect band-gap semiconductor [3].

Tuning of valley polarization in few-layer MoS2 by electric-field-induced symmetry breaking

Jakob Wierzbowski, Julian Klein, Armin Regler, Jonathan Becker, Walter Schottky Institut (Germany); Florian Heimbach, Technische Univ. München (Germany); Michael Kaniber, Walter Schottky Institut (Germany); Kai Müller, Walter Schottky Institut (Germany) and Stanford Univ. (United States); Jonathan J. Finley, Walter Schottky Institut (Germany)

The recent discovery of two-dimensional layered nanomaterials has paved the way towards novel optoelectronic and quantum devices. In particular, semiconducting transition metal dichalcogenides (STMDs) such as MoS2, MoSe2, WS2 and WSe2 are of interest for photonics and optoelectronics since they exhibit a direct band gap in the monolayer limit. Inversion symmetry breaking lifts the Kramer’s spin degeneracy at the K-points of the hexagonal Brillouin zone leading to coupled spin and valley pseudospin physics. Furthermore, well defined valley optical selection rules provide access to spin and valley degrees of freedom via excitation using circularly polarized light.

Here, we present the electrical control of exciton emission energies and spin-valley photophysics in few-layer MoS2 crystals embedded within electrically tunable Si(n)-SiO2-STMD-Al2O3-metal microcapacitors with optical access. By tuning the electric field, we induce strong static electric fields exceeding ±3.5 MV/cm resulting in significant DC Stark shifts of the interband emission (>15 meV) for mono- to pentalayer crystals. We find effective exciton permanent dipole moments and polarizabilities with typical values of \(p=(1.99±0.83) \text{ D}\) and \(\gamma=(0.53±0.46) \times 10^{-8} \text{ DmV}^{-1}\) independent on the number of monolayers probed. In polarization resolved PL measurements performed on mono- to trilayer MoS2, we observe pronounced electric field control of valley optical dichroism in bilayer and trilayer MoS2 crystals. We are able to continuously tune the degree of circular polarization of the emission from \(\gamma=20\%\) up to 58\%.

Our results demonstrate the potential for emergent spin- and valleytronic devices based on two-dimensional atomically thin crystals.
9747-1, Session 1

**Near-field responses of plasmonic terahertz geometries (Invited Paper)**

Weili Zhang, Oklahoma State Univ. (United States) and Tianjin Univ. (China)

Electromagnetic behaviors of subwavelength geometries in the near field are essential in understanding their interactions with the incident waves. We experimentally demonstrate the near-field mapping of electromagnetic responses of plasmonic metasurfaces using a fiber-coupled near-field scanning terahertz microscopic system recently developed based on a photoconductive-switched time-domain spectrometer.

9747-2, Session 1

**Sub-wavelength nano-electrode structures to improve the performance of terahertz photomixers**

Qing Yang Steve Wu, Hendrix Tanoto, Ding Lu, Chan Choy Chum, A*STAR Institute of Materials Research and Engineering (Singapore); Mei Sun. Institute for Infocomm Research, Agency for Science, Technology and Research (A*STAR) (Singapore); Zhi Ning Chen, Department of Electrical and Computer Engineering, National University of Singapore (Singapore); Soo-Jin Chua, Jinghua Teng, A*STAR Institute of Materials Research and Engineering (Singapore)

By utilizing the sub-wavelength metallic structures in the active region of the photomixer, the confinement and concentration of electric field from optical pump lasers on a photoconductive substrate can be efficiently achieved as these sub-wavelength metallic structures are exhibiting the nano-antenna effect over a high index photoconductive substrate. By designing the sub-wavelength metallic structures, branch-like nano-electrodes structures, a new strategy to improve carrier capture was developed in which more carrier collection points occupy across the area of the pumping laser source. These branch-like nano-electrode structures were found to improve THz emission intensity of a photomixer by approximately ten times higher. The more efficient THz photomixer will greatly benefit the enhancements were observed. The optical-to-THz conversion efficiency of the photomixer, the confinement and concentration of electric field under the branch-like nano-electrodes structures. This is attributed to a more efficient collection of generated carriers due to a more intense electric field under the branch-like nano-electrodes structures. This is coupled with increased effective areas where strong tip-to-tip THz field enhancements were observed. The optical-to-THz conversion efficiency of the photomixers with the new branch-like nano-electrodes was found to be 10 times higher. The more efficient THz photomixer will greatly benefit the development of continuous wave THz imaging and spectroscopy system.

9747-9, Session 1

**Simulation, fabrication, and measurement of a plasmonic-enhanced terahertz photoconductive antenna**

Nathan Burford, Magda El-Shenawee, Univ. of Arkansas (United States)

Generation and detection of ultrashort electromagnetic pulses through optically excited photoconductive antennas (PCAs) is an attractive method for producing terahertz (THz) frequency radiation. Wide spectral range, high signal-to-noise ratio, room temperature operation and stability of the experimental setup are all advantages of utilizing this technology for THz imaging and spectroscopy systems. However, one of the major problems currently limiting THz PCAs is low THz output power, which is a result of poor optical-to-THz conversion efficiency. This is due to the small active area of the device with respect to the spot size of the incident optical excitation. In this work, a new design for a THz PCA will be presented. Utilizing a novel architecture to increase the device active area along with plasmonic nanostructures to enhance the optical absorption in the photoconductor an increase in the optical-to-THz conversion efficiency will be realized. COMSOL® Multiphysics will be utilized to design and analyze the THz PCA. By modeling the optical interaction through the electromagnetic wave equation and the electrical interaction through the combined Poisson’s/Drift-Diffusion equations, the full optoelectronic behavior will be studied. Both conventional and plasmonic THz-PCAs will be fabricated and characterized by experimentally measuring the output THz power of each when excited by an ultrashort (100 fs) optical pulse. Comparing the power outputs of the proposed plasmonic enhanced antenna against a conventional antenna will allow for the degree of enhancement to be quantified.

9747-4, Session 1

**THz phase shifters based on graphene and liquid crystals**

Yang Wu, Yang Hyunsoo, National Univ. of Singapore (Singapore)

A new THz phase shifter utilizing liquid crystals and graphene has been studied at THz frequency range (0.2 to 1.2 THz). Due to a high mobility of the massless charge carriers in graphene, the conductivity of graphene is excellent meanwhile the absorption of THz waves is low. With graphene films as transparent electrodes, liquid crystal based THz phase shifters with a sandwiched structure are designed and a maximum 10.8 degree phase shift is obtained with a low bias voltage (5 V).

The phase shift is governed by the change of liquid crystal alignment induced by external bias voltages; subsequently the effective refractive index of liquid crystals reduces and leading to a time delay change in THz measurements. The numerical calculation agrees well with the experimental results. Stacked multi-layer graphene is applicable in the phase shifters to improve the electrode quality, mainly the conductivity. However, as the electrode conductivity improves, the THz wave absorption also increases. Thus, a trade-off between the electrode conductivity and insertion loss needs to be considered when graphene is utilized as transparent electrodes at THz range. Due to the pure electric control capability, the bulky magnet and mechanical motion parts are not required in the proposed phase shifters, which make it friendly for integrating into systems. In addition, our devices show a linear response at low bias voltage regime, which enables a continuous tunable operation. Spatial resolved modulation can be achieved by simply patterning the graphene films and control each pixels independently and larger phase shift can be realized by replacing liquid crystals with larger birefringence or operating the devices at higher frequencies.
Multilayer thickness measurement technique based on terahertz time-domain technology for industrial purposes (Invited Paper)

Frank Ellrich, Jens Klier, Soufiene Krimi, Joachim Jonuscheit, Georg von Freymann, Fraunhofer-Institut für Physikalische Messtechnik (Germany)

Aircrafts and cars derive their shiny appearances and their surface protection from several layers of coating. In the past it was sufficient to detect the total thickness of such coating systems. The dependence of the overall functionality from the correct thickness of the individual layers requires monitoring of each individual coating layer within a multi-layer system.

Industry established techniques for coating thickness control have limits when analyzing multi-layer coatings: Either they are unable to determine single layer thicknesses in multi-layer coatings (such as the eddy current method, the magnetic induction method, and the photo-thermic method) or they do not adequately penetrate relevant coating system thicknesses (such as optical coherence tomography) or they do not operate without physical contact (such as ultrasonic measurement systems). While x-ray fluorescence based methods are principally able to overcome the above listed drawbacks, they require an adequate radiation protection. Further limitations are imposed by the substrates as the technique should be applicable to metal, polymer and carbon-fiber-reinforced plastics (CFRP). So far, only terahertz radiation based systems have shown, recently, a great potential to fulfill all these requirements.

Using terahertz time-domain spectroscopy in combination with a time-of-flight-measurement principle we are able to determine coating thicknesses from 5 µm to 500 µm matching the industrial relevant range. Combining different evaluation algorithms we are able to measure and to calculate all layer thicknesses with an accuracy of 1 µm within only one second. This ability will be successfully demonstrated with relevant industrial samples.

Low-bias gate tuneable terahertz plasmonic signatures in chemical vapour deposited graphene of varying grain size

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The Terahertz (THz) region of the electromagnetic spectrum has been the subject of extensive research during the past decade, due to the technological importance this frequency range for various applications ranging from medical imaging and gas sensing to astronomy. In particular plasmonics in graphene is of special interest, due to strong light-plasmon coupling in the graphene, which occurs at THz frequencies (at room temperature) and can therefore be utilized in future THz components such as active optical modulators. In this work, we characterized large area graphene, with varying grain sizes, using THz time-domain spectroscopy and measured the plasmonic response of domains, revealing a d^-1 dependence on the diameter, d, of the domains. Charge carrier concentrations, n, up to 10-13 cm^-2 were realized using an ionic top-gate configuration. With an applied gate voltage as low as 1.2 V we achieve an frequency tuning up to 60 GHz. In conclusion this work not only provides fundamental insight into the plasmonic response of graphene grain and grain boundaries but also demonstrates a practical application of large area graphene, that is most sought after for future THz opto-electronic components.

Thickness measurement of thin film on metal substrate using ultra short THz pulses

Yuji Nishizawa, Toshifumi Kodama, JFE Steel Corp. (Japan); Tsubasa Minami, Kodo Kawase, Nagoya Univ. (Japan)

A non-contact thickness measurement method is extremely useful for inline monitoring of the thickness of films on coated steel sheet products. Conventional methods such as eddy current or electromagnetic inspection cannot be used because the transducers must be in contact with the surface. The conventional Terahertz-TDS (Time-domain spectroscopy) system using a PCA (photoconductive antenna) is also inapplicable because the duration of the generated pulse is too long compared to the travel time within a coated film 10-20um in thickness. In this research, a newly-developed THz-TDS system, which generates ultrashort pulses of 150fs, was adopted for thickness measurement. The system uses of a MgO:LiNbO3 ridge waveguide. The measured sample is a laminated steel sheet with a PET (Polyethylene terephthalate) film 13-19um in thickness. THz pulses are irradiated to the sample, and time domain waveform is acquired by using a PCA as a detector. To resolve the reflected echoes from the film surface and the interface with the metal substrate, a deconvolution technique was applied to the acquired waveform. The thickness can be estimated by using a refractive index (n=1.7 for PET) and the delay time. Estimation accuracy was sufficient, as estimation error was within 2um. This method is suitable for inline thickness measurement of thin films on production lines.
Microwave generation using a tunable dual-wavelength erbium with a single longitudinal mode

Soo Kyung Kim, Young Bo Shim, Juil Hwang, Sanggwon Song, Min-Seok Yoon, Sunduck Kim, Young-Geun Han, Hanyang Univ. (Korea, Republic of)

Photonic generation of microwave signal technique based on a fiber laser has attracted much attention in applications to radio over fiber systems, antenna remoting, radar, and broadband wireless access networks. Photonic generation of microwave signal has many advantages, such as low loss transmission of microwave through optical fiber, high frequency microwave generation based on light beating. To generate microwave signals, fiber-based dual wavelength (DW) single-longitudinal-mode (SLM) lasers have been proposed because of their advantages, such as wide tunability of wavelength spacing, and stability of the output power. In this paper, we propose a photonic generation of tunable microwave signals exploiting a dual wavelength erbium doped fiber (EDF) laser with a single longitudinal mode (SLM). A microfiber knot resonator (MKR) is implemented for realization of SLM oscillation in the proposed dual wavelength fiber laser. Dual wavelength output is realized by using nonlinear polarization rotation. By adjusting the wavelength spacing of the proposed dual wavelength fiber laser, frequencies of microwave signals can be flexibly controlled in a range from 17.3 to 23.2 GHz.

Use of optical speckle patterns for compressive sensing of RF signals in the GHz band

George C. Valley, George A. Seffler, Thomas J. Shaw, The Aerospace Corp. (United States)

Speckle patterns at the outputs of multimode optical waveguides appear random, and much of the work in compressive sensing (CS) employs measurement matrices (MMs) whose elements are pseudo-random numbers. Here we demonstrate that speckle patterns can be used for a CS MM to measure sparse RF signals in the GHz band (1-100GHz). In our system mode-locked femtosecond laser pulses are stretched to the interpulse time, modulated by the RF, and injected into a multimode waveguide. The speckle pattern out of the guide is imaged onto an array of photodiodes whose output is digitized by a bank of ADCs. We have measured the CS MM for different multimode fibers and used these MMs to demonstrate that sparse RF signals (sparsity K) modulated on a chirped optical carrier can be recovered after making a number of measurements M consistent with the CS relation M - Kr, where M is the number of samples needed for Nyquist rate sampling. We demonstrate experimentally that speckle sampling gives comparable results to the WDM sampling system used previously for periodic undersampling of RF chirp pulses. We have also calculated MMs for sparse RF signals (sparsity K) modulated on a chirped optical carrier can be calculated giving comparable results to the WDM sampling system used previously for periodic undersampling of RF chirp pulses. We have also calculated MMs for sparse RF signals (sparsity K) modulated on a chirped optical carrier can be calculated giving comparable results to the WDM sampling system used previously for periodic undersampling of RF chirp pulses.

High-efficiency W-band hybrid integrated photoreceiver module using UTC-PD and pHEMT amplifier

Toshimasa Umezawa, National Institute of Information and Communications Technology (Japan); Kenichi Kashima, Hitachi Kokusai Electric Inc. (Japan); Atsushi Kanno, Kouichi Akahane, Atsushi Matsumoto, Naokatsu Yamamoto, National Institute of Information and Communications Technology (Japan); Tetsuya Kawanishi, National Institute of Information and Communications Technology (Japan) and Waseda Univ. (Japan)

To be expanded with photonic wireless systems on Radio over Fiber (RoF) technology, the low power consumption is one of the essential factors in the system. Power over fiber (PoF), which provides electric power supply using optical power and optical-to-electrical converters using optical fibers, is suitable and compatible for RoF technology. It provides stable electric power supply through an optical fiber in the mountainous regions. In this paper, we designed and fabricated a compact high efficiency W-band photoreceiver module using UTC-PD and PHEMT amplifier with low power consumption and high output power, to take PoF operation into account. A zero-bias operational UTC-PD, which had a wide 3dB bandwidth over 110 GHz, was designed by an optimum layer thickness ratio between absorption layer and carrier collection layer with low carrier concentration. High gain, low power consumption (<100 mW) W-band PHEMT amplifier based on InP or GaAs was also designed by a 4-5 amplifier stage and Lange coupler element. High speed meatal package attached with a 1mm coaxial connector and an optical view window was worked well at up to 110 GHz. We successfully achieved a good RF output linearity and high output power level up to -1 dBm at 100 GHz, without output saturation at 0 V. The highest photocurrent density (48 kA/cm2) in previous reports would be also achieved at 0 V. Using the UTC-PD and PHEMT amplifier designed, the high output power of +9 dBm at 110 GHz could be successfully obtained. The design and performance will be discussed.

Optical resonators metrology using an RF-spectrum approach

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High quality factor optical resonators have found numerous applications in sensors, microwave optics and time & frequency applications. Therefore, a detailed knowledge of their properties is essential to accurately model these devices. A microwave domain characterization technique is proposed to measure the optical properties of such resonators, featuring a very high precision in frequency which can be as good as 1 Hz. This technique has been used to characterize several types of resonators, featuring Q factors in the 106 to 1010 range. It aims to acquire the full knowledge of the complex transfer function (amplitude and phase) characterizing the optical resonator, using a microwave vector network analyzer. It is shown that the amplitude response gives access to the measure of several parameters like the free spectral range, quality factor and the full-width at half-maximum. Moreover the overall profile and the slope of the phase transition at the resonance are used to define the coupling regime and to calculate the resonator essential parameters: transmission coefficient and intra-cavity losses. An experiment has been carried out to demonstrate the validity of this technique using an active optical resonator, which has been designed using an erbium-doped fiber amplifier and optical couplers. By varying the laser pump power, it is possible to change the intra-cavity losses and therefore to get different coupling regimes. The experimental results confirm the
channels to measure the reflected signal from the specimen. This paper on the development of THz endoscopes with photoconductive antennas, the interior surfaces of an organ or tissue. Researchers have been working content. Endoscopic imaging systems provide high flexibility in examining detecting cancers due to its non-ionizing nature and sensitivity to water

9747-14, Session 3

Oxygen detection system consisting of a millimeter wave Faby-Perot resonator and an integrated SiGe front-end

Julia Wecker, Steffen Kurth, Gauri Mangalgiri, Marco Meinig, Fraunhofer-Institut für Elektronische Nanosysteme (Germany); Thomas Gessner, Fraunhofer-Institut für Elektronische Nanosysteme (Germany) and Technische Univ. Chemnitz (Germany); Markus Gaitzsch, Technische Univ. Chemnitz (Germany); Andreas Bauch, Ismail Nasr, Robert Weigel, Dietmar Kissinger, Friedrich-Alexander- Univ. Erlangen-Nürnberg (Germany); Angelika Hackner, Ulrich Prechtel, Airbus Group Innovations (Germany)

Oxygen shows significant absorption lines in the millimeter wave spectrum. Resonators are widely used to achieve a strong absorption even with a short absorption paths length for concentration measurements. A sensor system based on a Fabry-Perot resonator for oxygen measurements at ambient pressure is presented here. The Fabry-Perot resonator consists of two metal mirrors with a diameter of 50 mm. For purpose of oxygen detection the resonator covers a frequency range between 55 GHz and 65 GHz with a resonant peak density of 1 GHz and a quality factor of 60000. To achieve a compact sensor system the concept envisages two integrated transceiver circuits directly coupling to coaxial ports in the metal mirrors of the resonator. The integrated SiGe frontend addresses a frequency band from 50 GHz to 100 GHz. They are realized as heterodyne structures with integrated directional couplers, thus it is possible to measure the same parameters as with a commercial Vector Network Analyzer. A first resonator sample was coupled to a commercial Vector Network Analyzer using horn antennas and a dielectric oil. The cavity was filled with different oxygen concentrations at ambient pressure and temperature resulting in a decrease of peak amplitude and quality factor close to the oxygen absorption line at 60.6 GHz. According to the measurements oxygen concentrations from 0% to 20% at ambient pressure are detected with a resolution of 1%. Compared to other oxygen sensors, this sensor is suitable for explosive environments due to no use of hot components.

9747-15, Session 4

Development of terahertz endoscopic system for cancer detection (Invited Paper)

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Terahertz (THz) imaging is emerging as a robust platform for a myriad of applications in the fields of security, health, astronomy and material science. The terahertz regime with wavelengths spanning from microns to millimeters is potentially a safe, noninvasive medical imaging modality for detecting cancers due to its non-ionizing nature and sensitivity to water content. Endoscopic imaging systems provide high flexibility in examining the interior surfaces of an organ or tissue. Researchers have been working on the development of THz endoscopes with photoconductive antennas, which necessarily operate under high voltage, and require at least two channels to measure the reflected signal from the specimen. This paper provides an overview of existing terahertz endoscopic approaches. We also present the design and development of a single-channel terahertz endoscopic system based on flexible metal-coated terahertz waveguides. The continuous-wave terahertz imaging system utilizes a single terahertz waveguide channel to transmit and collect the back reflected intrinsic terahertz signal from the sample and is capable of operation in both transmission and reflection modalities. To determine the feasibility of using a terahertz endoscope for cancer detection, the researchers have been working on the development of a terahertz remittance from human colon tissue specimens were collected at 584 GHz frequency. The two dimensional terahertz images obtained using polarization specific detection exhibited intrinsic contrast between normal and regions of fresh colorectal tissue. The core of the observed using endoscopic imaging correlates well with the contrast levels observed in the free space ex vivo terahertz reflectance studies of human colon tissue. The device developed in this study represents a significant step towards clinical endoscopic application of THz technology for in vivo colon cancer screening.

9747-16, Session 4

Characterizations of diffractive microlens in NbS5N6 microbolometers array for THz detection

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Terahertz (THz) wave band has received much attention for medical, communication, homeland security, and space technology applications, in which detectors are an important component. Nevertheless, the lack of low-cost and sensitive room-temperature detectors in this spectral region hampers the development of detection and imaging systems. We previously reported the use of NbS5N6 microbolometer array for THz detection. The core of the NbS5N6 microbolometer consists of a gold dipole planar antenna and an NbS5N thin film microbridge. In this detector, the absorber unit-NbS5N thin film microbridge is smaller than the wavelength of the incident signal, resulting in substantial decrease in signal-to-noise ratio. Hence a NbS5N microbolometer array with five staircases diffractive microlens were designed and fabricated. The lens exhibits good focusing and improves the coupling efficiency. The voltage response of the NbS5N microbolometer integrated with diffractive microlens is 16 times higher than that of the NbS5N microbolometer fabricated only on silicon substrate. An optical voltage responsivity of 71 V/W and a noise equivalent power of 10710 WHz/Hz obtained as room-temperature detectors. The diffractive microlens array features light weight, low absorption loss, and high resolution and can be mass produced using standard microfabrication techniques.

9747-17, Session 4

A spectral analysis of silicon wafers in terms of electrical characteristics using a continuous terahertz wave

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We present a continuous wave terahertz (cw-THz) spectrometer comprised of two laser diodes and photoductive antennae. The frequency of terahertz source was determined by the difference in the frequency of the two laser diodes, which was controlled by the temperature of laser diodes. We measured the cw-THz transmission spectra of Si wafers and characterized the electric resistance of the Si wafers using the results of transmission measurements. For comparison, the same Si wafers were also characterized using the time-domain terahertz spectroscopy setup.
Retroactive terahertz detection for imaging and remote sensing applications in a standard CMOS technology

Richard AI Hadji, Yan Zhao, Yilei Li, Yuan Du, Frank M. Chang, Univ. of California, Los Angeles (United States)

Terahertz detectors implemented in silicon technologies are exclusively operated actively above 0.3THz. By all means, artificial sources are needed in order to actively illuminate them. This introduces complexity, increases cost and affects the overall system performance. It is in contrast with passive detectors capable of detecting passively radiation emitted from the environment. The limited sensitivity of silicon based detectors is caused by the devices cutoff frequencies. In this paper, we will show a novel method to emit and detect terahertz radiation on the same CMOS chip without the need of external terahertz elements. The method is based on the exploitation of reciprocal properties of electrical and electromagnetic components constituting integrated terahertz sources. This method not only simplifies the conventional active imaging system, but also significantly improved the sensitivity compared to active power detectors. We name this method retroactive terahertz detection. This approach has been verified experimentally to image objects at terahertz frequencies, extracting physical properties of materials remotely and determining displacements of a hidden remote targets. Emitting and detecting cooperently multiple terahertz tones from 0.35THz up to 2.1THz on the same CMOS device have been verified. The device was implemented in a standard 65nm CMOS technology. Characterisation and imaging results will be detailed in the paper and will be presented at the conference.

Horn-type components based on optical devices at terahertz frequencies

Won-Hui Lee, Eui Su Lee, Namje Kim, Sang-Pil Han, Hyunsung Ko, Kyung Hyun Park, Electronics and Telecommunications Research Institute (Korea, Republic of)

Recently, there has been an increasing interest in terahertz (THz) frequencies. The photonics technologies are very effective for signal generation, modulation and detection not only to enhance the bandwidth and the data rate, but also to combine the networks of fiber optic and wireless. This paper presents photonics generation of high power continuous terahertz-wave signals using own-developed photonic devices. Photodiode (PD) and shottky barrier diode (SBD) chips were packaged into the module with a rectangular waveguide (WR-3.4) port. Horn type PD and SBD have a feature of high-speed, high-output power and high-responsivity operation owing to its unique carrier transport mechanism. Their application is giga-bit wireless interconnection systems. This system is intended for use in short distance applications, since there are no high power amplifiers at terahertz frequencies. An optical RF signal is generated by the two wavelengths of light from the wavelength-tunable light sources. The optical signal is digitally modulated by the optical intensity modulator driven by the pulse pattern generator (PPG). Finally, the optical signal is converted to an electrical signal by the horn type PD. The terahertz wave is emitted to the free space via a horn antenna with a gain of 25dBi. The receiver consists of a SBD and an IF filter followed by a low-noise preamplifier and a limiting amplifier.

Fourier domain interferometry-based spotlight-mode synthetic-aperture optical imaging system for use from low-earth orbit

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We present a design and experimental demonstration of an optical synthetic aperture imaging system based on developments in Fourier-domain optical coherence tomography, with the objective of demonstrating a transverse resolution substantially better than what is achieved in conventional OCT looking from a single (on-axis) direction. A fast wavelength tunable laser is combined with a fiber optic network to produce a phase sensitive imaging system that could be applied to high resolution imaging from orbit, or indeed, from any moving platform. We introduce the technique and, in particular, detail the constraints and challenges that need to be overcome for it to be applied to ground imaging from space. We compare and contrast this optical scheme and its associated signal processing with hardware and associated signal processing techniques used in conventional spotlight-mode synthetic-aperture radar (SAR) and give estimates for the performance and the achievable resolution under various conditions.

Optical properties of aluminum nitride in 1-8 THz region

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Aluminum nitride is a uniaxial III-V semiconductor whose material properties are well suited to a variety of optical and optoelectronic applications. The refractive indices and the absorption in bulk single crystals were measured by THz time-domain spectroscopy. Both indices exhibit normal dispersion with no pronounced absorption resonances. Average refractive indices are 2.9 and 31. Optical power loss coefficients are approximately 2 cm-1 and 4 cm-1, and the estimated static dielectric constants are 7.84 and 9.22, for the ordinary and extraordinary polarization, respectively.

Textured semiconductors for enhanced photoconductive terahertz emission

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There are severe limitations that photoconductive (PC) terahertz (THz) antennas experience due to Joule heating and ohmic losses, which cause premature device breakdown through thermal runaway. In response, the work introduces PC THz antennas utilizing textured InP semiconductors. These textured InP semiconductors exhibit high surface recombination properties and have shortened carrier lifetimes which limit residual photocurrents in the picoseconds following THz pulse emission—ultimately reducing Joule heating and ohmic losses. Fine- and coarse-textured InP semiconductors are studied and compared to a smooth-textured InP semiconductor, which provides a baseline. The surface area ratio (measuring roughness) of the smooth, fine-, and coarse-textured InP semiconductors is resolved through a computational analysis of SEM images and found...
Microfabrication of SU-8 Fresnel lenses for THz imaging

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This paper presents the design and fabrication of Fresnel microlenses which have been optimised for use in the terahertz region. The microlenses are fabricated using SU-8 photore sist and conventional UV photolithography. Free space focusing of terahertz light is normally achieved through the use of parabolic mirrors. Alternatively, for ‘local’ focusing on to a substrate or sample, polished high resistivity silicon lenses are commonly used. The lens design presented here provides a low cost alternative to silicon lenses. Fresnel lenses can have a large numerical aperture and a short focal length [1] and are well suited for use in terahertz imaging system [2]. The focal point of a Fresnel lens has been calculated to be approximately 1mm at 1THz using a commercial FDTD solver, Lumerical. The fabrication process forms a stack of patterned layers which define the lens profile. The first layer is made of negative photosist (SU-8) which was spun to a nominal thickness of 25 µm and then patterned by standard photolithography. In order to optimise the vertical profile of the sidewalls in the SU-8, a long-pass filter was used during the UV exposure. This process step was then repeated for a further three layers to achieve an overall thickness of approximately 100 µm. Characterization of the micro-lenses by VNA (Vector Network Analyser) operating in the frequency range of 750GHz to 1.1THz is presented and discussed. The measured focal length using the VNA approach corresponds well to the values calculated using the FDTD solver and demonstrates effective focusing from highly compact lenses.


Perfect absorber metamaterial for real-time detection and recognition of micro-poisons in aqueous solutions and atmosphere using millimeter wavelength spectroscopy

Amir Abramovich, David Rotshild, Meir Ochana, Daniel Rozban, Ariel Univ. (Israel)

Metamaterials are artificial materials not exist in the nature. They are also known as Left Handed Material (LHM) in which both the permeability and permittivity are negative. A perfect absorber metamaterial for millimeter wavelength can be artificially tailored and manufactured as two dimensional matrices of metal shapes on a dielectric substrate. Those perfect absorbers metamaterial can be designed to be frequency selective with high Q property.

In this study we present a new method that can provide real-time response by combining advanced spectroscopy methods in millimeter Wavelength (MMW) regime and perfect absorber metamaterial. This method is based on very inexpensive perfect absorber metamaterial, with a high Q factor. It was realized by printed metal shapes on FR4 substrate with ground plane on the bottom. The resonance frequency of the perfect absorber will be determined according to the geometrical metal shape dimensions and the dielectric constant of the substrate. The spectral measurements were carried out using high resolution coherence THz spectroscopy system. Due to the perfect absorber sensitivity and its high Q property, the perfect absorber metamaterial is very sensitive to environmental micro-poisons, which influence its resonance frequency. Using a high-resolution spectroscopy system it is possible to detect and quantify this influence.

In this study we present very promising experimental results of Malathion detection using perfect absorber metamaterial. The manufacturing of such perfect absorber metamaterial was carried out using the well-known and very inexpensive PCB technology.

Enhancement of water retention in UV-exposed fuel-cell proton exchange membrane studied using terahertz spectroscopy

Shaumik Ray, Nirmala Devi, Jyotirmayee Dash, Gutru Rambabu, Santoshkumar D. Bhat, Bala Pesala, C.S.I.R. Madras Complex (India)

Polymer Electrolytic Membrane (PEM) fuel cells are increasingly gaining importance as a clean energy source. The PEM should possess high proton conductivity and should be chemically and mechanically stable in the fuel cell environment. Among the various PEMs available, Nafion (sulfonated tetrafluoroethylene (Teflon)-based fluoropolymer) and SPEEK (Sulfonated –Poly-Ether-Ether-Ketone) membranes are widely preferred due to their inherent advantages. Nafion has high proton conductivity even with low water content compared to SPEEK but is also very expensive than SPEEK. The hydration of the membrane plays a very important role in the performance of the fuel cells. Excess water will saturate the membrane and too little will dry the membrane and hence the power output will drop in both the cases. So, an optimum level of membrane hydration is critical. Moreover, membrane hydration also determines the proton conductivity in the membrane. Higher water retention in the membrane at higher temperature is highly desired for practical applications. One approach is to add hydrophilic materials such as zirconium dioxide, titanium dioxide, and silicon dioxide to increase the water retention. Such membranes exhibit higher water retention capability at elevated temperatures. Water exhibits strong absorption in the THz frequency range and hence THz spectroscopy can be effectively used to characterize the water retention of PEM.

In this paper pristine and Carbon NanoTube (CNT) SPEEK and Nafion membranes have been exposed to UV radiation while immersed in water to enhance the water retention capacity. Pulsed terahertz spectroscopy (0.5 THz – 2 THz) is used as a tool to quantify and track the water retention capability of the membranes. Results show significant enhancement of water retention in UV exposed CNT and pristine SPEEK membranes compared to nafion membrane.
SOA-integrated dual-mode laser diode and a photodiode for a compact and cost-effective CW terahertz system

Eui Su Lee, Namje Kim, Sang-Pil Han, Il-Min Lee, Jun-Hwan Shin, Won-Hui Lee, Kyung Hyun Park, Electronics and Telecommunications Research Institute (Korea, Republic of)

We fabricated a semiconductor optical amplifier-integrated dual-mode laser (SOA-DML) as a widely tunable continuous-wave (CW) terahertz beat source and a photodiode as a CW THz emitter. The SOA-DML chip consisted of two distributed feedback lasers, a phase section for a tunable beat source, an amplifier, and a tapered spot-size converter (SSC). The SOA-DML can achieve a high side-mode suppression ratio of more than 35 dB throughout the tuning range and the SOA-DML module exhibited an output power of more than 15 dBm with the frequency tuning range from 380 GHz to 1120 GHz. The use of an integrated SSC ensures stable mode behavior by suppressing reflections from the output facet and provides high coupling efficiency to the fiber. As a CW THz emitter consisted of a diluted waveguide for a fiber-to-chip coupling, matching layer and the log-periodic antenna integrated the photodiode chip. The responsivity of the photodiode is over 0.3 A/W. Finally, we showed that the SOA-DML with a photodiode can be implemented as a compact and cost-effective source and emitter of a simple CW THz system by demonstrating THz frequency-domain spectroscopy of an 7-lactose pellet.

Dynamic measurements at THz frequencies with a fast rotary delay line

Hang Gu, Hichem Guerboukha, Maksim A. Skorobogatyi, Ecole Polytechnique de Montréal (Canada)

Fabrication, characterization, and applications of a fast rotary linear optical delay line (FRLDL) for THz time-domain spectroscopy are presented. The key component of the FRLDL is a rotary disk with two reflective surfaces that are designed by numerical calculation and manufactured using CNC machining. The incoming beam is parallel while spatially separated with the outgoing beam. A linear dependence of the optical delay on the rotation angle allows a straightforward extraction of the conversion factor between the acquisition time (in ns) and the terahertz pulse time (in ps). We also perform optical simulation of the FRLDL using Zemax and then discuss the accuracy of the rotary delay line detailing the possible sources of imprecision. The FRLDL has been tested using rotation speeds of up to 48 Hz, corresponding to an acquisition rate of up to 192 Hz with four blades incorporated on the same rotary disk. An error analysis is performed by experimentally evaluating the signal-to-noise ratio and the dynamic range. Then, we showed several applications for the FRLDL. Firstly, the evaporation process of similar transparent liquids (acetone, methanol, water) was monitored, providing a way to identify each liquid by its evaporation rate. Secondly, monitoring of the painting process was demonstrated. The spraying and drying phases of the paint were clearly visible in the time traces, with a shift in both amplitude and time delay. Thirdly, we showed detection of fast moving LDPE samples. We also used the shift in time to evaluate sample thicknesses of up to 44 mm.

highly sensitive terahertz spectroscopy of residual pesticide using nano-antenna array

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There has been great interest in fast and precise detection techniques for residual pesticides on farm produce, since the use of pesticide has been unavoidable for better productivity of farm product even though those materials are very toxic. In this research, a novel type of highly sensitive tool has been employed to detect residual pesticide (e.g., methomyl) using terahertz (THz) time-domain spectroscopy (TDS) with nano-antenna array. We designed a nano-antenna array based THz-metamaterial targeted for the methomyl molecule, which is one of famous pesticides. The nano-antenna array has a resonance at the specific frequency related to the THz optical characteristic of the methomyl. The THz absorption spectrum for the methomyl shows a sharp absorption peak near 1.0 THz and the nano-antenna array was also designed for this frequency. We observed different transmittance spectrum result with high sensitivity for the different concentration of the methomyl molecule even in solution state.

We also tested the performance of our nano-antenna array in reflection geometry to simply detect the contained residual pesticide at the real fruit surface as it is, without extraction or sampling. The clear difference in the obtained THz reflection image distinguishes the stained area with methomyl from the bare region. We verified the performance of pesticide sensing THz nano-antenna technique by both THz spectra and images of reflection. Our observation can offer the possibility for further application as a highly accurate small molecule monitoring tool.

Pulsed THz spectroscopy of substance under disordered opaque cover

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Remote sensing using the pulsed THz-TDS is of great interest because of its possible practical applications. Many ordinary materials (paper, for example) are transparent to THz radiation while the hazardous substances, which have to detect, possess fingerprints in this frequency range. However, covers of ordinary material can distort its spectrum in such a way that the spectrum of reflected THz pulse or transmitted THz pulse will contain absorption frequencies, which are inherent to dangerous substance (explosives, illicit drugs,...), despite their absence in the material under consideration. This is a consequence of covering material influence due to its density fluctuation or its structure variation, for example. As rule, covering material structure fluctuation may be comparable with some wavelengths of the probing THz radiation. Thus, the cover can act as a disordered photonic structure with respect to incident THz pulse and its action results in additional absorption spectral lines appearance and in turn, the incorrect substance identification will take place. In this paper we discuss a quasi-periodic structure influence with variable dielectric constant on the spectrum of a substance which is placed behind such structure. The investigation is conducted by means of computer simulations and direct experiments. We consider a single layer of optically active substance placed between two covers consisting of linear layers with random dielectric permittivities. Incident Gaussian pulse with a few-cycles falls on the substance covered by layers. Both transmitted pulse and reflected pulse are analyzed and their spectra are compared to those of the incident pulse. For description of a THz pulse interaction with an optically active substance covered by a disordered structures we use the Maxwell-Bloch equations [4]. The appearance of additional spectrum extremes due to the layered structure influence are illustrated. Computer simulation results were verified by physical experiment. In our investigations we exploited a commercially available spectrometer developed by the Teravil company, Lithuania. It can operate in both transmission and reflection modes. The spectral range of the spectrometer is 0.15-50 THz. To provide the measurements at long distance, additional part was developed: we use a parabolic mirror for focusing the THz beam on the object. Because the fiber
9747-30, Session 7

Frequency measurement of THz waves by electro-optic sampling using Mach-Zehnder-modulator-based flat comb generator

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In the recent progress in terahertz (THz) devices, various kinds of source devices, such as resonant tunneling diodes, quantum cascade lasers and so forth, have been developed. Frequency measurement of THz radiations, which is high speed and can operate at room-temperature, is important for development of high-performance THz source devices. Recently, frequency measurement using optical combs are demonstrated by some groups. In these techniques, mode-locked lasers (MLLs) are used for optical comb source, so that phase-locking techniques are required in order to stabilize the repetition rate of the MLLs. On the other hand, a modulator-based optical comb generator has high accuracy and stability in the comb spacing, which is comparable to that of microwave signal driving the modulator. Thus it is suitable for frequency measurement of THz waves. In this paper, we demonstrated frequency measurement of THz waves using a Mach-Zehnder-modulator-based flat comb generator (MZ-FCG).

The frequency measurement was carried out by an electro-optic (EO) sampling method, where an optical two-tone signal extracted from the optical comb generated by the MZ-FCG was used for the optical probe. A 100 GHz signal generated by a W-band frequency multiplier and the probe beam collinearly traveled through an EO crystal, and beat signals between them were measured by a combination of a balanced photodetector and a spectrum analyzer. As a result, frequency measurement of the 100 GHz wave was successfully demonstrated, in which the linewidth of the beat signal was less than 1 Hz.

9747-31, Session 7

Advances in optoelectronic oscillators

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We investigate novel architectures of optoelectronic oscillators at the theoretical and experimental level. OEOs are systems mainly designed for ultra-pure microwave generation, but they can also be useful for optical telecommunications or analog photonic computing. We first investigate OEO architectures where the usual long delay line is associated to a resonator with ultra-high Q-factor. Using Langevin equation methods, we evaluate the phase noise performance of the oscillator as a function of the main parameters of the system. We also study the noise properties of the customized measurement bench used to measure the spectral purity of the microwaves. We then study new architectures of OEO, notably those where the nonlinearity induced by the external intensity is replaced by the diode nonlinearity of the seeding laser itself. A full bifurcation analysis is performed and unveils the complex nonlinear dynamics of the system. In all cases, the analytical results are complemented with numerical simulations and experimental measurements.

9747-32, Session 7

All-optical real-time data format conversion in FBG sensing network

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In modern intelligent fiber Bragg grating (FBG) sensing network, spectrum resources become increasingly limited due to the complexity of the sensing link and the increasing number of multiplexed sensors. Therefore, it is important to realize dynamic allocation and efficient utilization of the spectrum resources. In this paper, we propose an all-optical real-time data format conversion system to realize the efficient-utilization of spectrum resource in FBG sensing network. The sensing network consists of one control center and many sensing nodes. The control center includes a wavelength step-sweep optical source and a demodulation unit. The sensing node is composed of a sensing link and an all-optical data format conversion unit. In the data format conversion unit, frequency domain sensing signals reflected by FBGs are converted into optical time division multiplexing signals with a specified wavelength in real time. Format converted data from each node are sent back to the control center for demodulation. Then each sensing link is marked by its specific wavelength that distinguishes from the others, which facilitates dynamically allocating spectrum. Meanwhile, all the sensing links in the FBG sensing network can share the same spectrum resource. Experimentally, data format conversion and demodulation of one sensing node is carried out with different temperature and static strain. The demodulation linearity and the sensitivity is about 0.99511 and 10.9pm/mm in temperature sensing while 0.99291 and 83.9pm/mm in static strain sensing. The spectra of sensing pulses before and after data format conversion indicates that the data format conversion is successful and the spectrum resource in this node is released.

9747-33, Session 7

A single longitudinal erbium-doped fiber laser based on a microfiber knot resonator

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Fiber lasers have been are utilized in various field of applications such as communication systems, medical devices, measurement tools, and manufacturing equipment because of advantages including high coherence, low propagation loss, ease of fabrication and maintenance. Multi-longitudinal-mode (MLM) oscillation due to long length of laser cavity in the fiber lasers should be suppressed to improve their practical performance. Saturable absorbers and sub-ring cavities are usually utilized as MLM filters to mitigate the MLMs. In this paper, we propose a novel single-longitudinal-mode (SLM) fiber laser based on a microfiber knot resonator (MKR) with a simple structure. The proposed SLM fiber laser is composed of an erbium-doped fiber, MKR, a linear polarizer, and a polarization controller. The MKR is fabricated by using a conventional single-mode fiber. Since the operation principle of the MLM suppression using the MKR is based on the Vernier effect between the laser cavity and the MKR with wide free-spectral range. The stability of the proposed SLM fiber laser was measured to be less than 0.1 dB for one hour.
A novel method to produce swept laser source using wavelengths parallel swept optical loop
Quan Yuan, Zhaoying Wang, Shiyuan Liu, Sha Luo, Rui Ma, Tianxin Yang, Tianjin Univ. (China)

Swept laser source changes its wavelength in the frequency domain by a particular step, which is valuable in the fields of optical sensing and optical communications, such as optical coherence tomography (OCT), medical imaging, dispersion measurement, and remote sensing of the atmosphere, wavelength-division multiplexing (WDM) networks, etc. In this paper, wavelengths parallel sweeping technique is proposed by using an optical sweeping loop outside the laser cavity. A frequency shifter in the sweeping loop shifts the frequencies of the incident optical signals simultaneously with a constant value in every circulation. This parallel sweeping technique has three main advantages. Firstly, for a certain sweeping range, the sweeping speed by using parallel sweeping method can be increased to two or more times as compared with single wavelength sweeping. Secondly, the optical signals are simultaneously swept outside the laser cavity, which does not affect the stability of the optical source. Thirdly, frequency shifter in the sweeping loop is precisely controlled by a radio frequency (RF) signal. Experimentally, the outputs of two Distributed Feed Back (DFB) lasers were parallel swept by using the optical sweeping loop. The experiments of different swept step were carried out. The sweeping step is also tunable from 300MHz to 15GHz depending on the electro-optical bandwidth of the frequency shifter used in our experiments. Dual-wavelength swept output at 214 kHz with 0.08nm sweeping step and 122 kHz with 0.04nm sweeping step were achieved respectively. The sweeping span of the swept source was 1.6nm with a flatness of ±1.5dB.

Piroxicam derivatives THz classification
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The principal component analysis (PCA) is a statistical procedure widely used in multidimensional data processing. It was employed in order to reduce the dimension of the terahertz spectra (N=1130) and extract the useful information to the principal component (PC) space. We reduced the input spectra to 2D and 3D space, preserving 75.7% and 85.1% of the variance (information), respectively. The generated 2D PCA map was used to study the THz spectra similarity of the molecules. We link the position on the cluster map to the corresponding physical and biochemical properties of a typed as a promising non-steroidal drug, i.e. Piroxicam. It belongs to the group of the oxicams whose chemical structure is unique, therefore its pharmacological character is a field of interest. Each terahertz spectrum in the set can be reconstructed from the principal components loadings by mixing them according to the PCA scores coefficients. Without employing statistical procedures it is almost impossible to distinguish spectral identities of examined samples. Presented results can find application in the drug development process in order to select the derivatives with desired chemical and implied biological properties.

Terahertz imaging and spectroscopy for detection and identification of drugs and explosives in letters and small packages (Invited Paper)
Frank Ellrich, Daniel Molter, Joachim Jonuscheit, Georg von Freymann, Fraunhofer-Institut für Physikalische Messtechnik (Germany); Maik Schubert, Daniel Hübsch, Thorsten Sprenger, HÜBNER GmbH & Co. KG (Germany)

For many post offices in government buildings, correctional facilities or even for some private offices it is a daily challenge to successfully screen the incoming mail for illegal drugs or explosives. We have developed a cascaded screening system based on the well-known advantages of Terahertz (THz) technology (high transparency of dielectric media and identification of crystalline substances). In the first step the THz imaging system «T-SENSE» working with continuous-waves at 78 GHz penetrates the mail and provides imaging information about absorption and delay. Depending on the desired spatial resolution this takes just a couple of seconds. Suspicious areas or objects like bank notes, powders or tablets can be highlighted by use of different filters.

If necessary, the material of the suspicious areas or objects is identified in the subsequent step using a THz time-domain-spectrometer called «T-COGNITION». Using the image information obtained by «T-SENSE» the measurement area of «T-COGNITION» can be reduced significantly, because the suspicious areas or objects have to be measured only.

In «T-COGNITION» the terahertz signals are analyzed in respect to fingerprints of known substances. Unfortunately the signals are distorted by covering materials like envelopes or filling material. Therefore a sophisticated evaluation procedure has to be applied to reveal the spectral information.

In the paper we introduce both systems and explain our evaluation procedures. Finally we show the improvement of the detection rate and the reduction in false alarm rate using our evaluation approaches.

Enhancement of THz signal intensity by plasmonic monopole nanoantenna (Invited Paper)
Ekmel Ozbay, Bayram Butun, Mert Bozaci, Tolga Kartaloglu, Bilkent Univ. (Turkey)

We have designed, fabricated and measured localized surface plasmon resonance (LSMR) based monopole nano-antenna coupled photoconductive antennas (PCAs) for THz-time domain spectroscopy (TDS) systems. LT-GaAs material was used to fabricate the THz PCAs. The performance of the nano-antenna coupled PCAs was compared to the standard PCAs. The THz signal level has increased by a factor of 2 by using the plasmonic monopole nanoantenna.

Photoconductive antennas based on low temperature grown GaAs on silicon substrates for broadband terahertz generation and detection
Matthias Klos, Technische Univ. Kaiserslautern (Germany); Richard Bartholdt, Technische Univ. Kaiserslautern (Germany) and Fraunhofer-Institut für Physikalische
Generation and detection of THz radiation using femtosecond lasers and photoconductive antennas is a well-established technique. Here we report on investigations aimed at the generation of broad bandwidth using “classical” PCAs based on LT GaAs. GaAs shows a strong phonon absorption around 8 THz which limits the useful bandwidth. In transmission geometry the generated THz pulse has to travel through a 400 µm thick GaAs substrate. To avoid this, the PCAs investigated here consist of only 2 µm thick layers of LT grown GaAs bonded on high resistivity silicon substrates. In order to utilize the drastically reduced absorption in the thin GaAs layer for generation of broadband THz radiation we have processed dipole antennas with dipole length between 20 µm and 60 µm. The larger dipole length is used in the emitter chip whereas the short dipole is used for detection. Our test system consists of a typical time domain THz setup with a 30 fs pump laser at a repetition rate of 80 MHz. The observed spectra show a bandwidth up to 12 THz with a maximum dynamic range exceeding 90 dB at 0.5 THz. Compared to regular PCAs fabricated on a GaAs wafer there is a clear increase in bandwidth with a dynamic range of more than 50 dB at 5 THz. The absolute THz power generated from a 60 µm dipole antenna was measured with a calibrated THz detector. For a pump power of 20 mW and a bias voltage of 75 V we obtained close to 100 µW of average power.

9747-38, Session 8

Electronic FM CW THz system for security applications (Invited Paper)

Janez Trontelj, Aleksander Se?ek, Univ. of Ljubljana (Slovenia)

We are presenting a sophisticated THz system with 3D imaging and narrow band spectroscopy capability. The key system components are THz source, THz detector/mixer array, scanning optics and signal processing unit. The system is all electronic and is portable and has battery operation option for several hours autonomy. Most important parameters for the THz source are output power, illumination beam size and directivity, frequency modulation range and max modulation frequency. The low phase noise is also a very important parameter.

Quality of the system critically depends on the generation of the local oscillator (LO) and its connection to the mixer.

Optimization of these parameters is discussed. The THz source is all solid state composed of phase-locked oscillator, amplifier and frequency multipliers. The most important element of the system is its sensor, which performs both signal detection and at the same time mixing of LO signal and received signal from the target. The sensor is antenna coupled nano-bolometer, which is fabricated in linear array of 8 pixels. The sensors are suspended in the vacuum to achieve an excellent signal to noise ratio.

The quadratic characteristic of the nano-bolometer extends over six decades allowing large dynamic range and very high LO signal levels. Scanning mirror integrated into the system allows for imaging of 1024 to 8192 pixels in x and y dimensions expanded to the third dimension with a resolution of few micrometers.

9747-39, Session 8

Terahertz imaging of composite materials in reflection and transmission mode with a time-domain spectroscopy system

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A fiber-coupled Terahertz time domain spectroscopy system based on photoconductive antennas, pumped by a 100-fs fiber laser, has been used to characterize materials in transmission and reflection mode. THz images are acquired by mounting the samples under investigation on an x-y stage, which is scanned through the beam while the transmitted or reflected THz waveform is captured. The samples include a carbon fiber epoxy composite and a sandwich-structured composite panel with an aramid fiber honeycomb core in between two skin layers of fiberglass reinforced plastic.

We take advantage of the fact that both the amplitude and phase of the transmitted or reflected Terahertz pulses are measured when characterizing the materials. In transmission mode, the propagation delay and transmission spectrum in each pixel provides useful information regarding the samples. In reflection mode, the measured THz waveform provides information regarding the structure of layered materials, and deconvolution of the time-domain data can help interpreting the measurements.

9747-40, Session 9

Measuring intensity correlations of a THz quantum cascade laser around its threshold at sub-cycle timescales

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The quantum nature of photonic systems is reflected in the photon statistics of the light they emit. Therefore, the development of quantum optics tools with single photon sensitivity and excellent temporal resolution is paramount to the development of exotic photon sources, and is particularly challenging in the THz range where photon energies approach kBT, leading to high dark counts at room temperature.

In this work, we report on the development of the first approach to measure field (g(dt)) and intensity correlations (g2(dt)) in the THz range with an unsurpassed characteristic sub-cycle temporal resolution of 146 fs over a bandwidth from 300 GHz to 3 THz. This technique uses no beam splitters since based on electro-optic sampling and is conveniently room temperature compatible. The ability to measure correlations is implemented with a two-probing beam scheme which sample the electric field of a free running THz wave in real-time.

With this technique, we map the photon correlations of a THz Quantum Cascade Laser lasing around 2.3 THz during its abrupt transition to lasing. We retrieve the spectrum of the emission from the measurement of g(dt), which is single-modeled around its threshold, and, in addition, observe the change in photon statistics; Poissonian statistics with a typical g2(dt = 0) = 1 during lasing above the threshold and, mixed Poissonian and Superpoissonian statistics due to mixed coherent and amplified spontaneous emission in the threshold region with a g2(dt = 0) - 1.3.

9747-41, Session 9

Terahertz quantum cascade laser with broad band extractor

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The terahertz quantum cascade laser is one of the most versatile sources of terahertz radiation. It is an active field of research, in the past two years it reached up to 1W of output power, a full octave of operation bandwidth or a comb operation.
The long wavelength nature of terahertz quantum cascade lasers places them far below the plasmonic resonance of metals and enables single or double surface plasmon polariton waveguide modes. Consequently, the laser feedback is determined by the impedance mismatch at the laser facet. Inspired by the millimeter waves, our approach consists in the use of a planar antenna on benzocyclobutene as a laser facet; consequently the laser feedback is determined by designing the impedance mismatch between the active region and the antenna.

The first integration of a one-dimensional patch array antenna to a terahertz quantum cascade laser was done using an active region lasing around 4.7 THz. A new integration of a two-dimensional array of phased elliptical patch antenna is realized on an active region lasing around 1.9 THz. Unlike usual double plasmon laser, this device features a vertical and single lobed far-field for a bandwidth of 10% from 1.8 to 2 THz. The divergence of the beam is 43 and 53 degrees in the longitudinal and transverse direction for a 2-by-2 array and 35 and 41 degrees for a 3-by-3 array.

9747-42, Session 9

Coherent THz light source based on photo-mixing with a UTC-PD and ASE-free tunable diode lasers

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We demonstrated the coherent tunable terahertz light source with high-stability and sub-milliwatt output. The system utilize a photo-mixing technique; the mixer is a high-speed, high-power photodiode (UTC-PD: Uni-Traveling Carrier Photodiode) developed by NTT and mixing-sources are ASE-free ECDL: External Cavity Diode Lasers with a novel configuration developed by Spectra Quest Lab Inc.. The mixing-source has fiber output over 50mW and narrow linewidth <100kHz. Thermal-induced frequency drift was suppressed below 100MHz/deg.C by an athermal cavities and twin-packaging design of the whole system. The stability is ensured by the external 1GHz etalon with invar frames the frequencies are locked in. Novel tuning mechanism using a tilted rotating disk allows a versatile frequency control; a high-resolution, 3MHz and a rapid scan, 1THz/sec.

Two types of photo-mixer module were used. One is waveguide-output-type and the other is quasi-optical-type with a silicon lens. The former is more efficient and generates sub-milliwatt output in the sub-THz frequency region. The high-power and high-SNR output is suitable for a local oscillator for the heterodyne detection in astronomical radio telescope and high capacity wireless communication.

The later with a Si hemi-sphere enables higher frequency over 1THz and broad-band operation. Employment of 1000nm tunable lasers helps to make the system simple and efficient, because Si hemi-sphere blocks the mixing light without extra filtering. The broad-band tunability and the narrow linewidth are suitable for high-resolution spectroscopy of gases.

Combination of ASE-free ECDL and a photo-mixer with UTC-PD provides a versatile tunable THz light source for many applications.

9747-43, Session 9

Highly efficient local-oscillator-free photonic microwave down-converters based on period-one nonlinear dynamics of semiconductor lasers

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Radio-over-fiber is a promising scheme for the next generation of broadband wireless access networks. To increase data capacity and to mitigate spectrum congestion, microwave subcarriers of high frequency are highly preferred and have attracted much research attention. To process and decode data with low speed electronics at receivers in order to achieve high link performance and efficiency, down-conversion of high frequency microwave subcarriers is required before such data processing and decoding. The simplest down-conversion method is to use an electrical mixer driven by an electrical local oscillator after photodetection. However, this electrical approach suffers from low electrical isolation and the need of high frequency photodetectors.

Microwave down-conversion based on the optical approach, by contrast, provides an attractive solution to overcome such challenges. In this paper we propose a photonic microwave down-conversion scheme based on period-one (P1) nonlinear dynamics of semiconductor lasers, which provides high conversion efficiency and requires no additional local oscillator. As will be shown, the proposed downconversion scheme using P1 dynamics depends solely on the property of the input optical signal for a given laser. Thus, only a typical semiconductor laser is required as the main conversion unit. Microwave down-conversion from 33.7 GHz to a frequency ranging from 10 to 14 GHz, limited by the electronics used in this study, is experimentally demonstrated for the proof of concept.

9747-44, Session 9

Hybrid polymer/InP dual DBR laser for 1.5 um continuous-wave terahertz systems

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The generation of continuous-wave (cw) THz signals via photo mixing has been established as mature technique within recent years. State-of-the-art systems operate at the optical communication wavelength of 1.5µm and usually apply distributed-feedback (DFB) lasers or external-cavity diode lasers (ECLDs) due to their off-the-shelf availability. However, ECLDs are bulky and expensive, whereas DFB lasers offer only a limited tuning range of ~ 4.5 nm. In this work, we present a hybrid integrated polymer/InP dual DBR laser as widely-tunable and low-cost alternative for the realization of the optical source in cw-THz systems.

The device comprises an InP chip with two gain sections end-fire coupled to a polymer chip with thermo-optically tunable phase sections and Bragg gratings. With such lasers, output optical powers higher than 15 dBm and optical linewidths narrower than 500 kHz have been achieved. To generate an optical beat note, both lasers are combined on the polymer chip by means of a Y-branch. By simultaneously driving the phase shifter and Bragg grating heater electrodes, continuous sweeps of more than 9 nm (1.1 THz) with one laser have been accomplished.

To demonstrate the suitability of the proposed device for the generation and detection of cw-THz signals, the manufactured device has been applied in a coherent cw-THz system. In the preliminary experiments, a continuous frequency sweep over 133 GHz has been achieved, well-resolving the H2O absorption peaks between 1.091-1.225 THz. Further experiments aiming to extend the continuous scan range towards 2 THz are intended to be presented in the conference.
9747-45, Session 10

High-power continuous-wave terahertz radiation through GaAs plasmonic photomixers
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Photomixers are one of the most promising sources of continuous-wave terahertz radiation, which have been extensively used in various terahertz systems due to their wide frequency tunability, excellent spectral purity, and room temperature operation. Despite their great promises, low radiation power of conventional photomixers has limited their practical use in many imaging, sensing, and communication applications. Here, we present frequency-tunable, continuous-wave GaAs plasmonic photomixers, which offer significantly higher terahertz radiation powers compared to conventional photomixers. With the use of plasmonic contact electrodes, a larger number of photocarriers can reach photomixers’ terahertz radiating elements within a fraction of the terahertz radiation cycle, leading to greatly enhanced optical-to-terahertz conversion efficiencies. Moreover, compared to InGaAs-based plasmonic photomixers, the presented GaAs plasmonic photomixers can be pumped at higher optical pump powers with 100% duty cycle without reaching thermal breakdown due to relatively higher thermal conductivity and resistivity levels of GaAs. We demonstrate a record-high radiation power of 17 W at 1 THz and 100% radiation duty cycle. Nearly identical terahertz radiation linewidth is observed over frequency tuning range of GaAs plasmonic photomixers, which is directly determined by linewidth of the optical pump beam and can reach as low as KHz-levels for existing continuous-wave optical pump sources. Therefore, the presented plasmonic photomixer is well suited for high-data-rate wireless communication and high-spectral-resolution spectroscopy applications.

9747-46, Session 10

Terahertz generation and detection using femtosecond mode-locked Yb-doped fiber laser
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We successfully demonstrate a THz generation using an Yb-doped mode-locked femtosecond fiber laser and a low-temperature grown (LTG) InGaAs PCA module for THz-TDS systems. The Yb-doped fiber ring laser consists of a pump laser diode (PLD), a wavelength division multiplexer (WDM) coupler, a single-mode fiber (SMF), a 25 cm-long highly ytterbium-doped fiber (YDF), two collimators, two quarter wave plates (QWPs), a half-wave plate (HWP), a band pass filter, an isolator, and a polarizing beam splitter (PBS). It uses the nonlinear polarization rotation (NPR) effect to achieve the passively mode-locked optical short pulse. The center wavelength and the 3 dB bandwidth of the mode-locked fiber laser are 1.03 μm and ~14 nm, respectively. It has 175 fs duration after pulse compression with 66.2 MHz repetition rate. The average output power of mode-locked laser has more than 275 mW. The LTG-InGaAs PCA modules are used as the emitter and receiver in order to achieve the THz radiation. The photoductive antenna modules comprise a hyper-hemispherical Si lens and a log-spiral antenna-integrated LTG-InGaAs PCA chip electronically contacted on a printed circuit board (PCB). An excitation optical average pumping and probing power were ~6.3 mW and 5 mW, respectively. The free-space distance between the emitter and the receiver in the THz-TDS system was 70 mm. The spectrum of the THz radiation is achieved higher than 1.5 THz.

9747-47, Session 10

Generation and evaluation of THz waves from electric-optic polymer films
Takahiro Kaji, Toshiki Yamada, Shingo Saito, Isao Morohashi, Yukihiro Tominari, Isao Aoki, Shukichi Tanaka, Akira Otomo, National Institute of Information and Communications Technology (Japan)

Electric-optic (EO) polymers have been attracted much attention as the materials for ultra-high-speed optical modulators, electric field sensors, and terahertz (THz) generators and detectors. Recently, we have developed EO side-chain polymers covalently coupling nonlinear optical (NLO) chromophores having large hyperpolarizability. The EO coefficient of the poled EO polymers is more than 100 pm/V, which is much larger than that of inorganic and organic NLO materials such as lithium niobate (LiNbO3), zinc telluride (ZnTe), and DAST. Therefore, the EO polymers having large EO coefficient can realize highly efficient THz generation via difference-frequency generation. This paper presents the reported THz-wave generation from the EO polymer films pumped with a 1.5-micrometer-band laser light having a pulse width of ~100 fs by terahertz time-domain spectroscopy (THz-TDS). Because compact 1.5-micrometer-band erbium-doped fiber lasers have been developed so far, compact THz light sources will be realized by using 1.5-micrometer-band light sources and EO polymers. The efficiency of THz-wave generation from the EO polymers is evaluated by comparing the efficiencies from the other NLO materials. We also characterize absorption coefficients and refractive indices of the EO polymers in the THz region by far-infrared spectroscopy and THz-TDS, and discuss the characteristics of the EO polymers compared to the other NLO materials.

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9747-48, Session 10

Enhanced terahertz guiding strength of two-wire line using dielectric coating
Tae-In Jeon, Jingshu Zha, Korea Maritime and Ocean Univ. (Korea, Republic of)

The guiding strength with respect to curvature of two-wire line is important to terahertz (THz) wire communication. The THz pulse propagating through the two-wire line with dielectric coating is much more tightly bound than that of the uncoated two-wire line. The two-wire lines with 7- and 25-μm-thick coated by silicone on 170-mm-length line are used to compare with the uncoated two-wire line. The THz pulse and spectrum of the 7- and 25-μm-thick coated lines are smoothly changing until a modest 10 mm curve depth. However, as the curve depth increases, notable changes occur in both the signal strength and the corresponding spectra, which show much larger reductions of the higher frequencies. Therefore, the EO polymers having large terahertz (THz) generators and detectors. Recently, we have developed larger number of photocarriers can reach photomixers’ terahertz radiating elements within a fraction of the terahertz radiation cycle, leading to greatly enhanced optical-to-terahertz conversion efficiencies. Moreover, compared to InGaAs-based plasmonic photomixers, the presented GaAs plasmonic photomixers can be pumped at higher optical pump powers with 100% duty cycle without reaching thermal breakdown due to relatively higher thermal conductivity and resistivity levels of GaAs. We demonstrate a record-high radiation power of 17 W at 1 THz and 100% radiation duty cycle. Nearly identical terahertz radiation linewidth is observed over frequency tuning range of GaAs plasmonic photomixers, which is directly determined by linewidth of the optical pump beam and can reach as low as KHz-levels for existing continuous-wave optical pump sources. Therefore, the presented plasmonic photomixer is well suited for high-data-rate wireless communication and high-spectral-resolution spectroscopy applications.

9747-49, Session 10

Fast terahertz optoelectronic amplitude modulator based on plasmonic metamaterial antenna arrays and graphene
David S. Jessop, Riccardo Degl’Innocenti, Univ. of
demonstrate several techniques, including RF detuning from resonance and GHz, using Autler-Townes splitting of Rydberg EIT in a Rb vapor. We also present SI-traceable electric field measurements of RF fields above 100 GHz, which puts the measurements in the low field strength regime. At high frequencies there is typically less power available, and accuracy, and there is no reliable method for calibrating probes above 100 GHz. Atomic systems provide a new way to measure RF fields that can improve sensitivity and traceability. RF fields have been shown to interact with electromagnetically-induced transparency (EIT) involving Rydberg states in alkali atoms. An RF field causes the EIT peak to split in frequency (Autler-Townes splitting). The separation is directly related to the strength of the RF field, converting an amplitude measurement to a frequency measurement. While Rydberg EIT-based RF field probes have the potential to work for a broad range of frequencies (from a few GHz to 100s of GHz) and field strengths (mV/m to kV/m), extending the measurement capabilities to a broad range of frequencies (from a few GHz to 100s of GHz) and field strengths (mV/m to kV/m), extending the measurement capabilities.

9747-50, Session 11

**Atom-based RF electric field metrology above 100 GHz**

Matt T. Simons, Joshua A. Gordon, Christopher L. Holloway, National Institute of Standards and Technology (United States)

Current methods for measuring RF field strengths are limited in sensitivity and accuracy, and there is no reliable method for calibrating probes above 100 GHz. Atomic systems provide a new way to measure RF fields that can improve sensitivity and traceability. RF fields have been shown to interact with electromagnetically-induced transparency (EIT) involving Rydberg states in alkali atoms. An RF field causes the EIT peak to split in frequency (Autler-Townes splitting). The separation is directly related to the strength of the RF field, converting an amplitude measurement to a frequency measurement. While Rydberg EIT-based RF field probes have the potential to work for a broad range of frequencies (from a few GHz to 100s of GHz) and field strengths (mV/m to kV/m), extending the measurement capabilities to the high frequency (>100 GHz) and low field strength (< 100 mV/m) regimes have been problematic, and in some ways intertwined. At low field strengths, the EIT peaks are not sufficiently separated for a direct measurement. At high frequencies there is typically less power available, which puts the measurements in the low field strength regime. We present SI-traceable electric field measurements of RF fields above 100 GHz, using Autler-Townes splitting of Rydberg EIT in a Rb vapor. We also demonstrate several techniques, including RF detuning from resonance and enhanced absorption, for increasing the probe sensitivity.

9747-51, Session 11

**The effect of carrier lifetime and substrate conductivity on the performance of large-area plasmonic photoconductive emitters**

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Incorporating plasmonic contact electrodes as nanoantennas in large area photoconductive emitters has proven to be a very efficient way for generating high power and broadband terahertz radiation with enhanced optical-to-terahertz conversion efficiencies. This is because of tight optical confinement near the plasmonic contact electrodes, which reduces average transport path length of photogenerated carriers to the terahertz radiating elements. Radiation specifications of large area plasmonic photoconductive emitters are highly dependent on electrical transport properties and recombination parameters of the photo-absorbing semiconductor substrate. Short carrier lifetimes, high carrier mobilities, and low substrate conductivities are required to achieve high optical-to-terahertz conversion efficiencies. An effective way to decrease the carrier lifetime and substrate conductivity in GaAs is using a superlattice of ErAs monolayers in the substrate. By changing the concentration of the ErAs particles and the number of monolayers, the carrier lifetime and substrate conductivity can be engineered. In this work, we investigate the impact of the carrier lifetime and substrate conductivity on the performance of large area plasmonic photoconductive emitters. For this purpose, identical large area plasmonic photoconductive emitters are fabricated on ErAs:GaAs substrates with different carrier lifetime and conductivities and their performance is characterized under the same experimental conditions. In specific, the terahertz radiation efficiency, radiation spectrum, and maximum radiation power are characterized for identical designs fabricated on substrates with various ErAs:GaAs compositions and their dependence on the carrier lifetime, electrical conductivity and thermal conductivity of the substrate is analyzed, which is in close agreement with theoretical predictions.

9747-52, Session 11

**Electromagnetic modelling of a space-borne far-infrared interferometer**

Anthony Donohoe, Créidhe O’Sullivan, Anthony Murphy, Colm P. Bracken, National Univ. of Ireland, Maynooth (Ireland); Giorgio Savini, Univ. College London (United Kingdom); Enzo Pascale, Cardiff Univ. (United Kingdom); Peter Ade, Rashmi Sudiwala, Amber Hornsby, Cardiff University (United Kingdom)

In this presentation I will describe work done as part of an EU-funded project “Far-infrared space interferometer critical assessment” (FISICA). The aim of the project is to investigate science objectives and technology development required for the next generation THz space interferometer. The THz/FIR is precisely the spectral region where most of the energy from stars, exo-planetary systems and galaxy clusters deep in space is emitted. The atmosphere is almost completely opaque in the wave-band of interest so any observation that requires high quality data must be performed with a space-borne instrument. A space-borne far infrared interferometer will be able to answer a variety of crucial astrophysical questions such as how do planets and stars form, what is the energy engine of most galaxies and how common are the molecule building blocks of life. The FISICA team have proposed a novel instrument based on a double Fourier interferometer that is designed to resolve the light from an extended scene, spectrally and spatially. A laboratory prototype spectral-spatial interferometer has been constructed to demonstrate the feasibility of the double-Fourier technique at far infrared wavelengths (0.1571 THz). This demonstrator is being used to investigate and validate important design...
9747-53, Session 11

Experimental demonstration of trapping waves with terahertz metamaterial absorbers on flexible polyimide films

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We present the design, numerical simulations and experimental measurements of terahertz metamaterial absorbers on ultra flexible polyimide films. The perfect metamaterial absorber composed of two structured metallic layers separated with a polyimide film with a total thickness of functional layers much smaller than the operational wavelength. We firstly investigate the influence of the film thickness on absorption, and the experiment results show that with any chosen metallic pattern, there is always an optimized spacer thickness where the absorption can reach unity. We also characterized the incidence angle dependence of the absorption, the experiment results demonstrate that the absorption peaks maintain near-perfect absorption at incident angles up to 70° for the TM polarization. Moreover, by adjusting the geometry of the metallic pattern layer as well as the film thickness, the resonance frequency can be tuned over the entire terahertz range. The experimental measurements show a good match with the simulation results. We believe that by fabricating THz metamaterial absorbers on flexible substrates can remove the limitations of conventional rigid substrates, and can be used on curved surfaces such as spherical lenses and mirrors, with its excellent performance, our design can be valuable in many applications such as solar cells, filtering, stealth systems and sensing.

9747-54, Session 11

Broadband frequency-chirped terahertz-wave signal generation using periodically-poled lithium niobate for frequency-modulated continuous-wave radar application

Junichi Hamazaki, Yoh Ogawa, Norihiko Sekine, Akifumi Kasamatsu, Atsushi Kanno, Naokatsu Yamamoto, Iwao Hosako, National Institute of Information and Communications Technology (Japan)

In recent years, radar systems have attracted much attention on enhancing civil safety and security such as foreign object debris detection on airport runways, vehicle collision avoidance system, and autonomous cars in future intelligent transport systems. In the scenario, a frequency-modulated continuous-wave (FM-CW) radar is promising for reducing the cost due to its intermediate frequency detection scheme; expected range by the FM-CW radar is directly provided by an intermediate frequency, which is down-converted by the mixing with source and reflected FM-CW signals. In this case, the range resolution is inversely proportional to the bandwidth of the FM-CW signal; 1-GHz bandwidth signal provides the range resolution of approximately 15 cm. In addition, a carrier frequency limits the size of the detection due to its wavelength. Thus, a high-frequency FM-CW signal with broader bandwidth is required for detection of small object with high range resolution.

In this paper, we have proposed new method to generate FM-CW signals in the terahertz (THz) band with much broader bandwidth by using nonlinear optical technique. To generate THz electromagnetic waves, periodically-poled lithium niobates (PPLNs) are excited by ultrashort pulses. By changing the periodicity of the PPLN gradually, frequency-chirped THz waves are obtained. Its bandwidth is achieved approximately 500 GHz at a center frequency of 1.3 THz. The expected range resolution is ~0.3 mm. Thus, our proposed technique is capable with the high spatial resolution and small-object detection feature for future high-resolution imaging system.

9747-56, Poster Session

Realization of optical isotropy using terahertz anisotropic metamaterials

Joong-Wook Lee, Chonnam National Univ. (Korea, Republic of)

We demonstrate the realization of optically isotropic filters at terahertz (THz) frequency range using structural anisotropic metamaterials. The proposed metamaterials with 2-dimensional arrangements of anisotropic H-shaped apertures indicate polarization-independent transmission due to the combined effects of dipole resonances of resonators and antennas. Our results may offer the possibilities for designing and realizing versatile THz devices and systems.

9747-73, Poster Session

Planar array antenna with director on indium phosphide substrate for 300GHz wireless link

Haruichi Kanaya, Tomoki Oda, Naoto Iizasa, Kazutoshi Kato, Kyushu Univ. (Japan)

Recently, research of terahertz (THz) waves at frequencies from 100 GHz to 10 THz has attracted much attention. In basic THz broadband wireless communications, photodiode and Schottky barrier diode based on indium phosphide (InP) substrate converted the optical beat signal into sub-mm-waves by photomixing. In transceivers, high gain and small size antenna should be needed. In this paper, we present a novel design of a 300 GHz-band 1 x 4 array antenna using four one-sided directional slot dipole antenna elements fed by branched coplanar wave guide (CPW). The proposed antenna is designed on an InP substrate. InP substrate was etched by using deep inductively coupled plasma reactive ion etching, and placed on the floating metal layer (thickness =1 um) and polyimide dielectric layer (thickness =16 um). Antenna is designed on the top metal layer (thickness =1 um). By optimizing the length of floating metal layer, one-sided directional radiation can be realized. The total antenna size is 1,217 um x 2,550 um x 18 um including in dicing clearance. In order to increase the gain of forward direction, director metal layer is placed over 100 um air gap from top metal layer. At 300 GHz, simulated realized gain in peak direction is 9.23 dBi which is 1.88 dB larger than that without director version. In the measurement, our proposed antenna has center frequency = 284 GHz. Our proposed antenna is suitable for implemented the InP based photo electronics device.

9747-74, Poster Session

Optimization method of a slot ring antenna integrated with a terahertz photomixer

Han-Cheol Ryu, Sahmyook Univ. (Korea, Republic of); Eui Su Lee, Kyung Hyun Park, Electronics and Telecommunications Research Institute (Korea, Republic of)

We propose an optimization method of a slot ring antenna integrated with a
terahertz (THz) photodiode (PD) type photomixer for optimum impedance matching. Proper impedance matching between the antenna and the photomixer is very important to increase the THz output power. The PD type photomixer has complex impedance which varies according to the operating frequency. Thus the both resistance and reactance of the antenna should be controlled; the bias circuit integrated in the device for the operation of the photomixer should be also optimized for the impedance matching. In this design, the coplanar waveguide (CPW) was used for the transmission line and antenna feeding line to exactly control the electric length, and minimize radiation loss from the line, and remove the transition structure from the transmission line to the antenna feeding line. There are several factors in optimizing the impedance matching condition in the device composed of the antenna, the photomixer, and bias circuit, such as size of the ring antenna, structure of the bias circuit and the CPW, the distance between the antenna and bias pad, and the length of the CPW between the bias circuit and the photomixer. The proposed optimization method of a slot ring antenna can successfully control both resistance and reactance for the impedance matching between the antenna and the photomixer. The optimization method for the terahertz photomixer integrated antenna can increase the output power of the device at the operation frequency.

9747-78, Poster Session
FDTD simulation of space-time cloaking structure based on transformation optics for terahertz frequency range
Egor A. Gurvitz, Mikhail V. Sharaevsky, Mikhail K. Khodzitsky, ITMO Univ. (Russian Federation)

Security systems are very actual field of scientific researches in all frequency ranges. High expectations are devoted to terahertz frequency range where interaction of the electromagnetic radiation and human body has non-invasive nature. Consequently, the systems for protection and cloaking are also developed. The most interesting approach of cloaking was suggested by transformation optics. In this work the development of space-time cloak [1,2], the most complicated case of cloaking designs, was considered. Four dimensional field tensors and components of 4 rank constitutive parameter tensor were derived for space-time mapping of 2 spatial and 1 temporal dimensions. Cloaking structure was simulated for obtained constitution parameters by FDTD method. The challenge of realization was discussed.


9747-55, Session 12
Multilayers for EUV, soft x-ray, and x-ray optics (Invited Paper)
Zhanshan Wang, Qiushi Huang, Zhong Zhang, Tongji Univ. (China)

We describe the development of multilayers prepared by magnetron sputtering for use as reflective coatings for extreme ultraviolet, soft X-ray and X-ray optics. We have used low angle X-ray reflectivity obtained with Cu K\(\alpha\) radiation to characterize the interfacial imperfections, and high resolution transmission electron microscopy and selected area electron diffraction to characterize interface structure and layer morphology. The working wavelength reflectivity measurements with synchrotron radiation were used to quantify the optical performance of different material combination multilayers. The good agreement between reflectivity measurements and fitted simulation made using different interfacial widths. The normal incidence Schwarzschild microscopes working at extreme ultraviolet range were fabricated for probing ultra-heated electron transmission in the plasma made by ultra-high power laser interacted with copper wire with and without silica coating. The grazing incidence Kirkpatrick-Baez microscopes were used to diagnose the dense plasma produced by high power lasers and got very good experimental results.

9747-56, Session 12
Design and optimization of polymer ring resonator modulators for analog microwave photonic applications
Arash Hosseinizadeh, Christopher T. Middlebrook, Michigan Technological Univ. (United States)

Efficient modulation of electrical signals onto an optical carrier remains the main challenge in full implementation of microwave photonic links (MPLs) for applications such as antenna remoting and wireless access networks. Current MPLs utilize Mach-Zehnder Interferometers (MZI) with sinusoidal transfer function as electro-optic modulators causing nonlinear distortions in the link. Recently ring resonator modulators (RRM) consisting of a ring resonator coupled to a basic waveguide attracted interest to enhance linearity, reduce the size and power consumption in MPLs. Fabrication of a RRM is more challenging than the MZI not only in fabrication process but also in designing and optimization steps. Although RRM can be analyzed theoretically for MPLs, physical structures need to be designed and optimized utilizing simulation techniques in both optical and microwave regimes with consideration of specific material properties. Designing and optimization steps are conducted utilizing full-wave simulation software package and RRM function analyzed in both passive and active forms and confirmed through theoretical analysis. It is shown that RRM can be completely designed and analyzed utilizing full-wave simulation techniques and as a result linearity effect of the modulator on MPLs can be studied and optimized. Using simulation techniques material nonlinearity response can be included in modulator design and can be extended to analyze other materials such as silicon or structures without available theoretical analysis.

9747-57, Session 12
Graphene plasmon modes near thin metallic layer in THz frequency regime
Il-Min Lee, Jun-Hwan Shin, Kiwon Moon, Eui Su Lee, Sang-Pil Han, Kyung Hyun Park, Electronics and Telecommunications Research Institute (Korea, Republic of)

Graphene surface plasmons have been extensively studied since they have a potential candidate for the highly-confined plasmonic field in the terahertz (THz) frequency regime. The THz regime is widely believed as a next territory in science and technologies for its wide variety of applications such as wireless communications, sensing, and imaging. Like as the plasmonics with noble metals in the optical regime does, graphene plasmonics in terahertz regime are expected to provide a wide variety of unprecedented functionalities. By applications of external voltage, the carrier density in graphene can be continuously varied. Therefore, the prospect of actively controlling plasmonic state via applying a gate voltage has been a fascinating feature of graphene plasmonics. Naturally, designing a plasmonic waveguide that can provide novel characteristics to the guided plasmonic mode consists of a core procedure in the graphene plasmonics. The majority types of graphene plasmonic waveguides are mono- or multi-layered graphene sheets as the metallic plane or line for the plasmonic waveguide. Recently, a few of studies have reported metal-graphene hybrid structures as the plasmonic waveguides. However, further studies are still required to investigate the possibilities in these noble types of plasmonic waveguide. In this study, we investigate the effect of the existence of a thin metallic layer nearby a graphene layer in the aspect of plasmonic waveguide mode. The variety of possibilities in selecting the materials and structural parameters will be investigated in analytical and numerical ways.
Graded index porous optical fibers: dispersion management in terahertz range

Tian Ma, Maxim Skorobogatyi, Ecole Polytechnique de Montréal (Canada)

A graded index porous optical fiber has been proposed for the terahertz transmission with low-loss and low dispersion. The radially graded index distribution of the proposed fiber is achieved by an air-hole array featuring variable air-hole diameters and inter-hole separations. We theoretically investigated the modal properties of the proposed GI-mPOF and the traditional mPOF with uniform air-hole diameters and lattice constants using a finite element method. The simulation results demonstrate that the proposed GI-mPOF design suppresses the excitation of higher order modes and reduces the intermodal dispersion. At the same time, both the intermodal and individual dispersion of the designed GI-mPOF are smaller than 2 ps/(THz·cm) in the spectral range from 0.1 to 1.6 THz leading to a smaller pulse broadening in the designed graded index fiber. We also experimentally confirmed that the designed GI-mPOFs have considerably superior optical properties when compared to the traditional mPOF. The transmission of these two fibers was also measured utilizing a THz-TDS setup using the cut-back method. Due to its high porosity, the absorption loss of the proposed GI-mPOF in the whole operation range varies from 0.025 cm⁻¹ at 0.3 THz to 0.15 cm⁻¹ at 1.5THz. The proposed fiber structure also improved the output pulse quality as all the modes reach the output facet of the fiber in one time-domain envelope. The pulse broadening has also been well restrained by the designed fiber structure, as the pulse duration of the designed GI-mPOF is much smaller than that of the traditional mPOF. Simultaneously, the transmission band of GI-mPOF is significantly wider than that of porous fibers due to better suppression of the excitation of higher order modes.

Coherent THz power combiner consisting of arrayed uni-traveling carrier photodiodes and planar lightweight circuit

Kazuki Sakuma, Jun Haruki, Kyushu Univ. (Japan); Goki Sakano, Kyushu University (Japan); Kazutoshi Kato, Kyushu Univ. (Japan); Shintaro Hisatake, Tadao Nagatsuma, Osaka Univ. (Japan)

Coherent THz wave is one of the most promising media for ultra-high data-rate wireless transmissions. A successful approach of generating the coherent THz wave is photomixing of two different lightwaves by using a high-speed uni-traveling-carrier photodiode (UTC-PD). For a practical THz-wave transmission with, for example, 100-m distance, the power of about 1 mW is desired. However, the UTC-PD has limitation of the output power of about 10 W at 0.3 THz. To obtain high-power THz wave, we propose and demonstrate, for the first time, the synchronous power combiner using a silica-based planar lightweight circuit (PLC) in which we monolithically integrates splitters, phase controllers and optical couplers. At the PLC, two lightwaves (ϕ₁, ϕ₂) from two lasers, whose wavelength difference corresponds to 0.3 THz, are split into eight optical paths, each optical phase is controlled to be synchronized, and then, eight pairs of optical paths of ϕ₁ and ϕ₂ are coupled. Each pair of lightwaves is introduced into each channel of the eight-channel 500-μm-spaced UTC-PD array with the bowtie antennas. The radiated THz wave power is detected at a distance of 15 mm with the Schottky barrier diode detector. We used three channels of the array, and detected normalized power of 1.97, 1.44 and 1.00 for each channel. The combined power of these three channels resulted in the relative power of 0.05, which successfully demonstrates synchronous power combination and even shows a directional gain of 2.6 dB. These results indicate the possibility of 1-mW coherent THz-wave with our proposed configuration.

Advancing sonic IR imaging for materials and structures (Invited Paper)

Xiaoyan Han, Wayne State Univ. (United States)

Sonic IR imaging is an effective non-destructive (NDE) technology which employs a short ultrasound pulse (fraction of a second), typically 20-40 kHz, injected into the target object under evaluation to produce localized frictional heating at any defects which may be present, such as cracks, delaminations, disbonds or thermally inhomogeneous regions. A thermal imager system such as infrared (IR) camera images the heating of the surface resulting from the effects of friction or other irreversible effects in the vicinity of defects. These effects result from the fact that the two surfaces of internal defects do not move in unison when sound propagates in the object. Thus, for instance, the faying surfaces of a closed crack appear as a planar heat source when they move in response to the presence of the acoustic field. The response of materials and structures to the sonic excitation input is very nonlinear. The nonlinearity introduces chaotic behavior in the sound and enhances the signal of the IR images. The Probability of Detection (POD) of defects can be dramatically affected. We will present results on the development of this technique as well as its practical applications.

Non-destructive characterization of nanocomposite deep-level defects using terahertz technique

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There are high demands for non-destructive technique (NDT)
characterization of thick carbon composite laminates. The requirements of deep penetration and high sensitivity make the current NDT challenging and difficult. Terahertz (THz) NDT technologies are developed to detect the localized deep level of defects and porosity on sharp curved composite structures. First, the Terahertz signal is designed to be collected at the subsurface to avoid direct reflection due to Terahertz shallow penetration. Secondly, small elastic deformation caused by external perturbation is applied. The external perturbation is exerted on the overall structure. The interactions of the perturbation and structure will change the Terahertz wave propagation at the subsurface. Therefore, the deep level defect information can be transferred onto subsurface to be detected by Terahertz wave. Finally, the location and size of deep level of defects and non-uniformity are derived. The perturbation can be divided into two categories: contact method and non-contact method, such as: mechanical force, light, heat etc. The advantages and disadvantages of the above methods are evaluated systematically. Low level porosities (0-4%) are differentiated by Terahertz technologies. Delamination position and defect depth are derived and all the above results are benchmarked by the existing X-ray Computed Tomography (XRay-CT) method. Our technology using Terahertz in NDT overcame the Terahertz’s bottleneck of limited penetration and demonstrated the feasibility for complex thick conducting composite characterization which hindered current NDT development in the composite application.

9747-63, Session 13

Low-loss and low-dispersion transmission line over DC-to-THz spectrum

Faeezeh Fesharaki, Tarek Djerafi, Ecole Polytechnique de Montréal (Canada); Mohamed Chaker, Institut National de la Recherche Scientifique (Canada); Ke Wu, Ecole Polytechnique de Montréal (Canada)

Transmission lines or waveguides are the most fundamental building blocks of all electronic and photonics circuits and systems. In this work, we devise and demonstrate a DC-to-THz low-loss and low-dispersion signal traveling wave structure. This is designed to be an automatic mode-selective transmission line (MSTL) that operates under TEM-mode over low frequency range and its operating mode is gradually converted to low-loss TE10-mode for operation at high frequency of millimeter-wave (mmW) and THz. MSTL, effectively covering the DC to THz frequency range, is suitable for full DC-THz electromagnetic propagation, ultra-high-speed THz pulsed signal transmission, and tera-bit-per-second interconnects. Full-wave analysis is done with the semi-theoretical technique of method of lines (MOL) to examine the propagation characteristics, and 3D simulation is carried out to visualize the field propagation. An optimized design is fabricated on fused Silica substrate, and measured up to 0.5 THz showing less than 0.35 dB/mm attenuation over all the frequency range, which is more than 20 times less than the microstrip counterpart. Dispersion-less characteristic is verified by time domain characterization using a 1ps FWHM Gaussian pulse through straight and curved MSTL. It shows an excellent performance for high data-rate applications that is also confirmed by eye diagram. MSTL, providing a self-packaging structure in a fully integrated form, combines the benefits of a low-cost planar processing technology with the low-loss intrinsic to the operation mode. MSTL presents a promising candidate as a key-enabling technology towards the development of a new generation broadband DC-THz electronic and photonic modules and high-speed interconnects.

9747-64, Session 13

RF beam transmission/reception of x-band PAA system utilizing large-area, light-weight, and conformal polymer-based true-time-delay module developed using imprinting and inkjet printing

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Phased-array antenna (PAA) technology plays a significant role in modern radar and communication networks. True-time-delay (TTD) enabled networks provide several advantages over their electronic counterparts, including squint-free beam steering, low RF loss, immunity to electromagnetic interference (EMI), and large bandwidth control of PAs. However, conventional TTD systems based on bulk optics are heavy and voluminous. Chip-scale and integrated solutions promise a miniaturized, light-weight option, however, the modules are still rigid and they require complex packaging solutions. Moreover, the total achievable time delay is still restricted by the wafer size. In this work, we propose a lightweight and large-area, conformal true-time-delay beamforming network, comprising of electro-optic polymer modulator array and thermo-optic polymer true-time-delay module, fabricated on light-weight and flexible or conformal surfaces utilizing low-cost “printing” techniques. In order to prove the feasibility of the approach, 1x2 electro-optic polymer Mach-Zehnder Modulator (MZM) array and 2-bit thermo-optic polymer TTD network are developed using a combination of imprinting and ink-jet printing. Utilizing these developed components, RF beam transmission and reception of an X-band signal is demonstrated. The development of such active components on large area, light-weight, and low-cost substrates promises significant improvement in size, weight, and power (SWaP) requirements over the state-of-the-art.

9747-65, Session 14

Large-dynamic range plasmonic photomixer for heterodyne terahertz detection

Ning Wang, Univ. of Michigan (United States) and Univ. of California, Los Angeles (United States); Hamid Javadi, Jet Propulsion Lab. (United States); Mona Jarrahi, Univ. of California, Los Angeles (United States)

Heterodyne terahertz detectors are widely used in applications requiring high spectral resolution. A typical heterodyne terahertz detection system uses a mixer to down-convert terahertz signals to lower frequencies that can be easily analyzed by radio frequency (RF) measurement instruments. Schottky diode mixers, superconductor insulator superconductor (SIS) mixers, and hot electron bolometer (HEB) mixers are the most commonly used mixers in conventional heterodyne terahertz detection systems. Despite their high detection sensitivities, the potential use of the conventional heterodyne detection systems is still limited by lack of available terahertz local oscillators with sufficient output powers and mixers with high efficiencies at high terahertz frequencies. Here we present a novel design of plasmonic photomixers, which can provide high sensitivities, broad bandwidths, and large dynamic ranges to improve the heterodyne terahertz detection performance. The presented plasmonic photomixer employs optical beams from two wavelength-tunable lasers with a terahertz
frequency difference as the local oscillator. It consists of plasmonic nanostructures integrated with terahertz antennas, which can efficiently couple the optical local oscillator and terahertz waves into the photomixer active region to produce a photocurrent at an RF intermediate frequency. A proof-of-concept plasmonic photomixer is fabricated on a low temperature grown GaAs substrate and characterized in a heterodyne terahertz detection system with two wavelength tunable 800 nm wavelength lasers serving as the local oscillator of the heterodyne terahertz detector. The experimental results show that this novel plasmonic photomixer can offer significantly larger dynamic range and broader frequency tuning range compared to existing heterodyne terahertz detectors.

9747-66, Session 14

Fully packaged high-performance RF sensor featuring slotted photonic crystal waveguides in silicon-on-sapphire

Chi-Jui Chung, The Univ. of Texas at Austin (United States); Harish Subbaraman, Omega Optics, Inc. (United States); Jingdong Luo, Alex K. Y. Jen, Univ. of Washington (United States); Robert L. Nelson, Charles Y. C. Lee, Air Force Research Lab. (United States); Ray T. Chen, The Univ. of Texas at Austin (United States) and Omega Optics, Inc. (United States)

A fully packaged, low loss, and high sensitivity RF sensor working at X band based on an electro-optic (EO) polymer infiltrated silicon slot photonic crystal waveguides (PCW) and bowtie antenna in silicon-on-sapphire (SOS) wafer is proposed and experimentally demonstrated. By taking advantage of the slow light effect in the PCW(>20X), large EO coefficient of the EO polymer(>33×200pm/V), as well as significant electric field enhancement within broad frequency range of bowtie antenna on sapphire substrate(>10000), we realize an in-device EO coefficient over 1000pm/V so as to realize a compact high performance RF wave sensor. On-chip Mach-Zehnder interferometer (MZI) layout working under push-pull configuration is also adopted to further increase the sensitivity of the sensor. Furthermore, the inverse taper coupler and EO polymer infiltrated slotted photonic crystal waveguides are carefully designed and discussed in this paper to reduce the insertion loss of the RF sensor so as to increase the device signal-to-noise ratio. The fully packaged photonic RF sensor has several important advantages over RF sensors based on electrical schemes, including high data throughput, compact size, and immunity to electromagnetic interference (EMI). Moreover, the fully packaged RF sensor has not only successfully shown the potential of commercialization but also addressed the reliability issues, such as the tolerance to the fiber tip displacement and rotation and the mechanical durability of the couplers.

9747-67, Session 14

Optical fiber based microwave-photon interferometric sensors

Jie Huang, Missouri Univ. of Science and Technology (United States); Liwei Hua, Lei Yuan, Clemson Univ. (United States)

Optical fiber interferometers (OFIs) have been extensively used for precise measurements of various physical/chemical quantities (e.g., temperature, strain, pressure, rotation, refractive index, etc.). However, the random change of polarization states along the optical fibers and the strong dependence on the materials/geometries of the optical waveguides are problematic for acquiring high quality interference signal. Meanwhile, the difficulty in multiplexing has always been a bottleneck on the application scopes of OFIs. Interrogated in optical domain, FOIs are commonly implemented using single-mode fibers with tightly-controlled state of polarization (SOP) to obtain high quality interference signals.

We present a sensing concept of optical carrier based microwave interferometry (OCMI) by reading optical interferometric sensors in microwave domain. It combines the advantages from both optics and microwave. The low oscillation frequency of the microwave can hardly distinguish the optical differences from both modal and polarization dispersion making it insensitive to the optical polarization and waveguides/materials. The phase information of the microwave can be unambiguously resolved so that it has potential in fully distributed sensing. The OCMI concept has been implemented in different types of interferometers (e.g., Michelson, Mach-Zehnder, Fabry-Perot) among different optical waveguides (e.g., singlemode, multimode, and sapphire fibers) with excellent signal-to-noise ratio (SNR) and low polarization dependence. A spatially continuous distributed strain sensing has also been demonstrated based on cascaded weak reflectors along an optical fiber fabricated by femto-second laser micro-machining.

9747-68, Session 14

High-power MUTC photodetectors for RF photonic links

Steven Estrella, Leif A. Johansson, Milan L. Mashanovitch, Freedom Photonics, LLC (United States); Andreas Beling, Univ. of Virginia (United States)

High power photodiodes are needed for a range of applications. The high available power conversion efficiency makes these ideal for antenna remoting applications, including high power, low duty-cycle RF pulse generation. The compact footprint and optical connection allows densely packed RF aperture arrays with low cross-talk for phased and directionality emitters. Other applications include linear RF photonic links and other high dynamic range optical systems. Freedom Photonics has developed packaged modified uni-traveling carrier (MUTC) photodetectors for high-power operation and applications. Both single and balanced photodetector pairs are mounted on a ceramic carrier, and packaged in a compact module optimized for high power operation. Representative results include greater than 100mA photocurrent, >100mW generated RF power and >20GHz bandwidth. In this paper, we evaluate the saturation and bandwidth of these single and balanced photodetectors for detector diameter in the 16µm to 34µm range. Packaged performance is compared to chip performance. Further new development towards the realization of >100GHz packaged photodetector modules with optimized high power performance is described. Finally, incorporation of these photodetector structures in novel photonic integrated circuits (PICs) for high optical power application areas is outlined.

9747-69, Session 14

THz dual-band metasurfaces

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Metasurfaces utilizing engineered sub-wavelength structures have recently emerged as an important and effective means to tailor the electromagnetic wave propagation in a prescribed manner. Most of the proposed metasurfaces could only work at one single wavelength. Recently, a metasurface is proposed to deflect waves at three telecommunication wavelengths by the same angle, which aimed to address the issue of chromatic aberrations. However, the required phase compensation within the metasurface was obtained through extensive parametric studies without separate control of any wavelength. Studies, the realized frequency ratio of the operating wavelengths (i.e. frequency) is relatively small, which is less than 1.5. In this paper, we propose a sub-wavelength metasurface that could tailor wave propagation in reflection mode at two THz wavelengths,
the ratio of which could be flexibly controlled and larger than 3. The wave propagation could be manipulated individually at these two wavelengths. A unit cell of the metasurface is composed of a top metallic C-shape antenna, a dielectric spacer, and a bottom ground layer with a C-shape slot antenna and a circle slot. In addition to the broadband characteristic of the C-shape/C-slot antennas, the magnitude of the transmission/reflection can also be controlled by rotating the C-shape/C-slot structure. Two beam-steering metasurfaces are numerically studied: one is a periodic structure at both wavelengths with a constant phase interval so that the incident wave will be steered to different angles at the two wavelengths according to the generalized Snell’s law; the other is an aperiodic structure with phase compensation so that the incident wave could be reflected to the same angle at the two operating wavelengths. The simulated results agree very well with the theoretical predictions. The proposed metasurface structure could be widely applied in beam-steering, beam-focusing, and holographic applications.

9747-70, Session 15
Large cross-phase modulation driven by intense THz field
Carlo Vicario, Mostafa Shalaby, Paul Scherrer Institut (Switzerland); Christoph P. Hauri, Paul Scherrer Institut (Switzerland) and Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Intense THz fields can induce linear and nonlinear response of the matter. We present nonlinear electro-optical interaction and strong cross-phase modulation (XPM) on an optical pulse driven by intense single-cycle terahertz (THz) field. THz pulses carrying energy up to 50 µJ and frequency contents in the range between 0.1 and 5 THz are realized by optical rectification in organic crystal DSTMS. The irradiation is focused to diffraction-limited waist for the realization of field strength up to 10 MV/cm. The time-dependent evolution of the THz electric field induces transient XPM leading to significant spectral modification and broadening of a co-propagating 60 fs, 800 nm probe pulse. At the maximum amplitude, the THz field strongly changes the optical index of refraction of the EO crystal resulting in large spectral broadening and shift of the central wavelength. At the positive and negative THz peaks the optical spectrum is enlarged by more than a factor 3. The THz-induced XPM effect presented here can be used to control the spectral and temporal properties of ultrashort laser pulses.

9747-71, Session 15
Experimental studies on WDM to TDM signal conversions using gigahertz electro-absorption modulators
Tianxin Yang, Peirui Gao, Tianjin Univ. (China)

The conversion between the wavelength divisions multiplexing (WDM) signals and time divisions multiplexing (TDM) signals in optical domain is analogous to the conversion between the parallel data and serial data in electronic domain. However in optical domain it is not only the data format conversion but also is related to mathematic transform operations, such as all-optical Fourier Transformation when a special TDM signal is transformed to the WDM signals in a silicon nanowire based on the optical nonlinear four-wave mixing process[1]. In this paper a WDM-to-TDM conversion is demonstrated experimentally using the cross-absorption modulation effects in a high speed electro-absorption modulator (EAM). This technique can be used in a WDM network for improvement of the spectrum resource efficiency and also in an orthogonal frequency division multiplexing (OFDM) network for simplification of the receiver systems. In our system multi-wavelength with the spacing of 100 GHz continuous-wave laser is set up to generate the WDM signals with an intensity modulator driven by a high speed arbitrary digital pattern generator (APG). Those WDM signals are delayed properly by a length of dispersion fiber in time domain, and then enter an 40 GHz EAM along with a CW laser beam at a single probe wavelength which is different from any multi-wavelength signals. All WDM signals are transported to the probe wavelength in sequence in the EAM based on the cross-absorption modulation effects to produce corresponding TDM signals. The wavelength band of WDM signals which can be processed in our system can cover 50 nm over the C and L band in current optical fiber communication.


9747-72, Session 15
Effective THz modulators by ionic liquid gating on graphene
Yang Wu, Yang Hyunsoo, National Univ. of Singapore (Singapore)

In this study, we design and fabricate THz modulators based on graphene/ionic liquid/graphene sandwich structures. By applying a 3 V gate voltage, 83% modulation is obtained from a mono-layer graphene based device; while up to 99% modulation is demonstrated by stacking two devices. The modulators work in a broadband frequency range (0.1 to 2.5 THz).

The excellent performance of the modulators benefits from two key factors: the conical band structure of the graphene films and the efficient gating effect of the ionic liquid. First, due to the linear band structure of graphene, the optical conductivity is linearly controllable by applying the gate voltage, which consequently modulates the transmittance of THz waves. Second, the effective gating of the ionic liquid results from the fact that electrons and holes accumulate within only few nanometers at the interfaces between graphene and ionic liquid. As a result, the electric field on graphene is enormous large, which leads to effective tuning of the Fermi level of graphene. The electrical measurement and the numerical simulations provide concrete support to our understanding of the THz modulation. Furthermore, the simulation results indicate that the reflection of the THz wave dominates the modulation at high gate voltage region. This interesting behavior is confirmed by THz reflection measurements and up to 33% THz reflection is observed from a gated single layer graphene device. The proposed device has great potential for applications due to the high performance, simple structure, and easy operation.
9748-1, Session 1

Properties and applications of hexagonal boron nitride single crystals (Invited Paper)

James Edgar, Tim Hoffman, Jared Sperber, Yi Zhang, Song Liu, Kansas State Univ. (United States)

While polycrystalline hexagonal boron nitride (hBN) has been used for decades for its thermal and chemical stability, high thermal conductivity, and high electrical resistivity, new applications based on hBN single crystals are being developed which exploit its wide energy band gap (6.4 eV), anisotropic optical constants, birefringence, flexoelectricity, weak bonding between layers, ultrasmooth surfaces, and the large thermal neutron capture cross-section for the B-10 isotope. Examples of specific devices envisioned include ultraviolet emitters, interference-less absorbers, neutron detectors, and substrates for atomically thin 2D and conventional semiconductors. These applications require single crystals or epitaxial layers with low residual impurity concentrations and low structural defect densities. In this study, hBN single crystals were precipitated by slow cooling (1-4 °C/h) of a molten nickel-chromium solution initially saturated with hBN at 1500 °C. Water-clear crystals up to 4 mm2 in area and more than 200 μm thick were produced in this random nucleation process. Both platelet and pyramidal crystal shapes were produced. The highest energy room temperature photoluminescence peak occurred at 5.75 eV, indicative of high quality crystals. Non-basal plane defect densities, as determined from etch pit densities after defect selective etching in a sodium hydroxide + potassium hydroxide eutectic at 450 °C for 1 minute, were approximately 5 x 107 cm-2. Solution crystal growth was also demonstrated with isotopically pure elemental boron, which enabled the growth of nearly isotopically pure hBN and h1BN crystals. The FWHM Raman peak widths for such crystals were under 5 cm-1.

9748-2, Session 1

Hexagonal boron nitride (h-BN) epilayers: growth, properties, and applications (Invited Paper)

Hongxing Jiang, Jingyu Lin, Texas Tech Univ. (United States)

As a member of the III-nitride semiconductor family, boron nitride (BN) is the least studied material system. Hexagonal boron nitride (h-BN) possesses extraordinary physical properties including wide bandgap (Eg ~ 6.5 eV), high temperature stability and corrosion resistance, and large optical absorption and neutron capture cross section. Furthermore, having a layered-structure, h-BN represents an ideal platform for probing fundamental 2D properties in semiconductors. We have demonstrated the synthesis of wafer-scale h-BN epilayers by MOCVD [1-5]. It was shown that the unique 2D structure of h-BN induces high density of state and large exciton binding energy, which results in high optical absorption and emission intensity [5]. Polarization-resolved PL revealed that h-BN epilayers are predominantly a surface emission material [4,5]. This is in contrast to AIN, in which the band-edge emission is known to be polarized along the c-axis [6]. The h-BN deep UV detectors exhibit a sharp cut-off wavelength around 230 nm [7]. P-type conduction in h-BN via Mg doping was obtained [1]. Hall effect measurements revealed an in-plane resistivity of ~ 2.3 Ω cm for Mg doped h-BN epilayers grown on insulating AIN templates [2]. A novel deep UV emitter layer structure based on h-BN and AlGaN p-n junction has been explored [2,3]. The attainment of p-type h-BN could potentially overcome the intrinsic problem of low p-type conductivity in Al-rich AlGaN for deep UV photonic devices. BN thermal neutron detectors exhibit very high charge collection efficiency and spectral resolution of the nuclear reaction products [8]. These results represent a major step towards the realization of h-BN based practical devices.

The h-BN emitter work is supported by NSF ECCS-1402886; the effort on the fundamental optical studies of h-BN is supported by DOE (FG02-09ER46552); and the detector work is supported by DHS ARI Program (2011-DN-077-AR1048).

References


9748-3, Session 1

Chronological Advances in Two Dimensional Hexagonal Boron Nitride Growth (Invited Paper)

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Bulk hexagonal boron nitride (h-BN) is a crystalline material composed of stacked two-dimensional (2D) layers with alternating B and N atoms bonded in a honeycomb structure. Due to weak interlayer van der Waals force, atomically thin layers including monolayer h-BN can be exfoliated from its bulk crystal. Owing to its atomic smoothness and electrically non-conducting properties, h-BN is highly utilized as a substrate material for almost all other 2D materials. To date, there are several methods to obtain such atomically thin h-BN films such as mechanical and liquid phase exfoliation as well as controlled synthesis by chemical-vapour-deposition(CVD). Among those, CVD has become an imperative technique to grow high-quality 2D h-BN due to its potential for up-scaling. Large area h-BN films were grown on various transition metals such as Cu and Ni. To achieve the highest quality films by CVD, monolayer h-BN single crystals have been attempted. The shape of the domains is mostly triangular due to its asymmetric N- and B-edge energies and the sizes are typically in the micrometers regime. Continual efforts to increase the domain sizes were contributed and the largest single-crystal domain at present exceeds 100 µm in dimensions. In addition, the recent discovery of hexagonal shaped h-BN domains poses an interesting growth mechanism for theorists which could have potentially different edge interactions to its triangular shaped counterparts. Here we summarize chronologically the advances made in the growth of 2D h-BN via CVD methodology from the first evidence of nanometre size domains to current sub millimetre flakes.
Heteroepitaxial growth of cubic boron nitride films on diamond(001) substrates and their n-type doping (Invited Paper)

Hong Yin, Jilin Univ. (China)

As the simplest III-nitride, cubic boron nitride (c-BN) exhibits the widest band gap (6.4 eV), the most stability against the chemical and physical harsh environments at high temperatures and high thermal conductivity. Thus, it is very promising to apply c-BN as high power and high temperature semiconductor devices which can be operated in extremely severe conditions. In order to achieve such goal, high-quality epitaxial growth of c-BN film with appropriate semiconducting properties is highly desirable. Attempts to achieve epitaxial growth of c-BN films have been made either by ion beam assisted deposition (IBAD) or electron cyclone resonance chemical vapor deposition (ECR-CVD), or recently a plasma-assisted molecular beam epitaxy (PA-MBE). All these efforts have pushed the development of c-BN films towards the electronic applications.

This paper reviews our recent advances of heteroepitaxial growth of c-BN films on diamond(001) substrates and various doping methods aiming to their n-type conductivity. We mainly demonstrate that: (i) phase-pure c-BN films have been epitaxially grown on diamond(001) substrates at 900 °C by IBAD. A simple growth mechanism will be discussed. (ii) high-quality c-BN epitaxial films have been heavily doped through Si implantation, which conserve pure cubic phase up to a dose of 2.71020 cm-3 and a related implantation damage of 0.5 dpa (displacement per atom). (iii) in-situ n-type doping has been achieved by continuously adding Si during c-BN film growth and the sequential growth of nominally undoped (p-) and Si doped (n-) layers with well-controlled thickness (down to several nanometer range) in the concept of multiple delta doping. The electronic transport process will be proposed for each of the doping strategy.

Optical properties of hexagonal boron nitride (Invited Paper)

Guillaume Cassabois, Univ. Montpellier 1 (France); Pierre Valvin, Bernard Gil, Univ. Montpellier 2 (France)

Hexagonal boron nitride (hBN) is a wide bandgap semiconductor with a large range of basic applications relying on its low dielectric constant, high thermal conductivity, and chemical inertness. The growth of high-quality crystals in 2004 has revealed that hBN is also a promising material for light-emitting devices in the deep ultraviolet domain, as illustrated by the demonstration of lasing at 215 nm by accelerated electron excitation, and also the operation of field emitter display-type devices in the deep ultraviolet. With a honeycomb structure similar to graphene, bulk hBN has recently gained tremendous attention as an exceptional substrate for graphene with an atomically smooth surface, and more generally, as a fundamental building block of Van der Waals heterostructures. In spite of this rising interest for hBN and the large number of studies devoted to this material of seemingly simple crystal structure, the very basic question of the bandgap nature is still controversial. There is a strong contrast in the literature between ab initio band structure calculations predicting an indirect bandgap crystal and optical measurements concluding to a direct one.

In this paper, we present our recent results demonstrating that hBN has an indirect bandgap at 5.95 eV. We show that the optical properties of hBN are profoundly determined by phonon-assisted transitions. We provide a comprehensive analysis of the emission spectrum in the deep ultraviolet in terms of phonon-assisted transitions involving either virtual or real excitonic states, the latter being provided by structural defects.
HVPE-GaN growth on GaN-based Advanced Substrates by Smart Cut(TM) (Invited Paper)

Malgorzata Iwinska, Institute of High Pressure Physics (Poland); Mikolaj Amlusik, Institute of High Pressure Physics (Poland) and TopGaN Ltd. (Poland); Michal Fijalkowski, Institute of High Pressure Physics (Poland); Tomasz Sochacki, Boleslaw Lucznik, Institute of High Pressure Physics (Poland) and TopGaN Ltd. (Poland); Anna Nowakowska-Siwinska, TopGaN Ltd. (Poland); Izabella Grzegory, Institute of High Pressure Physics (Poland); Pascal Guenard, Raphael Caulmilone, Soitec S.A. (France); Martin Seiss, Tobias Mrotzek, PLANSEE SE (Austria); Michal Bockowski, Institute of High Pressure Physics (Poland) and TopGaN Ltd. (Poland); Elzbieta Wodyńska, Institute of High Pressure Physics (Poland) and TopGaN Ltd. (Poland); Makoto Saito, Tohoku Univ. (Japan) and Mitsubishi Chemical Corp. (Japan); Quanxi Bao, Kohei Kurimoto, Tohoku Univ. (Japan) and The Japan Steel Works, Ltd. (Japan); Daisuke Tomida, Kazunobu Kojima, Tohoku Univ. (Japan); Yuji Kagamitani, Mitsubishi Chemical Corp. (Japan); Rinzo Kayano, The Japan Steel Works, Ltd. (Japan); Tooru Ishiguro, Shigefusa F. Chichibu, Tohoku Univ. (Japan).

Acidic ammonothermal method is one of the most promising techniques which enables the mass production of large diameter bulk GaN crystal. State-of-the-art high-power light-emitting diodes and laser diodes are usually fabricated on GaN substrates grown by hydride vapor phase epitaxy. However, to realize vertically conducting high-power GaN switching devices, bowing-free large-diameter GaN substrates are essential, because the size of such devices is much larger than that of optical devices. The ammonothermal growth of GaN crystals was carried out using 4 kinds of ammonium halide mineralizers. To prevent contaminating the crystals and the Ni-based superalloy autoclave from corroding, the inner wall was covered with Pt. A circular Pt baffle plate with holes was placed at the center in the autoclave to separate the growth region and nutrient region. After charging the precursor and the seed crystals, ammonium halide powder was added. Then, filter-purified NH3 gas was fed into the autoclave. The autoclave was heated using a two-zone vertical furnace. The convection causes the mass transport, by the temperature gradient between the two regions.

The crystal quality and the growth rate are strongly influenced by mineralizer species. We have also studied the dependence on temperature and pressure, and found it possible to achieve the growth rate faster than 1000µm/day in the optimum growth condition. The full width at half-maximum of the (0002) x-ray ½-rocking curve was smaller than 30 arcsec. Based on these studies and optimization above, we have successfully demonstrated high speed bulk GaN growth by this method at the pressure condition at 100MPa.

High rate InN growth by two-step precursor generation hydride vapor phase epitaxy (Invited Paper)

Rie Togashi, Quang Tu Thieu, Hisashi Murakami, Tokyo Univ. of Agriculture and Technology (Japan); Yoshihiro Ishitani, Chiba Univ. (Japan); Bo Monemar, Tokyo Univ. of Agriculture and Technology (Japan) and Linköping Univ. (Sweden); Akinori Koukitsu, Yoshioo Kumagai, Tokyo Univ. of Agriculture and Technology (Japan).

For the improvement of the performance of green laser diodes (LDs) and development of LDs emitting longer wavelengths, it is necessary to develop bulk InxGa1-xN substrates with In composition near high-In-content InxGa1-xN quantum wells grown on them. Previously, some of the present authors investigated the growth of InN by the generation of InCl3 by flowing Cl2 over In metal in the source zone of a conventional hydride vapor phase epitaxy (HVPE) system. However, the maximum growth rate obtained was only 0.53 µm/h since the major gaseous In species generated was still InCl3 which does not contribute to the InN growth. In order to generate InCl3 preferentially and increase InN growth rate, an atmospheric pressure HVPE system with two-step InCl3 generation was newly developed based on the results of thermodynamic analysis.
An elevated growth rate of InN on a GaN/(0001) sapphire template was achieved by the complete conversion of InCl generated in the first source zone to InCl3 in the second source zone, by the supply of additional Cl2. The growth rate reached 12.4 μm/h at a growth temperature of 600 °C, and the rate was observed to decrease above this temperature. InN layers grown at 650 °C exhibited a sharp room temperature photoluminescence peak at 0.73 eV with a bulk electron concentration of 1.2 · 1018 cm-3. Therefore, this technique is important for the fabrication of high-quality bulk InxGa1-xN substrates with desired In solid compositions.

9748-11, Session 3
Hydride Vapor Phase Epitaxy for High Conductivity N-type AlN
Jacob H. Leach, Kevin Udwary, Keith R. Evans, Kyma Technologies, Inc. (United States)
Wide-bandgap power electronics devices represent a game-changer in the ability to handle and convert large amounts of power efficiently, compactly, and at high temperatures (~200°C) over the incumbent Si-based technologies. SiC and to a lesser extent GaN have both enjoyed some commercial successes in this space, but AlN appears to be a much more promising material according to the often-cited unipolar figures of merit. Having said this, AlN suffers from an acute challenge in attempting to realize power devices with low on-resistance, namely that doping the material is notoriously difficult. This difficulty appears to stem from a combination of both compensation by native acceptors and impurities, and additionally from the point that the incumbent n-type dopants, silicon, appears to form a DX-center some 150meV below the AlN conduction band edge. We will report on two novel schemes for realizing highly conductive n-type AlN; both involve the use of high growth rate, high chemical purity hydride vapor phase epitaxy. The first scheme involves the use of sulfur as the n-type dopant in accordance with recent first-principles calculations supporting the notion that S does not undergo a DX transition and additionally has high solubility, and the second involves a UV-assisted HVPE growth technique for control of the Fermi level, and therefore the DX transition, during growth.

9748-12, Session 3
Challenges and future perspectives in HVPE-GaN growth
Michal Bockowski, Institute of High Pressure Physics (Poland)
The use of GaN crystals grown by hydride vapor phase epitaxy as substrates for optoelectronic (laser diodes) and electronic (transistors) devices will be presented. After a brief review of development of the HVPE growth method, the state of the art of HVPE-GaN growth on 1-, 1.5- and 2-inch seeds will be demonstrated. Particular attention will be paid to the growth rate and its influence on the structural quality, homogeneity, and purity of the HVPE-GaN layers. Uniform and unique properties of GaN crystals grown on MOVPE-GaN/sapphire templates and ammonothermal GaN substrates will be shown and compared. New directions in the development of HVPE-GaN growth and future challenges and perspectives of HVPE technology will be presented and discussed. Methods of doping by donors (silicon or germanium) and acceptors (carbon or iron) will be demonstrated. Due to the high purity of HVPE-GaN, free carriers can be compensated at a very low level of doping. Thus, high-quality HVPE-GaN with a high resistivity should easily be obtained. On the other hand, high-quality n-type HVPE-GaN with the free carrier concentration of the order of 5x1018 cm-3 should also be crystallized. MOVPE and MBE growth of quantum nanostructures at high growth rate reached 12.4 μm/h at a growth temperature of 600 °C, and the rate was observed to decrease above this temperature. InN layers grown at 650 °C exhibited a sharp room temperature photoluminescence peak at 0.73 eV with a bulk electron concentration of 1.2 · 1018 cm-3. Therefore, this technique is important for the fabrication of high-quality bulk InxGa1-xN substrates with desired In solid compositions.

9748-69, Session 3
High-conductivity p-type layer with an alternating p-GaN/u-GaN structure
Hao-Tsung Chen, Yu-Feng Yao, Ching-Gan Tu, Chia-Ying Su, Chun-Han Lin, Chieh-Hsieh, Chih-Chung Yang, National Taiwan Univ. (Taiwan)
To increase the p-type conductivity of a light-emitting diode (LED) for improving the current spreading effect and reducing the required p-type layer thickness, we consider a structure of alternating p-GaN and u-GaN thin layers. A p-GaN layer is used for generating a high hole concentration. The high-concentration holes diffuse into the neighboring u-GaN layers for high-mobility migration. The combination of high-doping p-GaN layers and high-mobility u-GaN layers (due to their low impurity density) can lead to low overall resistivity of the alternating-layer structure. Based on the growths with molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD), we compare the characteristics of a p-type sample of a typical LED grown with MOCVD (sample A), a uniform Mg-doped layer grown with MBE (sample B), an alternating structure of 4.4/4 nm p-GaN/u-GaN grown with MBE (sample C), and another alternating structure of 2.5/2.5 nm p-GaN/u-GaN grown with MBE (sample D). From Hall measurements, we obtain hole concentrations of 0.24, 1.36, 3.4, and 1.8 x 1019 cm-3 up to 18 per cubic cm for samples A-D, respectively. The corresponding hole mobility values are 7.31, 3.0, 15.2, and 151 square cm per volt-sec and hence their resistivity levels are 3.54, 1.65, 0.12, and 0.023 Ohm-cm for samples A-D, respectively. We can see that by using the alternating structure, the p-type resistivity can be tremendously reduced.

9748-13, Session 4
Control of surface kinetics during the growth of III-nitrides on native substrates (Invited Paper)
Zlatko Sitar, Ramon Collazo, Isaac Bryan, Zachary Bryan, Anthony Rice, North Carolina State Univ. (United States)
INVITED: AlGaN alloys are the building blocks of deep UV optoelectronics and high-power devices. Metal polar, Al-rich AlGaN films were grown on both single crystalline AlN and sapphire substrates. The role of dislocation density on surface kinetics and morphology of these thin films will be presented. With the reduced dislocation density of the films grown on AlN substrates, atomically smooth bilayer stepped surfaces are achieved with RMS roughness of less than 50 pm. By controlling the surface supersaturation during MOCVD growth, a transition from 2D nucleation to step flow was achieved. Depending on growth conditions, a critical substrate misorientation angle for onset of step-bunching was observed. In order to predict and control the surface morphology, an all-inclusive surface kinetic framework was developed that connects vapor supersaturation, surface supersaturation, surface diffusion length, and substrate misorientation angle. In general, transitioning from a surface with 2D nucleation to one with bilayer steps required a decrease in supersaturation or an increase in miscut, whereas the suppression of step-bunching required the two parameters to change in the opposite direction. The composition of bilayer stepped AlGaN was found to strongly depend on substrate misorientation angle. Step-bunching resulted in compositional inhomogeneity as observed by photoluminescence and scanning transmission electron microscopy studies.

The talk will discuss MOCVD processes for control of AlGaN composition and heteroepitaxy, approaches to control strain, point defects, and doping in this material, and implications of this technology for further development of UV optoelectronic and electronic devices.
In-situ monitoring of InGaN growth by laser absorption and scattering method (Invited Paper)

Yoshio Honda, Tetsuya Yamamoto, Akira Tamura, Maki Kushimoto, Hiroshi Amano, Nagoya Univ. (Japan)

We investigated the surface morphology under varied TMI supply rate by 407 nm laser scattering. We also observed the 442 nm laser scattering of which light was partly absorbed by InGaN layer. InGaN growth was performed under 620–710 OC. The scattering of 407 nm laser was stable, so it means the surface morphology was smooth. For the 442 nm laser, the absorption was increased rapidly when the TMI was supplied. This is because that the surface state was change where the In layer was created at the surface. If we stopped the TMI supply, the decreasing of the 440 nm laser absorption still continued because the InGaN kept growing. We suggested that In layer did not evaporate so fast that the residual In at the surface continued to incorporate into the solid. The phenomenon was significant at low temperature. From these results, we found that the surface In should be controlled and our in-situ system is very useful to investigate the surface state of InGaN.

Fabrication of high-quality AlN on sapphire using high-temperature annealing technique (Invited Paper)

Hideto Miyake, Chia-Hung Lin, Kazumasa Hiramatsu, Mie Univ. (Japan)

AlN growth on a sapphire substrate is one of the most important issues in the realization of high-efficiency AlGaN UV devices. To prevent the generation of threading dislocations in the AlGaN epitaxial layer, the control of the AlN nucleation layer has been attempted. We focused on high-temperature annealing of AlN nucleation layer. Thin AlN films are formed by nitridation of sapphire surface.

In this work, we investigated re-crystallization of the AlN buffer layer with thickness of 100–300 nm on a sapphire substrate using high-temperature annealing technique by AFM and TEM observation and X-ray diffraction analysis. FWHMs of X-ray rocking curves for (0002) and (10-12) of the obtained AlN are less than 100 arcsec and 400 arcsec, respectively. We also performed growth of high-quality AlGaN on the AlN underlying layer, in order to fabricate deep UV light source.

Control of defects and compensation by MOVPE growth conditions in heavily n- and p-type doped GaN

Marc Hoffmann, Christoph Berger, Jonas Hennig, Andreas Lesnik, Otto-von-Guericke Univ. Magdeburg (Germany); Silvio Neugebauer, Otto-von-Guericke-Univ. Magdeburg (Germany); Ronny Kirste, Felix Kaess, Ramon Collazo, Zlatko Sitar, North Carolina State Univ. (United States); Armin Dadgar, Otto-von-Guericke-Univ. Magdeburg (Germany); André Strittmatter, Otto-von-Guericke Univ. Magdeburg (Germany)

Heavy n- and p-type doping during metalorganic vapor phase epitaxy (MOVPE) is discussed in detail with respect to compensation mechanisms. Particular MOVPE growth conditions, such as V/III-ratio and growth temperature, are studied for their combined impact on crystal quality as well as for incorporation of native and extrinsic point defects. Vacancy formation and impurities like carbon can be confirmed as limiting mechanisms for the conductivity in GaN. Since the formation energy of a point defect depends on its chemical potential, MOVPE growth conditions are identified which control the chemical potential of native defects. In the case of n-type doping of GaN with Ge, a self-compensation mechanism related to VGa can be found at doping concentrations exceeding 6E19 cm-3. Photoluminescence measurements reveal that at doping concentrations above 6E19 cm-3, an intense yellow luminescence at 2.2 eV is observed. In contrast, reduced compensation and high free carrier concentration of up to 2E20 cm-3 have been achieved in GaN:Ge by adjusting growth conditions such as growth temperature. In the case of p-type doping of GaN with Mg, typically a self-compensation of Mg by VN can be observed at doping concentrations exceeding 2E19 cm-3. Under such circumstances, the achievable free carrier concentration is limited to low 1E17 cm-3. Growth conditions, such as those determined by V/III-ratio are shown to increase the available hole concentration up to 1E18 cm-3 which is explained in terms of reduction of compensating defects.
Optical and Crystal Quality Improvement in Green Emitting InxGa1-xN Multi-Quantum Wells through Optimization of MOCVD Growth

Erkan A. Berkman, Soo Min Lee, Frank Ramos, Eric Tucker, Ronald A. Arif, Eric A. Armour, George D. Papasouliotis, Veeco Instruments Inc. (United States)

Developments in crystal growth and device fabrication technologies enabled new niche markets for LEDs, such as micro-LED displays, light-field mapping, adaptive lighting, horticultural lighting and biomedical optics. One major obstacle for commercialization in these markets is the “green gap” - lack of semiconductor materials with high internal quantum efficiency (IQE) emitting between 500-600nm. In this study, we report on the effect of metalorganic chemical vapor deposition (MOCVD) growth parameters, including quantum well growth rate, pressure, V/III ratio, gas velocity, and ambient gas composition, on optical/electrical emission properties, surface morphology and crystal quality of InxGa1-xN multi-quantum wells (MQW) emitting at 530nm. III-N growth was carried out in Veeco TurboDisk MaxBright™ MOCVD reactor on planar c-plane (0001) sapphire, miscut 0.2° towards the m-plane.

The optical properties of the MQW samples were studied by room temperature photoluminescence (PL) and power-dependent PL (PLE), while sub-micron scale emission properties were analyzed by cathodoluminescence (CL). Structural quality and morphology were evaluated by atomic force microscopy (AFM) and X-ray diffraction (XRD) techniques. Optimized MQW conditions at 100T pressure, 0.5nm/min growth rate with high V/III ratio displayed PL intensity improvement of more than 20% and AFM morphology of high quality 2D step-flow growth. It was observed that introduction of H2 during quantum barrier growth removed indium inclusions and improved PL emission intensity while increasing V-pit size. Detailed micron level CL analysis is also presented with emphasis on emission characteristics across bright and dark regions, and V-pits.

Quantum Well Intermixing and Radiation Effects in InGaN/GaN Multi Quantum Wells (Invited Paper)

Katharina Lorenz, M. C. Sequeira, A. Freitas, Marco B. Peres, Andrés Redondo-Cubero, L. C. Alves, Eduardo P. Alves, Instituto Superior Técnico (Portugal); M. P. Leitão, Joana Rodrigues, Nabiha Ben Sedrine, Maria R. Correia, Teresa Monteiro, Univ. de Aveiro (Portugal)

Compositional grading of InGaN/GaN multi quantum wells (MQW) was proposed to mitigate degradation effects and Auger losses in GaN-based light emitting diodes [1]. Quantum well intermixing (QWI) is successfully used in III-V arsenide and phosphide MQW to introduce such gradients with the possibility of monolithic lateral patterning [2]. Ion implantation followed by thermal annealing was also successfully applied for QWI in ZnO-based structures [3]. In III-nitride MQW, however, little is known on the effects of irradiation and annealing on structural and optical properties.

We will review our recent work on QWI in InGaN/GaN blue and green emitting MQW. Annealing up to 1400 °C resulted in negligible interdiffusion of QWs and barriers revealing a surprising thermal stability, well above the typical MOCVD growth temperatures [4]. The defect formation upon nitrogen implantation was studied in detail. Despite strong dynamic annealing effects which keep structural damage low, the created defects strongly quench the QW luminescence. Effective QWI could be achieved by swift heavy ion irradiation and first results will be presented. The effect of irradiation defects on QW properties and implications for their use in radiation environment will be critically discussed.

Investigation of mechanical wear rates in III-nitride materials

Guosong Zeng, Chee-Keong Tan, Brandon A. Krick, Nelson Tansu, Lehigh Univ. (United States)

The optoelectronic properties of gallium nitride have been well studied for decades. The progress in the understanding of GaN material has enabled the technological implementations in solid state lighting and lasers, thermoelectricity, and solar cells. However, in comparison with the more well-understood electronics and optoelectronic properties, there is a significant lacking on the understanding of the mechanical properties of the GaN material up to today. Specifically, the analysis on the mechanical wear characteristics of III-Nitride materials in different harsh environments is still lacking. Therefore, our research aims to explore the mechanical wear performance and mechanism of III-Nitride materials, as well as to identify the controlling factors resulting in the wearing in this material systems.

In this work, we employed our custom type microtribometer to generate wear scars on III-Nitride materials for the mechanical wear rates characterization. Different testing conditions have been set for determining the controlling factors on wear rate, such as crystal orientation effect, humidity effect, and alloy compositions. Several characterization techniques such as SEM/EDS, LEIS, and AFM were employed to understand the wear mechanism in III-Nitride systems. In addition, a simulation model was built to explain the crystal orientation dependency for the wear mechanism. Our results demonstrate that GaN material is an ultra-low wear material with its wear rate (~ 0.8-2 x 10?? mm?/(Nm)). The low wear rate in GaN accompanied with excellent electronics and optoelectronics properties opens up new application directions of the technologies.

Structural Properties of AlGaN-Layers for UV-Detectors Deposited on AIN/Sapphire-Templates and AIN-Substrates

Lutz Kirste, Susanne Kopta, Lars Hahn, Jannik Richter, Mario Prescher, Martin Walther, Oliver Ambacher, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

UV-photodetectors based on the semiconductor material aluminum gallium nitride (AlGaN) are particular suited for monitoring of ultraviolet radiation sources. Typically, AlGaN-detector structures are fabricated on sapphire substrates. Due to the large lattice mismatch, a high density of threading dislocations (TDDs) of ~10^9 cm?2 is present in AlGaN-layers grown on sapphire substrates. Therefore, freestanding AlN-substrates with low defect density and high UV-transparency are the substrate material of choice for the realization of AlGaN-based detectors with superior properties. Recently, AlN-substrates have become available by various manufacturers. The AlN-substrates differ considerably in the structural perfection, homogeneity and deep UV-transparency.

In this work we present a detailed analysis of the structural properties of AlGaN- heterostructures for UV-detectors deposited on AIN/sapphire (0001) templates and freestanding AIN (0001) substrates. The structural perfection of the AlN-substrates is investigated by X-ray topography and HRXRD. The UV-transparency of the AlN-substrates is analyzed by optical transmission measurements. All AlGaN-layers are grown by MOVPE. After growth HRXRD is used for measurement of the Al-concentration and mosaicity of the
device structures. We will show that the AlN-substrates contain a heterogeneous distribution of TDDs, basal plane dislocations and grain boundaries. The comparison of AlGaN-layers grown on AlN/sapphire-templates with layers grown on AlN-substrates clearly shows that a significantly improved material quality can be achieved on AlN-substrates.

9748-22, Session 5

Application of high-resolution dark-field electron holography for study of a composition distribution in blue and green (In,Ga)N LEDs

Maxim Korytov, Nikolay Cherkashin, Martin Hytch, Ctr. d'Elaboration de Matériaux et d'Etudes Structurales (France); Andrei F. Tsatsulinikov, Alexey V. Sakharov, Andrey Nikolaev, Wsevolod V. Lundin, Ioffe Physical-Technical Institute (Russian Federation); Philippe De Mierry, Lars Kappee, Jesús Zúñiga-Pérez, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France); Matthias Auf der Maur, Aldo Di Carlo, Univ. degli Studi di Roma "Tor Vergata" (Italy)

Transmission electron microscopy (TEM) is a well-established tool to measure a composition distribution in III-nitride ternary alloys. Among different techniques high-resolution TEM (HRTEM) is the most commonly used, since it combines a good precision with a sub-nanometre spatial resolution. We report recent developments of the dark-field electron holography (DFEH), which allowed a twofold improvement of the measurement precision, as compared to HRTEM, while keeping a 0.6 nm resolution. Besides, the DFEH is less affected by the sample drift, defocus or extinction length difference, so it does not contain any artefacts. The DFEH is used to study composition profiles of (In,Ga)N/GaN quantum wells (QWs) as dependent on the growth conditions. We found that in the case of metalorganic vapour phase epitaxy a surface segregation of indium results in an unintentional penetration of 1-7% of In into the GaN barrier over a distance of few nanometers. The magnitude of this effect is changing with the growth temperature. The same effect takes place if In flow is enabled ahead of the Ga flow, which results in formation of a metal In coverage prior to the (In,Ga)N QW growth. The latter approach allows to achieve In concentrations up to 30%, but produces a composition gradient in the growth direction due to a delayed In incorporation. We also make an accurate quantitative comparison of the In incorporation in polar and semi-polar (11-22) QW realised in identical growth conditions. The obtained indium composition profiles are used to calculate the electroluminescent properties of the studied LEDs.

9748-23, Session 6

Multimode mapping of III-nitrides in the scanning electron microscope (Invited Paper)

Robert Martin, Univ. of Strathclyde (United Kingdom)

The scanning electron microscope (SEM) provides an excellent platform for investigating wide bandgap semiconductors with high spatial resolution. This presentation describes sub-micron scale mapping of the structural, optical and electrical properties of III-nitride structures and devices using a combination of X-ray microanalysis, cathodoluminescence (CL), electron beam induced current (EBIC), and electron channeling contrast imaging (ECCI). This combination provides structural information on a nm scale together with optical information on length scales down to 10s of nm and at wavelengths down to 200nm (beyond the band-gap of AlN). This presentation will describe the study of AlGaN multilayers, InGaN/GaN nanorods and III-nitride LEDs using combinations of these techniques, i.e. multimode SEM mapping. A range of examples will be discussed, including series of InGaN/GaN LEDs with variations in the quantum well and barrier regions, AlGaN-based heterostructures, arrays of core-shell nanorods and direct visualization and identification of the density, distribution and type of threading dislocations in eplayers. Optical information from CL, supplemented by spatially-resolved electroluminescence (EL), will be considered alongside conductivity data from EBIC and structural information from ECCI. The data highlight various influences of point defects and threading dislocations on the performance of devices.

9748-24, Session 6

New Advances in GaN Photonics (Invited Paper)

Jung Han, Yale Univ. (United States)

The utilization of GaN in photonics devices and structures, which seek to manipulate photonic density of states (DOS) and optical propagation problems, through linear and nonlinear interactions, has received much less attention. While traditional on-chip semiconductor photonics tend to focus on near-infrared telecommunication wavelengths, the use of GaN as a photonic material could open up important links to visible and ultraviolet applications. Having relatively strong piezoelectric and electrooptic coefficients, GaN could be unique in facilitating photonic signal processing in the short wavelengths. The purpose of this talk is to review the effort in making III-N resonators in one, two, and three dimensions, as well as the implementation of waveguide-based photonic devices. The main challenges in the fabrication of GaN photonic devices are a lack of low-index materials that can be integrated monolithically to encase the III-N active region, and a lack of suitable wet etchants to create photonic structures. With the use of a novel electrochemical (EC) anodic process, we demonstrated the etching and porosifying GaN in a very flexible way. The EC process provides a much increased tunability in index profiles and makes it possible for manufacturable on-chip GaN photonic devices. Structures such as free-standing membranes and one-dimensional distributed Bragg reflectors can be made with very high controllability.

9748-25, Session 6

Comparison of high indium content InGaN quantum wells grown on c and (20-21) planes by means of time resolved photoluminescence with applied bias

Lucja Marona, Institute of High Pressure Physics (Poland); Michał Baranowski, Wrocław Univ. of Technology (Poland); Dario Schiavon, TopGaN Ltd. (Poland); Piotr Perlin, Tadek Suski, Institute of High Pressure Physics (Poland)

High indium content quantum wells are extremely needed for long wavelength light emitting devices. However due to complex nature of nitrides heterostructures, the realization of such devices poses substantial problems and their optical properties are difficult to control. There are two main reasons for such behavior: the presence of high electric fields and large indium composition fluctuations. These effects leads to the reduction of radiative recombination probability due to Quantum Confined Stark Effect and to the emission peak broadening and optical gain dilution caused by in fluctuations. To avoid the influences of the internal electric field, epitaxial structures can be grown on different plane than the c-plane of GaN.

Depending on the choice of the growth plane, we can decrease or eliminate completely the electric field. But even then, the issue of the indium fluctuations still remains challenging. In this work we try to distinguish between two mentioned effects, electric field and composition fluctuation.
To achieve this goal we manipulate the electric field in the quantum structure either by changing the growth plane orientation (c-plane, (20-21) semipolar plane) or directly applying the external voltage to the structures. For all these cases we perform time resolve photoluminescence measurements. Surprisingly there is no effect of the applied bias on the recombination life times for the polar structure. These results strongly suggest that indium fluctuations play the main role in radiative recombination in high indium content QWs. In this work we also compare and discuss the dispersions of the recombination lifetimes of polar and semipolar structures.

9748-27, Session 6

Analysis of radiative and non-radiative lifetimes in GaN using accurate internal-quantum-efficiency values estimated by simultaneous photoluminescence and photo-acoustic measurements

Kouhei Kawakami, Takashi Nakano, Atsushi A. Yamaguchi, Kanazawa Institute of Technology (Japan)

High-power nitride-based LEDs suffer from the efficiency droop, and the understanding of recombination mechanism can be clue to solve the problem. Radiative and non-radiative lifetimes are usually estimated from time-resolved and temperature-dependent photoluminescence (PL) measurements by assuming that internal quantum efficiency (IQE) at cryogenic temperature is unity. The assumption is, however, not necessarily valid. Recently, we measured the IQE absolute values for GaN samples with different qualities by newly-developed simultaneous measurements of PL and photo-acoustic (PA) signals, and found that IQE values are much less than unity for low-quality samples even at extremely low temperature. That means the conventional method to estimate the radiative and non-radiative lifetimes cannot give accurate values. In this study, we have developed a new method to estimate accurate radiative and non-radiative lifetimes, and have demonstratively measured the temperature dependence of the lifetimes in various GaN samples with different qualities. Although the time-resolved and temperature-dependent PL measurements are also performed in our method, we utilize the reliable IQE values estimated by the simultaneous PL/PA measurements in the analysis, instead of the doubtful assumption. It is found, from the analysis results, that radiative lifetime in GaN increases almost linearly with temperature, and that non-radiative lifetime shows little temperature dependence although the non-radiative lifetime itself largely depends on sample quality. Therefore, it is considered that the decrease in luminous efficiency with temperature in GaN, is not caused by the enhancement of non-radiative recombination rate, but caused by the reduction of radiative recombination rate.

9748-28, Session 7

Direct microscopic correlation of optical and structural properties of individual GaN/AlN quantum dots formed at threading dislocations using nanoscale cathodoluminescence (Invited Paper)

Frank Bertram, Gordon Schmidt, Otto-von-Guericke-Universität Magdeburg (Germany); Christoph Berger, Otto-von-Guericke-Universität Magdeburg (Germany); Peter Veit, Otto-von-Guericke-Universität Magdeburg (Germany); Gordon Callesen, Stefan Kalinowski, Technische Universität Berlin (Germany); Armin Dadgar, Otto-von-Guericke-Universität Magdeburg (Germany); Axel Hoffmann, Technische Universität Berlin (Germany); André Strittmatter, Otto-von-Guericke-Universität Magdeburg (Germany); Jürgen H. Christen, Otto-von-Guericke-Universität Magdeburg (Germany)

We give direct evidence of single photon emission from GaN quantum dots (QDs) nucleated in close proximity to threading dislocations (TDs) using cathodoluminescence spectroscopy performed in a scanning transmission electron microscope (STEM-CL) at 15 K. These QDs result from GaN layer growth by MOVPE on AlN/sapphire templates. After deposition of few monolayers of GaN forming initially a two-dimensional layer a growth interruption without ammonia supply led to QD formation. Cross-section STEM clearly resolves the AlN/sapphire template and the two-dimensional GaN (2D-GaN) layer. Originating from the AlN/sapphire interface vertically running TDs show up in the STEM images. In dislocation free regions, the 2D-GaN layer with 1-2 monolayer thickness is observed. In regions of high TD density small islands of GaN with twice the 2D-GaN thickness are formed with lateral extensions up to about 100 nm. By comparison of the STEM images with the simultaneously recorded panchromatic CL mappings at 15 K the highest intensity is clearly asserted to these islands and are attributed to emission from GaN quantum dots. The QD emission is observed in a spectral range between 220 nm to 310 nm exhibiting the brightest emission intensity despite threading dislocations in their immediate neighborhood.

Ultra narrow emission line widths down to 440 eV of individual QDs are measured by photoluminescence experiments. Single photon emission of the QD luminescence is verified through photon anti-bunching by Hanbury Brown-Twiss photoluminescence experiments at 8 K yielding a value of g(2)(0) = 0.42.

9748-29, Session 7

Approaches to highly efficient UV emitters based on AlGaN quantum wells (Invited Paper)

Shuhei Ichikawa, Mitsuru Funato, Yoichi Kawakami, Kyoto University (Japan)

Deep ultraviolet light emitters based on AlGaN quantum wells (QWs) have very low efficiencies with respect to the InGaN-based light sources in the blue-region. The internal quantum efficiencies (IQE) of AlGaN QWs are especially degraded under weak excitation conditions and at shorter wavelengths. In order to improve the IQE, it is important to achieve high radiative recombination probabilities and to reduce nonradiative recombination centers (NRCs) like crystal defects. AlGaN QWs are generally fabricated on the polar (0001) and inevitably suffer from large spontaneous and piezoelectric polarization fields. These polarization fields induce electric fields in the QWs, which drastically decrease the radiative recombination probabilities. Then, we fabricated high-quality AlGaNAIN QWs on semipolar (1-102), (11-22), and (20-21) AlN bulk substrates using the optimized MOVPE conditions for the semipolar plane growths. They have atomically smooth surfaces and very abrupt QW interfaces. The estimated internal electric fields are less than one third of that in the conventional (0001) QW. As a result, the semipolar QW emissions are 75 times stronger than the (0001) QW emissions.

To further improve the IQE, we investigated dominant NRCs in AlGaN related structures using cathodoluminescence mapping and found that the contrasts of dark spots originating from threading dislocations (TDs) drastically decrease when we increase the temperature to 293 K. This result indicates that point defects more predominantly act as NRCs than TDs at room temperature in current Al-rich AlGaN and AlN crystals. In this presentation, detailed recombination dynamics and optical properties in polar and semipolar QWs will be presented.
Room-temperature ballistic transport in III-Nitride semiconductors (Invited Paper)
Elison Matioli, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

In this talk, we present and discuss the experimental observation of ballistic transport of electrons, even at room temperature, in III-Nitride semiconductors. Ballistic transport has been largely investigated at low temperatures in low band-gap III/V materials due to their high electron mobilities. However, their application to room-temperature ballistic devices is limited by their low optical phonon energies, close to KT at 300 K. In addition, the short electron mean-free-path at room-temperature requires nanoscale devices for which surface effects are a limitation in these materials.

We explore the unique properties of wide band-gap III-Nitride semiconductors to demonstrate room-temperature ballistic devices. We propose theoretical models to corroborate experimentally their optical phonon energy of 92 meV, which is 4x-larger than in other III/V semiconductors. This allows room-temperature ballistic devices operating at larger voltages and currents. In addition, the short carrier depletion at device sidewalls of III-Nitrides allows top-down nanofabrication of very narrow ballistic devices. We also present an additional model to determine experimentally the characteristic dimension for ballistic transport in this material. These results open a wealth of new systems and basic transport studies possible at room temperature.

Influence of vacancies on GaN/AlN interface characteristics
Yahor V. Lebiadok, Tatyana V. Bezuyzchnaya, Dzmitri M. Kabanau, Gennady I. Ryabtsev, B.I. Stepanov Institute of Physics (Belarus); Konstantin S. Zhuravlev, Rzhavan Institute of Semiconductor Physics (Russian Federation)

The influence of gallium, nitrogen and aluminum vacancies on GaN/AlN heterointerface characteristics was calculated. The DFT calculations with the hybrid functionals B3LYP with Hay-Wadt effective core potentials for all the heavy atoms in a combination with Hay-Wadt valence basis were used and realized in GAMESS program [1].

It was ascertain that the presence in the interface of nitrogen vacancy for cluster with 40% and more atom mixing facilitates the mixing of atoms in the GaN/AlN interface. As it was ascertained in [2], the isolated N vacancies are formed in the GaN compounds under electron beam irradiation. So, the irradiation of GaN/AlN interface facilitates gallium and aluminum atoms mixing. The influence of Ga and Al vacancies on GaN/AlN interface characteristics is discussed in the report also.


Band gap narrowing with dilute-anion GaN materials for visible emission
Chee-Keong Tan, Damir Borovac, Nelson Tansu, Lehigh Univ. (United States)

The development of InGaN semiconductor alloy as the high efficiency active region for the solid state technology has been hindered by the low material quality issue at high In-content, especially for red emission. Realizing a high In-content InGaN material for long wavelength emission has remained as a fundamental challenge due to the phase separation issue in the alloy. Recent studies revealed the potential of using dilute-As GaNAs alloy as the alternative candidate to achieve emission in visible spectral regime. In addition, recent work identified the dilute-As GaNAs alloy as the material to suppress the long-standing Auger recombination issue in nitride-based devices. Thus, exploring for alternative GaN-based materials to overcome the usage of high In-content is critical in realizing the high efficiency visible light emitters.

In this work we present the analysis of dilute-anion GaN-based materials involving the incorporation of different group-V species (P, As, Sb and Bi) into the GaN alloy. The optoelectronic properties of the GaN-based materials with dilute anion-content will be discussed. The electronic properties of the dilute-anion GaN-based ternary alloys are analyzed as follow: (a) band gap energy, (b) carrier effective masses and (c) split-off energy. Our findings reveal varying band gap narrowing effects with the incorporation of different anion in the GaN material, in which the incorporation of 1% Bi-content resulted in most significant band gap reduction. In addition, the absorption spectrums and dielectric functions of the dilute-anion GaN-based alloys are significantly modified with the varying impurity-content. The comparison between the dilute-anion GaN-based alloys will be discussed.

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circuits. To further develop the GaN-based digital integrated circuits, the monolithic inverters integrated with the enhancement-mode/depletion-mode (E/D-mode) AlGaN/GaN MOSHEMTs were investigated. Using the photoelectrochemical (PEC) method and the surface treatment to form the gate-recessed structure, the gate-recessed D-mode MOSHEMTs were fabricated. Furthermore, the ferroelectric LiNbO3 (LNO) gate oxide layer and the PEC-recessed structure were simultaneously utilized to fabricate the E-mode AlGaN/GaN MOSHEMTs. Among the ferroelectric materials, the high dielectric constant LNO film with the larger spontaneous polarization of 80 \( \text{C/cm}^2 \), the wider bandgap of 3.9 eV, and the lower interface state density on the GaN-based semiconductor was beneficial not only for modulating the two-dimensional electron gas (2DEG) channel but also for reducing the gate leakage. Besides, using the PEC-recessed structure could improve the transconductance of the E-mode MOSHEMTs and adjust the operation current of the D-mode MOSHEMTs without destroying the etched AlGaN surface. The inverter was built using monolithic integration of the D-mode MOSHEMTs and the E-mode MOSHEMTs. Instead of the typical tuning gate area size method, the PEC etching method was used to adjust the current ratio (\(?\)) of the E/D-mode MOSHEMTs with keeping the matched gate area size to minimize the area of the inverters. From the voltage transfer curve of the inverters, the corresponded VOUT was equated to \( V_{\text{IN}} = V_{\text{DD}}/2 = 2.5 \text{ V} \), and the output swing was about 4.9 Vp-p, when the input signal was 5 Vp-p. It revealed that the resulting AlGaN/GaN MOSHEMT inverter with the \(?\) of 25 could be operated as a high performance unskewed inverter.

9748-35, Session 8

Power conversion with Gallium Nitride devices (Invited Paper)

Srabanti Chowdhury, Arizona State Univ. (United States)

Recent studies in power conversion indicate that power converters designed with high efficiency GaN-based system architectures, eliminating or reducing losses at all levels and potentially leading to lower cost. Enabled by the growth of GaN on Si and availability of bulk GaN substrates (with defect densities lower that 104cm-2), lateral and vertical geometry devices are perfectly positioned to address a large spectrum of power electronic application with increased power density. 600V lateral HEMTs, where the gate to drain distance absorbs the off-state high voltage, can switch 1.5 times higher operating currents and at least 10 times faster than the state-of-the art Si-based devices without compromising the efficiency of the converter. This allows designing the full converter to operate at high frequencies, which reduces the size of the passive components thereby reducing the form-factor. The ability to operate at higher temperature allows smaller heat sinks further reducing the form-factor of the converter. A 40% reduction in volume of a PV inverter was realized by Yaskawa, switching from Si switches to GaN, due to reduction in size of the output filter and the heat sink.

Higher power (10KW-1MW) application requires vertical GaN devices. The better economy of using bulk GaN material to hold the off-state voltage, which when added to the reliable results that has been steadily seen in vertical geometry Lasers and LEDs, create a very encouraging picture for bulk GaN power devices. Lateral together with Vertical GaN devices offer a disruptive roadmap for power converters.

9748-36, Session 8

High Breakdown Voltage AlGaN/GaN HEMTs by Fluorine Plasma Treatment

Ray-Hua Horng, Chih-Tung Yeh, Yi-Siang Shen, National Chung Hsing Univ. (Taiwan)

This report presents the development of fabricating high voltage enhancement mode (E-mode) AlGaN/GaN high electron mobility transistors (HEMTs) by fluorine plasma treatment on Silicon wafer. In our work, we successfully shift the threshold voltage (Vth) from -8 V in a conventional depletion mode (D-mode) GaN-on-Silicon HEMTs to 2.3 V in an E-mode GaN-on-silicon HEMTs. According to the observation by Transmission electron microscopy, the surface of epitaxial layer is not have etched phenomena. In addition, the fluorine ion is indeed doped into semiconductor which confirm by secondary ion mass spectrometer (SIMS). The fabrication of E-mode AlGaN/GaN MIS-HEMT with 3 \( \mu \text{m} \) gate and 2 side field plates that were 1 \( \mu \text{m} \) and 3 \( \mu \text{m} \), respectively. The device exhibit a maximum drain saturation current of 210 mA/mm at \( V_{\text{GS}} = 10 \text{ V} \), a peak gm of 44.1 mS/mm. Furthermore, low off-state gate leakage current of 10-6 mA/mm, ION/IOFF ratio is about 108 and high breakdown voltage of 1480 V was also demonstrated.

9748-37, Session 8

Investigation of the channel mobility in vertical and lateral normally-off GaN MOSFETs using Monte-Carlo methods

Sara Shishehchi, Hanqing Wen, Enrico Bellotti, Boston Univ. (United States)

Nitride material systems are of great interest in the new generation power electronic devices, compared to the conventional Si devices, due to their wide bandgap, superior electron mobility and large critical electric field. Furthermore, GaN devices offer high blocking voltage and efficient heat dissipation. Among the various GaN-based device architectures that have been explored and reported in the literature, such as MOSFETs and HFETs, GaN MOSFETs have much lower leakage current due to the presence of the oxide layer. Moreover, certain designs have the ability to achieve positive threshold voltages that make them more favorable and reliable in high power switching applications compared to the normally-on devices. Vertical channel normally-off GaN MOSFETs offer a number of advantages compared to their lateral counterparts. In this work, we present both vertical and lateral normally-off GaN MOSFETs and using an advanced particle-based Monte-Carlo approach we evaluate the mobility of electrons within the two dimensional electron gas in the channel area of the MOSFETs. Channel mobility is one of the key parameters in understanding the performance of power devices and more specifically, the dynamic on resistance. Within the Monte-Carlo method, besides the common carrier scattering mechanisms, the carrier-interface and surface-roughness scatterings are also considered which in addition to the mobility studies, provide valuable insights into the GaN-oxide interface properties.

9748-38, Session 8

A study of GaN-based semiconductor devices using 3D self-consistent Monte-Carlo approach incorporating quantization effects

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Due to the superior opto-electronic properties of GaN, such as high electron mobility, large band gap energy and high thermal conductivity, GaN-based semiconductor devices have been widely employed in the blue light-emitting diode and high performance power switches. A key feature of the GaN-based material system that enables those advantageous material properties is the 2D electron gas (2DEG) formed in the device channels. Consequently, understanding the carrier scattering mechanisms in the channel is of crucial importance to the design of novel GaN-based devices. However, due to the quantum-mechanical nature of the 2DEG, the classical drift-diffusion model cannot describe the carrier transport in the channel area. Hence, and a model that fully appreciates the spatial confinement feature of 2DEG is therefore highly desirable.

In this work, a self-consistent 2D Schrodinger-Poisson solver is developed to accommodate the carrier energy quantization in the channel region of the devices whereas the usual continuum model is used in the bulk...
material region to reduce the overall computation load. The resulting charge distribution information together with the carrier scattering rate calculated from Green's function theory is then fed into the 3D Monte Carlo program to solve the Boltzmann transport equation, from which the total current in the channel at different electric field can be obtained. In particular, GaN-based HFET power switches will be investigated as an example, where the blocking voltage, specific on-resistance as a function of doping, device geometry and crystal orientation will be studied.

9748-39, Session 9
Progress of GaN/AlGaN THz-quantum cascade lasers (Invited Paper)
Hideki Hirayama, Wataru Terashima, RIKEN (Japan)
Quantum cascade lasers (QCLs) are promising as practical terahertz (THz) laser sources, because they have a lot of advantages such as compact, continuous-wave operation, narrow line-width, high-power, high-efficiency, maintenance-free, and low-cost. III-nitride semiconductors are material having a potential for realizing wide frequency range of QCL including unexplored frequency from 5 to 12 THz, as well as realizing room temperature operation of THz-QCL. We demonstrated lasing of GaN/AlGaN THz-QCLs by introducing an unique quantum cascade structure whose active region is consisting of 2 quantum wells (QWs) per one period. We grew GaN/AlGaN QC structures by using molecular beam epitaxy (MBE) in order to obtain a precise control of the QC layer thickness, as well as, 1-nm layer accuracy sharp hetero-interfaces. The layer structure of the GaN/AlGaN THz-QCL was consisting of a 100-200 periods of QC active layers sandwiched by Si-doped GaN upper contact layer and Si-doped AlGaN lower contact layer, which were grown on a high-quality AlGaN/AIN template grown on a c-plane sapphire substrate by metal organic chemical vapor deposition (MOCVD). Lasing spectrum was obtained at 3.59 THz measured under pulsed current injection at 5.8 K. The threshold current density Jth and the threshold voltage Vth of this sample were 1.75 kA/cm2 and 14.5 V, respectively. We also fabricated similar design GaN/AlGaN QCL by using MOCVD and obtained lasing at 6.97 THz measured at 5.2 K. We recently obtained a maximum operating temperature of 40 K.

9748-40, Session 9
Development for Ultraviolet Vertical Cavity Surface Emitting Lasers
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In the past few years, research work has been carried out on the development of III-nitride based vertical-cavity surface-emitting lasers (VCSELs) for various applications, including high-speed printing and atomic clock applications. Laser operation of GaN-based VCSELs under electrical-injection has been reported by several research teams; however, all the reported electrically pumped III-N VCSELs have peak emission wavelengths in the visible blue-green spectral range. The development for ultraviolet (UV) VCSELs has been impeded due to limitations of electrical conductivity for high aluminium content AlxGa1-xN, lack of high reflectivity in the UV for III-nitride distributed Bragg reflectors (DBRs), and relatively high sub-bandgap absorption from p-type materials. Even for electrical-injection edge-emitting Fabry-Perot III-N laser diodes, the shortest wavelength reported to date is limited to 336 nm.

In this work, we report our current development progress for UV VCSELs targeting a peak emission wavelength of 369.5 nm for atomic clock applications. An electrically conducting n-DBR was demonstrated which consists of 40-pairs of Si-doped quarter-wavelength layers of Al0.12Ga0.88N and GaN. A peak reflectivity of 91.6% at 368 nm was measured and a series resistance of 17.772 near the maximum measured current density of 3.5kA/cm2 was extracted from the current-voltage characteristics. Furthermore, a micro-cavity light emitting diode with 2? cavity was demonstrated. A peak wavelength of 371 nm was observed while the Q-factor was determined as ~ 70. Further discussion on the material growth, material characterization, optically pumped lasers, as well as numerical simulation for structural design and laser properties will be presented in the conference.

9748-41, Session 9
MOVPE growth of p-AlGaN super-lattices for UV-C lasers
Christian Kuhn, Martin Martens, Frank Mehneke, Tino Simonetz, Felix Krueger, Technische Univ. Berlin (Germany); Arne Knauer, Viola Kueller, Mickael Lapeyrade, Sven Einfeldt, Ferdinand-Braun-Institut (Germany); Tim Wernicke, Technische Univ. Berlin (Germany); Markus Weyers, Ferdinand-Braun-Institut (Germany); Michael Kneissl, Technische Univ. Berlin (Germany) and Ferdinand-Braun-Institut (Germany)
AlGaN based laser diodes would be superior in size, robustness, costs and energy efficiency compared to conventional UV laser sources.

In this paper we investigate the p-doping of AlGaN waveguide and cladding layers to achieve current injection and wave guiding in a 270 nm laser diode. Super-lattices (SL) promise an increased conductivity compared to a single thick AlGaN:Mg layer. SLs with varying average aluminum content between x= 0.37 and 0.81 were grown by MOVPE and absorption, strain and conductivity were investigated. The SLs show sharp absorption edges at wavelengths between 300 nm and 230 nm. The SLs with average aluminum content above x= 0.6 have no band-to-band absorption at the target emission wavelength. However, to achieve optical mode confinement, the refractive index in the p-cladding must be lower, i.e. the aluminum content higher compared to the Al0.7Ga0.3N waveguide layer. This is only achieved for SLs with x= 0.81.

UV-C laser diode heterostructures emitting near 270 nm were grown to investigate the influence of the aluminum content in the p-SLs on the current injection. Reciprocal space maps of asymmetric X-ray reflections show that all layers are pseudomorphically strained to the AlN buffer including the p-SLs and therefore no occurrence of relaxation or defect generation is observed. The operation voltage of broad area laser structures increases with the aluminum content from 18 V (at 20 mA) for x= 0.37 to 25 V for x= 0.81. For x= 0.81 pulsed currents with a density of up to 4.7 kA/cm2 could be injected without device failure.

9748-42, Session 10
Continuous wave operation of high power GaN-based blue vertical-cavity surface-emitting lasers using epitaxial lateral overgrowth (Invited Paper)
Tatsushi Hamaguchi, Noriyuki Fuutagawa, Shouichiro Izumi, Masahiro Murayama, Hironobu Narui, Sony Corp. (Japan)
We have succeeded in achieving continuous-wave operation of gallium nitride(GaN) based vertical-cavity surface-emitting lasers(VCSELs) which was fabricated by epitaxial lateral overgrowth using dielectric distributed Bragg reflectors(DBRs) as masks for selective growth. The wavelength was 453.9nm and degree of polarization was more than 99%.above threshold current. The maximum output power was 11 mW, which is the highest value among reported GaN-VCSELs.

The device proposed in the present study was fabricated by the following
process. First, DBR islands consisting of 14.5 SiN/SiO2 bilayers were deposited on an n-GaN substrate. Seed crystals of n-type GaN were grown by MOCVD in the regions between the DBR islands where the GaN substrate was exposed. As MOCVD proceeded, the seed crystals grew in size, engulfing the DBR islands and finally forming planar surfaces roughly 4 ?m above them. Structures including quantum wells, p-type GaN, dielectric DBR and other materials like electrodes are fabricated over the planar surface. The first GaN-VCSEL had DBR grown by MOCVD[Appl. Phys. Lett., 92, 141102, 2008], which could suffer from cracks in the DBR. Another Report[Appl. Phys. Exp., 1, 121102, 2008] shown a GaN-VCSEL where crack-free dielectric DBRs were deposited on either side of a thinned substrate, but it requires precise control of polishing for thinning the substrate to a few microns. In the proposed VCSEL, two crack-free dielectric DBRs could be easily formed in the correct positions without the need for delicate processes such as polishing the substrate to a thickness of a few microns, which offers large advantages for mass productivity.

9748-43, Session 10
Optical-loss suppressed InGaN laser diodes using undoped thick waveguide structure (Invited Paper)
Masao Kawaguchi, Osamu Imafuji, Shinichiro Nozaki, Hiroyuki Hagino, Shinichi Takigawa, Takuma Katayama, Tsuyoshi Tanaka, Panasonic Corp. (Japan)

High-power InGaN-lasers have received great attentions as potential light-sources of various applications. The optical-internal-loss in a laser cavity is a major factor of the radiating power limitation because it reduces the slope efficiency of lasers. The reported internal losses of InGaN lasers still remain around 10cm-1 while those of the InGaAs lasers reach 1cm-1, because conventional loss reduction method of diluting the p-type impurity causes severe tradeoff between the loss and the operating-voltage in wide-bandgap InGaN lasers.

Here we propose optical-loss suppressed thickened waveguide InGaN lasers without drawback in the operating-voltage. The thickened waveguide enables to confine major part of the propagating light into the transparent undoped region, and thus significantly reduces the optical -loss. An electron-overflow-suppression (EOS) layer placed on the waveguide plays an important role to reduce the operating voltage after introduction of the undoped thick waveguide layer. We executed a self-consisted calculation of the voltage-current characteristic taking into account Schrödinger and Poisson equations in conjunction with a carrier continuity equation. The calculation result indicates possible presence of conductivity-modulation in the waveguide filled with electrons reflected from backward of the EOS layer and holes injected from the p-type cladding layer.

We successfully demonstrated the optical-loss suppressed operation of 1cm-1 by using a thickened waveguide with a thickness of 1.3um while the loss of the conventional waveguide with a thickness of 0.3um is 7cm-1. It is noted that the operating voltages of these lasers made little difference thanks to the EOS layer on the waveguide layer as predicted by the calculation.

The presented result suggests that our thickened waveguide structure can overcome the optical-loss drawback of the InGaN lasers, and hence will lead them to the applications requiring high wattage light sources.

9748-44, Session 10
AlGaN/InN laser diode technology for systems applications
Stephen P. Najda, Piotr Perlin, Tadek Suski, Lucja Marona, Michal Bockowski, TopGaN Ltd. (Poland); Przemek Wisniewski, TopGaN Ltd. (Poland); Robert Czernecki, Robert Kucharski, Ammono S.A. (Poland); Grzegorz Targowski, TopGaN Ltd. (Poland); Scott Watson, Anthony E. Kelly, Univ. of Glasgow (United Kingdom)

The latest advances in AlGaN/InN laser diode technology are reviewed for various system applications including display, defence, automotive, and communications. The AlGaN/InN material system allows for laser diodes to be fabricated over a very wide range of wavelengths from u.v. - 380nm, to the visible - 350nm, by tuning the indium content of the laser GaInN quantum well. Ridge waveguide laser diode structures are fabricated to achieve single mode operation with optical powers of >100mW with high reliability. Visible light communications at high frequency (up to 2.5 Gbit/s) using a directly modulated 422nm Gallium-nitride (GaN) blue laser diode with single longitudinal mode operation is reported in free-space and underwater. In addition, plastic optical fibre (POF) communication at 4GHz is also reported for GaN laser diodes.

High power operation of AlGaNInN laser diodes is also reviewed. Low defectivity and highly uniform GaN substrates allow arrays and bars of nitride lasers to be fabricated. We demonstrate the operation of laser bars with up to 20 emitters at optical powers up to 4W cw at ~395nm with a common contact configuration. An alternative package configuration for AlGaNInN 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.

9748-45, Session 10
InGaN/GaN DFB laser diodes at 434 nm with deeply etched sidewall gratings
Thomas J. Slight, Compound Semiconductor Technologies Global Ltd. (United Kingdom); Opeoluwa Odedina, Univ. of Glasgow (United Kingdom); Wyn Meredith, Compound Semiconductor Technologies Global Ltd. (United Kingdom); Kevin E. Docherty, Kelvin Nanotechnology Ltd. (United Kingdom); Anthony E. Kelly, Univ. of Glasgow (United Kingdom)

We report on deeply etched sidewall grating DFB lasers in the InGaN/ GaN material system emitting at a single wavelength around 434 nm. GaN lasers have a wide range of applications in communications, displays and storage. The availability of a single wavelength device with a good side mode suppression ratio (SMSR) would allow further applications to be addressed such as sources for laser cooling and Fraunhofer line operation for solar background free communications. Sidewall etched gratings have the advantage of fabrication with no need for overgrowth and have been demonstrated in a range of other material systems and wavelengths. Importantly for GaN based devices, this design has the potential to minimise fabrication induced damage to the epi structure.

We investigated two laser designs, one with 80 % duty-cycle 3rd order gratings and another with 39th order partial gratings. Simulation of the 2D waveguide sections was carried out to find the optimal grating width. For fabrication, the laser ridge and gratings were patterned in a single step using electron beam lithography and ICP etched to a depth of 500 nm. Contact metal was deposited and the sample thinned and cleaved into 1 mm long cavities. The as-cleaved 3rd order lasers emit in the pulsed regime with a SMSR of 22 dB and a peak single-mode output power of 40 mW. The output power is similar to that of parallel processed FP lasers. The 39th order lasers also exhibit narrow spectral width at an output power of 10 mW.

9748-46, Session 10
Comparison of nonpolar III-nitride vertical-cavity surface-emitting lasers with tunnel junction and ITO intracavity contacts
John T. Leonard, Erin C. Young, Ben P. Yonkee, Daniel A. Cohen, Univ. of California, Santa Barbara (United States);
We report on the first III-nitride vertical-cavity surface-emitting laser (VCSEL) with a III-nitride tunnel junction (TJ) intracavity contact. The violet nonpolar VCSEL employing the TJ is compared to an equivalent VCSEL with a tin-doped indium oxide ITO intracavity contact. The TJ VCSEL shows a threshold current density (Jth) of ~3.5 kA/cm², compared to the ITO VCSEL Jth of ~8 kA/cm². The differential efficiency of the TJ VCSEL is also observed to be significantly higher than that of the ITO VCSEL, reaching a peak power of ~550 µW, compared to ~80 µW for the ITO VCSEL. Both VCSELS display filamentary lasing in the current aperture, which we believe to be predominantly a result of local variations in contact resistance and current spreading, which may induce local variations in refractive index and free carrier absorption. Beyond the analyses of the lasing characteristics, we discuss the molecular-beam epitaxy (MBE) regrowth of the TJ, as well as its unexpected performance based on band-diagram simulations. Furthermore, we investigate the intrinsic advantages of using a TJ intracavity contact in a VCSEL using a 1D mode profile analysis to approximate the threshold modal gain and general loss contributions in the TJ and ITO VCSEL.

9748-47, Session 11

III-nitride nanowires for optochemical sensing (Invited Paper)

Martin Eickhoff, Justus-Liebig-Univ. Giessen (Germany)

Group III-nitride (III-N) nanowires (NWs) and nanowire heterostructures (NWHS) are a topic of intense current research. Part of these activities is motivated by the possibility of realizing novel, nanoscaled optoelectronic devices with improved stability and efficiency or the perspective of improving electronic devices due to the low density of structural defects. We report on recent results concerning the growth of (Al)InGaN/GaN nanowire heterostructures and their properties as a model system for the effect of internal electric fields on the relation between structural and optical properties of axial NWHS.

We demonstrate the presence of strain-induced radial and polarization-induced internal electric fields and show that the axial internal electric field can be probed by studying the effect of external electric fields on the photoluminescence properties of electrically contacted complex NWHS. Efficient n-type doping of GaN NWs can be achieved with Germanium as a donor. Temperature-dependent analysis of the Seebeck coefficient for single NWs yields a free carrier density of ~10^20 cm^-3 and Ge-doping of optically active GaN NWs in AlGaN/GaN NWHS facilitates electrostatic screening of polarization-induced internal electric fields. Due to the high carrier density in the NDs we also observed infrared absorption due to intersubband transitions.

We further show that the photoluminescence properties of GaN- and InGaN-NWs in electrolyte solutions sensitively depend on the applied bias and the pH-value. We discuss this behavior in terms of photoactivated hole-transfer to RedOx levels in the electrolyte, facilitating the application as spatially-resolved electrochemical sensors and biophotonic probes.

9748-48, Session 11

Dislocation-free c-oriented platelets based on GaN nanowire seeds (Invited Paper)

Lars Samuelson, Lund Univ. (Sweden) and Glo AB

There are a number of application-areas in GaN and III-N technologies, wherein device limitations are still the result of dislocations and defect density levels in the semiconductor crystal. Such applications are, for instance, UV-emitting LEDs, red-emitting LEDs, and GaN-based electronics - for high power and RF. In this work, we present a method to fabricate wafer-scale arrays of dislocation-free platelets with smooth c-oriented surfaces. On these c-planes high quality device-layers are grown for electronic and optoelectronic devices. We also show how the technique can be extended to ternary nitride-platelets, for an eventual realization of III-N platelet-wafers of choice (InGaAs) compositions. Conventional selective growth of nanostructures is known to minimize any open c-plane at an early stage, due to the fast growing nature of the c-plane surface. The presented platelet technology, however, exposes a dominant c-plane surface. This semi-planar design facilitates general device fabrication appreciably, bringing device process technology closer to typical planar wafer technology as compared to 3D NW process-technology. Uniform wafer-scale arrays of GaN platelets are grown by a sequence of selective growth of GaN nanowire seeds, used to filter out dislocations, subsequent growth of high purity GaN, grown under conditions similar to optimal planar GaN. We will show how c-plane can be obtained through a controlled change of epitaxial regime, leading to the formation of GaN platelets. In a similar approach, we can sequentially seed the formation of fully relaxed alloys of InGaN, which enable growth of In-rich c-oriented QWs, emitting in the green, yellow and red spectral regions.

9748-49, Session 11

Linearly polarized single-photons from small site-controlled GaN nanowire quantum dots

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We report the generation and discuss the origins of linearly polarized single photons from site-controlled GaN nanowire quantum dots grown using selective area MOCVD. We furthermore show that for a subset of the quantum dots (dots with small size), single photon emission can be achieved in the solar blind spectral region, opening a new spectral range for short distance quantum communication where the solar-related photonic background at the earth's surface is extremely suppressed due to absorption in stratospheric ozone. The highly linear polarized emission most likely arises due to a suppression of one of the bright exciton doublet peaks, probably due to a degree of anisotropy in the QD/nanowire shape (although other possibilities will also be discussed). Completely linearly polarized single photon emission will be of use for future quantum information processing devices, and the prospects for controlling the polarization by inducing a controlled shape anisotropy during the growth process would be very advantageous. We envisage that the fabrication of arrays of even smaller devices, or AlGaN/AlN structures, would result in emission at energies of low solar irradiance even in orbit (the solar irradiance measured in orbit at a wavelength of 100 nm is suppressed by over 4 orders of magnitude compared to that at 500 nm), suggesting that such devices may be suitable for secure satellite-satellite communications: an application to which GaN would be particularly suitable due to its robustness against radiation damage.

9748-50, Session 11

Bandgap emission modulation of gallium nitride nanomembranes due to external stretching

Rami T. ElAfandy, Pawan Mishra, Mohammed A. Majid, Tien...
Investigation of active region degradation in InGaN laser diodes

Pengyan Wen, Shuming Zhang, Deyao Li, Jianping Liu, Liquan Zhang, Aiqin Tian, Hui Yang, Suzhou Institute of Nano-Tech and Nano-Bionics (China)

The InGaN/GaN laser diodes (LDs) have attracted much attention due to their wide applications in data storage and laser display. However, studies on the degradation mechanism of the LDs are still needed to achieve more reliable devices. In this study, investigation of active region degradation is carried out on InGaN/GaN laser diodes (LDs). Gradual degradation of the
LD is observed with the threshold current increase and the slope efficiency decrease. In order to make more clear understanding of the gradual degradation mechanism of InGaN/GaN LEDs, we carried out extensive studies on the micro-photoluminescence (PL) characterization on both the aged and non-aged LEDs. The results of the aged LD show a uniform degradation of the active region under the ridge. Detailed studies on the temperature-dependent micro-photoluminescence are performed. The integrated PL intensity of the non-aged LD shows a gradual decrease with the temperature increase while the aged LD shows an anomalous sharp decrease at temperature around 100K, which corresponds to an activation energy of about 10meV. This degradation of the active region in our LDs is attributed to the generation of non-radiative centers with activation energy of about 10meV.

9748-74, Poster Session

Numerical analysis on the carrier characteristics of active region in deep-ultraviolet AlGaN-based light-emitting diodes

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The deep-ultraviolet (DUV) light-emitting diodes (LEDs) are of special interest for biochemistry, DNA research, and water purification applications. The AlGaN-based LEDs possess the advantages of direct energy bandgap and quantized quantum wells (QWs) structure, which thus has the possibility to attain high wall-plug efficiency (WPE) in the DUV region. Moreover, the AlGaN-based LEDs are mechanically hard and free from harmful arsenic, lead and mercury. The development of high-performance DUV AlGaN-based LED devices is thus urgently required. However, there remain various challenges for producing high-performance DUV AlGaN-based LEDs, including high threading dislocation density, low light extraction efficiency, difficult acceptor activation in p-type high-Al-content AlGaN, etc. Furthermore, the carrier transportation and distribution near the active region are critical to the optical and electrical performance of nitride-based LEDs. In DUV AlGaN-based LEDs, the large potential barrier in valance band, which is due to the large valance band offset, between the p-AlGaN and p-GaN layers and the low hole concentration, which is owing to the difficult acceptor activation, of p-AlGaN layers may cause the difficulty for holes to inject into the active region and the issue of electron leakage. In this study, in order to probe into the above issues and seek relevant solutions, the characteristics of 260-nm DUV AlGaN-based LED structure are systematically investigated by a finite element approach. Specifically, the energy band profiles, carrier transportation and distribution, optical and electrical performance of device, etc., are analyzed numerically.

9748-77, Poster Session

Determination of the ideality factor of GaN-based light-emitting diodes by the measurement of photovoltaic characteristics

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Solid-state lighting based on white light-emitting diodes (LEDs) is successfully commercialized as a result of the considerable progress in the performance of GaN-based LEDs over the last decade. However, in GaN-based LEDs, there still remain some fundamental questions that have not been fully understood such as the efficiency droop and the diode ideality factor. A high value of the diode ideality factor in GaN-based LEDs is a still unresolved problem that cannot be explained by the Sah-Noyce-Shockley analysis of semiconductors. In this study, we present a method for determining the ideality factor of GaN-based LEDs based on the photovoltaic characteristics and compare the results with the conventional method using the I-V relation below turn-on voltage. In the photovoltaic method, I-V relations are measured as the incident power of a laser diode emitting at 405 nm is varied. By using the data of the short-circuit current and the open-circuit voltage, the ideality factor of commercial blue and green LED samples is evaluated. From the photovoltaic measurement results, the ideality factor of a blue and a green LED is determined to be 1.16 and 1.78, respectively, which is found to be much smaller than those obtained by the I-V curve without illumination. The difference in the ideality factor between the two methods is believed to result from the different carrier generation and transport mechanisms. Therefore, investigating the photovoltaic characteristics of GaN-based LEDs is expected to provide insight into the origin of the high ideality factor in GaN-based devices.

9748-76, Poster Session

Fabrication of AlN-based transparent electrodes with conducting filament: its application to lateral-type GaN light-emitting diodes

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Transparent conductive electrodes (TCEs) having high optical transmittance and low electrical resistance that can serve as ohmic contacts are essential components to further improve the performance of GaN-based light-emitting diodes (LEDs), particularly in the ultraviolet (UV) region. However, trade-offs between the conductivity and transmittance have made it difficult to achieve such ideal TCEs so far. Recently, we have reported a universal method to get wide-bandgap materials conductive using electrical breakdown (EBD), and successfully demonstrated its validity for vertical-type GaN LEDs using SiN-based TCEs. In this study, we demonstrate improved performance of lateral-type GaN LEDs emitting at 450 nm and 385 nm using AlN-based TCEs. To minimize the electrical shock during the EBD process, we contrived a unique bias method to form conducting paths in the TCE. In addition, we inserted a thin conductive layer below AlN TCE to enhance the current spreading effect. As a result, we accomplished much higher light-output power (-14.9 %) and lower forward voltage (-4.2 %) for 385 nm UV LED with AlN TCE, when compared to those of the UV LED with ITO. This improvement is attributed to enhanced current spreading (via insertion layers) in addition to higher optical transmittance (> 95% at 385 nm) and lower contact resistance (via conducting filament, 3.32?10^-3 ?cm^2). More details on the experimental result will be presented at the conference.

9748-78, Poster Session

Compressive strain induced enhancement of indium incorporation to InGaN MQWs on strained AlN/GaN multilayers

Morteza Monavarian, Shohan D. Hafiz, Ümit Özgür, Hadis Morkoc, Vitaliy Avrutin, Virginia Commonwealth Univ. (United States)

Tailoring strain in InGaN heterostructures through modification of in-plane lattice parameter of buffer layers for strain-compensation and/or enhanced indium incorporation efficiency has recently gained an attention as a potential solution to the green gap issue. Application of GaN buffer layer under tensile strain reduces the total strain of the structure and thus improve radiative recombination efficiency of the InGaN active layers while the situation is opposite in case of compressively-strained GaN under-layer.
On the other hand, amount and sign of strain in InGaN heterostructures has a strong effect on indium incorporation; tensile strain reduces while compressive strain enhances the incorporation efficiency. In this work, the effect of compressive strain on indium incorporation to the overgrown InGaN multi-quantum wells (MQWs) is studied. Ten periods of 3 nm In0.15Ga0.85N QWs separated by 8 nm In0.02Ga0.98N barriers have been grown side by side on both relaxed GaN layers and compressively strained template composed of 10 pairs of AlN/GaN (15nm/4nm and 12nm/2.5nm). The photoluminescence (PL) emission peak wavelength were 435nm and 530 nm for the relaxed and strained layers, respectively. While the effect of strain on InGaN growth rate was found to be negligible based on X-ray diffraction analysis, excitation dependent PL measurements revealed 120meV blue-shift in QW emission for the structures grown on strained AlN/GaN compared to less than 60meV shift in those grown on relaxed GaN when photo-excited carrier concentration was changed by two orders of magnitude. Consequently, the indium incorporation was determined by using the PL peak positions at the highest excitation density, which eliminated the contribution from the quantum confined Stark effect. The obtained results for various degrees of relaxation in the under layer achieved by varying thicknesses of strained GaN on AlN, are in agreement with theoretical calculations indicating enhanced indium incorporation for compressively strained InGaN active layers. The relationship between the value of strain and indium incorporation is quantified for the emission wavelength ranging from blue to green.

9748-79, Poster Session

Exciton localization in (11-22)-oriented semi-polar InGaN multiple quantum wells

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Semi-polar InGaN heterostructures have attracted attention as potential candidates for high brightness light-emitting devices due to high recombination efficiency associated with reduction in quantum confined Stark effect. Excitonic recombination dynamics in semi-polar (11-22)-oriented In0.16Ga0.84N multi-quantum well (MQW) structure grown on GaN/m-sapphire templates has been investigated by temperature dependent time resolved photoluminescence (TRPL). The structure consisted of six 3-nm wide In0.16Ga0.84N MQWs separated by 6-nm In0.08Ga0.92N barriers. To reduce the density of threading dislocations (TDs) and stacking faults (SFs), the GaN templates were fabricated using in-situ deposition of nano- porous SiNx interlayers followed by epitaxial lateral overgrowth of semi-polar GaN. The PL peak intensity reduced by a factor of about 3 at 300 K compared to 30 K. The radiative and non-radiative recombination contributions to the PL intensity at different temperatures were evaluated by analysing temperature dependences of PL peak intensity and decay times. When temperature increased from 30 K to 300 K, the non-radiative decay time reduced from 22 ns to about 750 ps. The radiative decay time, on the other hand, is roughly constant below 180 K (~1 ns) and increases with a slope of 5.8 ps/K afterwards indicative of coexistence of localized and free excitons in the layers for which relative proportions are statistically calculated. Temperature evolution of energy position and intensity of PL indicates the existence of strong localization with delocalization temperature of Tdeloc = 170 K in the InGaN MQWs structure on semi-polar (11-22)-oriented structure compared to Tdeloc = 100 K reported for c-plane layers with similar structure design. Correlation of exciton delocalization with temperature evolution of PL intensity, temperature dependence of radiative and non-radiative decay times, and change in free and localized exciton populations are discussed. The increase in non-radiative recombination was found to happen with increase of the free exciton populations particularly for temperatures above the delocalization temperature which means that excitons will tend to recombine more non-radiatively after delocalization starts to take place. The origin of the high degree of localization could be described by presence of potential fluctuations due to indium fluctuations in the wells and barriers and presence of high density of stacking faults. Exploration of the temperature dependence of localization energy and correlation it with those for excitonic transitions on certain defect states are used to reveal the genesis of the strong exciton localization in these layers. In spite of potential limitations in carrier transport, strong exciton localization in semi-polar (11-22)-oriented structures could lead to robust temperature dependence and improved excitonic emission which are favourable for various optoelectronic applications.

9748-80, Poster Session

Wurtzite/zinc-blende electronic-band alignment in basal-plane stacking faults in semi-polar GaN

Morteza Monavarian, Shohan D. Hafiz, Natalia Izyumskaya, Umit Ozgur, Hadis Morkoc, Vitaliy Avrutin, Virginia Commonwealth Univ. (United States)

Basal-plane stacking faults (BSFs) in GaN represent inclusions of zinc blende structure in wurtzite matrix. Knowledge of electronic band structure of BSFs in GaN is of critical importance for understanding their effects on optical emission as well as transport properties particularly in light emitters with nonpolar and semipolar orientations grown on non-native substrates where typically high density of stacking faults exists. Results of experimental and theoretical studies devoted to band alignment at the zinc blende/wurtzite interface are contradictory. Moreover, only a few experimental studies on internal electric field in these structural defects are available in literature. Motivated by the afore-mentioned ambiguity, we intended to take a step toward solving this problem by determination of band alignment and internal electric field by means of ultra-fast spectroscopy of semi-polar (11-22) GaN/m-sapphire with high stacking fault (SF) densities and c-GaN/sapphire with practically no SFs. In order to gain insight into the band alignment, the differential transmission in femtosecond pump-probe beam experiment in time-resolved differential transmission (TRDT) measurements with excitation wavelength varying from 360nm (to excite GaN near band edge) to 375nm (to excite type-I, type-II and extrinsic BSFs separately) has been compared to the c-plane reference GaN. Band alignment in BSFs has been discussed as type of Band alignment at the wurtzite/zinc blende interface governs the response in differential transmission; fast decay after the pulse followed by slow recovery due to spatial splitting of electrons and heavy holes for type-II band alignment in contrast to decay with no recovery in case of type I band alignment. Time evolution of emission energies for pulsed excitation and PL decay times for different types of BSFs featured by different widths are investigated to determine internal electric field across BSFs via quantum confined Stark effect (QCSE). For the calculations, the well widths of 1.7, 2.7, and 3.7 bilayers for type-I, type-II and E-BSFs, respectively have been used as effective electronic thicknesses which are determined by microscopic electrostatic potential of the E-BSF. The value of polarization charges and charge distributions are calculated under the assumption of abrupt quantum well/barrier interfaces. Based on the results, band profile in zinc-blende segments in wurtzite matrix is constructed.

9748-81, Poster Session

Optical investigation of microscopic defect distribution in semi-polar (1-101 and 11-22) light-emitting diodes

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Near-field scanning optical microscopy was applied to investigate the spatial variations of extended defects and their effects on the optical quality for semipolar (1-101 and 11-22) InGaN light emitting diodes (LEDs). (1-101) and (11-22) oriented LEDs emitting at 450-475 nm were grown on patterned Si (001) 7° offcut substrates and m-sapphire substrates by
means of nano-epitaxial lateral overgrowth (ELO), respectively. At room temperature the photoluminescence from the near surface c-wings was found to be relatively uniform across the sample and mainly dominated by the strong active region emission. However, emission from the c-wings was substantially weaker due to the presence of threading dislocations as well as basal plane and prismatic stacking faults. Spatial distribution of extended defects and luminescence spectra was also explored at low temperature (85K) where the effect of non-radiative recombination is significantly reduced and stacking faults appear as separate emission lines.

9748-82, Poster Session
Characterization of dynamic channel resistance of GaN-based HEMTs

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GaN-based high electron mobility transistors (HEMTs) have attracted tremendous attention for high efficiency power switching applications over the past few years. Despite the recent introduction of high efficiency power converters to the market, GaN-based transistors still suffer from the degradation of dynamic on-resistance (Ron) as the applications are extended to switching circuits with higher voltages and higher frequencies. The concern of product reliability continues. This issue has been attributed to the charge trapping/detrapping processes in the surface and buffer regions of the transistors based on a number of electrical transient measurements. However, the correlation between the physical distribution of trapped charges and the degradation of device dynamic performance remains to be clarified.

It has been shown that field plates can greatly enhance breakdown voltage as well as alleviate degradation in dynamic Ron after high voltage off-state stress on AlGaN/GaN MIS-HEMTs. In-depth understanding of the sources of dynamic performance is pursued by using three measurement methodologies, including transient Id-Vg, stressed C-V, and three-terminal synchronous voltage switching. Threshold voltage shift is studied by transient Id-Vg method and buffer layer-dependent. Stressed C-V measurement are used to extract the profiles of trapped charges in the buffer layer. The tree-terminal synchronous switching scheme with substrate bias is used to study the influence of buffer trapped charges on the degradation of dynamic Ron, and to correlate with the position of gate field plate edge and source field plate edge.

Recently, lattice-matched AlInN/GaN heterostructure is considered a promising contender for rf and power device applications because of its stronger spontaneous polarization, which induces higher carrier concentration and therefore lower channel resistance than its AlGaN/GaN counterpart. Detailed study on the dynamic performance of AlInN/GaN HEMTs is also a subject to be explored. It is found that a thick GaN cap layer remains to be clarified.

Our approach is to reduce the influence of defects by confining carriers in QDs, which confine excitons along both the growth direction and the growth plane, instead of in quantum wells where excitons can freely move in the growth plane. In this work, we investigate and compare AlGaN-QD growth conditions (deposited amount, Al composition, growth temperature and/or crystal orientation) on the QD structural and optical properties in order to fabricate “small and high-density” QDs on different AlGaN-xN matrices. The structures are investigated by combining in-situ (reflection high energy electron diffraction - RHEED) and ex-situs (microscopy - AFM, TEM) and photoluminescence (PL, TRPL) techniques. We show that the change in growth conditions can have a strong impact on the morphological and optical properties of the QDs and propose different routes to go deeper into the UV range. The potential of different active region designs are discussed and the main characteristics of QD-based LED devices presented and compared.

9748-55, Session 12
(Al,Ga)N-based quantum-dot heterostructures grown by molecular beam epitaxy for the fabrication of UV LEDs (Invited Paper)

Julien Brault, Benjamin Damilano, Ctr. de Recherche sur l’Hétéro-Epitaxie et ses Applications (France)

The growth and optical properties of AlxGa1-xN self-assembled quantum dots (QDs) are investigated and their use as UV emitters in light emitting diodes (LEDs) presented.

AlxGa1-xN-based UV LEDs are seen as the next technology in replacement to the mercury lamp, but a drop in the efficiency of these LEDs at shorter wavelengths is observed. Part of this drop is due to the usually low structural quality of the active region hetero-epitaxially grown on sapphire. Our approach is to reduce the influence of defects by confining carriers in QDs, which confine excitons along both the growth direction and the growth plane, instead of in quantum wells where excitons can freely move in the growth plane. In this work, we investigate and compare AlGa1-yN QD growth conditions (deposited amount, Al composition, growth temperature and/or crystal orientation) on the QD structural and optical properties in order to fabricate “small and high-density” QDs on different AlGaN-xN matrices. The structures are investigated by combining in-situ (reflection high energy electron diffraction - RHEED) and ex-situ (microscopy - AFM, TEM) and photoluminescence (PL, TRPL) techniques. We show that the change in growth conditions can have a strong impact on the morphological and optical properties of the QDs and propose different routes to go deeper into the UV range. The potential of different active region designs are discussed and the main characteristics of QD-based LED devices presented and compared.

9748-56, Session 12
Realization of high-performance AlGaN-based UV emitters and photodetectors (Invited Paper)

Motoaki Iwaya, Tetsuya Takeuchi, Satoshi Kamiyama, Meijo Univ. (Japan); Isamu Akasaki, Meijo Univ. (Japan) and Nagoya Univ. (Japan)

Recently, high performance AlGaN-based UV light-emitting diodes are developed for sterilize and medical application. In contrast, the developments of UV photodetector and laser are also important in practice. The AlGaN alloy is candidate material for such photodetector and laser, because of direct wide bandgap ranging from 3.4 to 6.0 eV. In this presentation, we will discuss the realization of high performance AlGaN-based UV photodetectors and lasers.

In photodetectors, we fabricated high-performance AlGaN/AlN heterostructure photodetector with a p-GaN optical gate for the only detection of 200-275 nm. The photodetector achieved a high external photosensitivity, close to 104 A/W. This photosensitivity greatly surpassed those of commercially available Si pin, Si avalanche, AlGaN-based pin photodiodes, and was comparable to those of photomultiplier tubes. Furthermore, a dark current density of approximately 6 pA were obtained at 4 V of anode-cathode voltage. The S/N ratio was on the order of 105. We attempted to use this sensor for flame detector utilizing high S/N and solar-blind characteristics. As a result, we can detect the flame directly.

In contrast, the expansion of the laser emission wavelength is a major concern for the research on UV AlGaN-based lasers. The shortest wavelength reported for current injection-type laser diodes is 336 nm.
For wavelengths less than 336 nm, the development of UV laser diodes is strongly hampered because of the difficulties with current injection technology such as the realization of both a high hole concentration and low resistivity p-type AlGaN with a high AlN molar fraction. Because laser oscillation from AlGaN, with a high AlN molar fraction, can be obtained under optical pumping UV lasers with controllable wavelengths should be realized if this problem can be solved. One promising technique for avoiding these problems is the use of electron beam excitation. The conductivity control of nitride semiconductors is unnecessary using electron beam excitation. Therefore, it would be possible to expand the wavelength region for the laser action of AlGaN-based lasers to deep UV region. However, laser oscillation excited via an electron beam using nitride semiconductors has not yet been investigated. Therefore, in this study, an electron beam excitation laser using a nitride semiconductor was investigated. We will also discuss these results.

9748-57, Session 12

Advances in AlGaN-based deep UV LED technologies (Invited Paper)

Michael Kneissl, Frank Mehnke, Christian Kuhn, Christoph Reich, Martin Guttmann, Johannes Enслиn, Luca Sulmoni, Tim Wernicke, Technische Univ. Berlin (Germany); Viola Kuehler, Arne Knauer, Ute Zeimer, Mickael Lapeyrade, Jens Rass, Neysha Lobo-Ploch, Tim Kolbe, Johannes Glaab, Sven Einfeldt, Markus Weyers, Ferdinand-Braun-Institut (Germany)

Many applications would greatly benefit from the availability of high efficiency, high power AlGaN-based ultraviolet light emitting diodes (UV-LEDs). UV-LEDs are compact, robust, and environmentally friendly; they can be rapidly switched on/off, are operated at moderate dc voltages, and exhibit long lifetimes. Furthermore, their emission can be tuned to cover any wavelength in the UVA, UVB and UVC spectral range, which makes them ideally suited for applications like water purification, UV curing, sensing, plant growth lighting, and phototherapy. This presentation will provide an overview of the state-of-the-art in UV-LED device technologies and present novel approaches to improve the internal and external quantum efficiency of UV light emitters in the wavelength range between 325 nm and 230 nm. We will discuss the correlation between substrate polarity, such as AlN or Mg-doped AlGaN, and the growth of low resistance n-AlGaN current spreading layers. The impact of the AlGaN quantum well width and barrier composition on the optical polarization of deep UV-LEDs and present new approach for efficient carrier injection into AlGaN-based UV-LEDs emitting below 240 nm based on Mg-doped AlGaN/AlGaN electron blocking heterostructures. Finally, we will present advanced methods for light extraction utilizing graphene electrodes for UV-LEDs.

9748-59, Session 12

Influence of the LED heterostructure and chip package on the lifetime of high power UV-B and UV-C LEDs

Neysha Lobo Ploch, Ferdinand-Braun-Institut (Germany) and Leibniz Institut für Höchstfrequenztechnik (Germany); Johannes Glaab, Christoph Stölzle, Jens Rass, Tim Kolbe, Ferdinand-Braun-Institut (Germany) and Leibniz-Institut für Höchstfrequenztechnik (Germany); Tim Wernicke, Frank Mehnke, Christian Kuhn, Johannes Enслиn, Technische Univ. Berlin (Germany); Sven Einfeldt, Markus Weyers, Ferdinand-Braun-Institut (Germany) and Leibniz-Institut für Höchstfrequenztechnik (Germany); Michael Kneissl, Ferdinand-Braun-Institut (Germany) and Technische Univ. Berlin (Germany)

LEDs emitting in the UV-B and UV-C spectral regions are interesting for applications such as phototherapy, gas sensing, water purification and UV curing. However, currently the lifetime of UV LEDs is very low ranging from less than hundred hours to a few thousand hours. For UV LEDs to become commercially viable, it is necessary that the lifetime of the LEDs is extended to nearly 10,000h as in the case of visible LEDs. To achieve such long lifetimes, investigations on the influence of the LED heterostructure design and package on the lifetime of the LEDs is essential.

In this paper, the degradation mechanisms in high power UV LEDs grown by metal-organic vapor phase epitaxy on sapphire substrates has been investigated. Firstly, the degradation of 290nm and 310nm LEDs has been investigated at constant current densities of 28A/cm² and 140A/cm². Two main modes for the reduction of the optical power are observed, which dominate at different times of operation. The first mode, occurring in the first 250h, is dependent on the heterostructure design and the current density while the second mode, occurring at longer operation times, is independent of both. A long lifetime (L10) of 3,500h has been obtained for the 310nm LEDs at a high current density of 140A/cm². Secondly, the influence of hermetic packaging on the lifetime of 310nm LEDs will be presented and the use of different encased gases will be investigated. Finally, the influence of the template defect density on the lifetime of 265nm LEDs will be presented.

9748-58, Session 12

A surface-emitting electrically-injected near-vacuum ultraviolet light source with aluminum nitride nanowires

Songrui Zhao, David Lalayan, Mehrdad Djavid, Binh H. Le, Xianhe Liu, Zetian Mi, McGill Univ. (Canada)

An efficient light source that can operate in the wavelength range - 200 nm, or shorter, is in demand for a broad range of applications from industrial manufacturing to laboratory research. To date, however, it has remained challenging to realize an electrically injected, surface emitting all-semiconductor based high efficiency light source in such a wavelength range. In this work, we demonstrate such a light source with molecular beam epitaxially (MBE) grown AlN nanowires on low cost, large area Si substrate. In this experiment, catalyst-free AlN nanowires were grown on Si substrates by RF plasma-assisted MBE under nitrogen-rich conditions. The growth conditions included a plasma power of 350 W, a nitrogen flow rate of 1 sccm, and a Al flux of ~ 2-6x10⁻8 Torr. The device structure consisted of n-GaN contact layer, n-AlN, p-AlN, and p-AlGaN contact layer. The electrical injection was realized through Ni/Au and Ti/Au as top and back contacts, respectively. Strong electroluminescence across 207 nm was measured from the fabricated AlN nanowire LEDs. Detailed angle dependent electroluminescence studies indicated that the dominant light emission direction was from the c-axially grown nanowire top surface, and an electrical efficiency of > 85% was realized from such AlN nanowire LEDs. In addition, our detailed studies further suggested that the performance of AlN nanowire LEDs was predominantly limited by electron overflow. Current work is focused on the passivation of AlN nanowire LEDs, which will also be reported.

9748-60, Session 13

GaN IC applied in LED lighting driver (Invited Paper)

Chiacheng Liu, Schang-jing Hon, Epistar Corp. (Taiwan)

The rapid advancement in LED technology has propelled the growth of
solid-state lighting market in recent years. While the efficacy of LED itself has been improved tremendously, a high efficiency compact LED driver is also actively pursued because the DC-driven LEDs operate in different principle from what the traditional light bulbs and fluorescent lamps do.

Currently, a general solution for LED drivers is based on a Si MOS integrated circuit coupled with a few resistors and capacitors. Compared to the Si driver IC, a GaN-based driver IC has many advantages, such as high breakdown voltage, high power density, and low impedance.

In this talk, we will demonstrate a GaN IC that can perform all the functions of traditional RC drivers while in a much smaller size. The variation ratio of output power to input power is around 14%, which is much better than 61% of an RC circuit. The total harmonic distortion (THD) is 50%, much lower than 87% of an RC circuit. The power factor correction (PFC) is 89%, higher than 70% of an RC circuit.

In view of these advantages, GaN drivers are very promising for future LED lighting applications.

9748-61, Session 13

Interrelations between the forward voltage and the internal quantum efficiency of InGaN-based light-emitting diodes

Jong-In Shim, Dong-Pyo Han, Dong-Soo Shin, Won-Jin Choi, Hanyang Univ. (Korea, Republic of); Kyu-Sang Kim, Sangji Univ. (Korea, Republic of)

Although the performances of InGaN-based light-emitting diodes (LEDs) have significantly improved so far, higher wall-plug efficiency (WPE) is still required for further replacement of the conventional lamps. To improve the WPE, it is necessary to enhance the internal quantum efficiency (IQE) and to reduce the forward voltage (VF) simultaneously. While the IQE and the VF have been studied intensively, they are still considered separately as the so-called “efficiency droop” for the former and the current crowding and metallic contact problems for the latter indicate. The interrelations between them have not yet been carefully examined and reported. In this study, we report that the IQE and the VF of InGaN-based LEDs are closely related to each other via carrier recombination processes. The radiative and nonradiative recombination current components are separately analyzed by combining with the IQE curves as a function of injection current. It is found that the radiative recombination current does follow an ideal Shockley diode equation with an ideality factor of 1 and a constant series resistance. However, the nonradiative recombination current is dominated by the so-called double injection current, which results in an additional potential drop owing to insufficient recombination rate and subsequent carrier accumulation. We propose to use a modified diode current-voltage equation for an LED as a sum of the radiative and nonradiative current components instead of using a single exponential form of the Shockley diode equation. This is because the radiative and nonradiative recombination processes are different and their recombination rates are comparable to each other in an LED. This approach provides a new insight to improving the IQE and VF simultaneously.

9748-62, Session 13

Bipolar non-quasiequilibrium carrier dynamics in III-N LEDs

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Light-emitting diodes (LEDs) based on III-Nitride (III-N) materials are enabling huge global energy savings with their near-unity peak efficiencies. As the conventional multi-quantum well (MQW) LED technology is reaching its maturity, future scientific research needs to generate much deeper understanding of the microscopic physical processes underlying the device operation than what is presently available. One of the topics requiring notable further understanding is the non-quasiequilibrium carrier dynamics and its effects on the device operation. Such understanding will enable, e.g., assessing the validity of the conventional drift-diffusion (DD) models in predicting the macroscopic device characteristics of III-N devices. These involve several distinct features that are quite different from devices based on conventional III-V materials, such as droop, very high ideality factors, and the non-exponential decay of the high-energy emission spectrum.

In this work we develop and carry out device-level bipolar Monte Carlo (MC) simulations of electron and hole transport to systemically compare results from MC and DD. This gives detailed understanding of the validity ranges of the DD model in III-N LEDs and also establishes the essential predictive advantages brought by the MC model. Additionally, comparing MC simulations with DD simulations will enable more in-depth insight on the large ideality factors, carrier distribution functions, thermalization and heat exchange effects, as well as emission spectra, revealing in part the importance of the non-quasiequilibrium contribution to these characteristics.

9748-63, Session 13

Tunable full-color nanowire light-emitting diode arrays monolithically-integrated on Si and sapphire

Renjie Wang, Yong-Ho Ra, Songrui Zhao, Hieu P. Nguyen, Ishiang Shih, Zetian Mi, McGill Univ. (Canada)

The monolithic integration of red, green and blue (RGB) GaN-based light-emitting diodes (LEDs) directly on a single chip is critically important for smart lighting and full-color display applications. In this context, we have demonstrated RGB InGaN nanowire LED pixels on Si and sapphire substrate. RGB InGaN/GaN dot-in-a-wire LED arrays were laterally arranged on a Si wafer using a three-step SAG technique, wherein blue, green, and red-emitting LEDs were grown in sequence. In this process, a SiOx mask layer was used to protect the previously grown devices and also to precisely define the growth position of each nanowire LED pixel. By separately biasing such lateral-arranged multi-color LED subpixels, the CCT value can be varied from ~1900 K to 6800 K. The devices show excellent CRI values (> 90, or higher). We have further investigated the molecular epitaxial growth and fabrication of multi-color nanowire LED arrays on GaN/sapphire substrate. By controlling the nanohole diameter and spacing, full-color InGaN/GaN nanowires with much reduced sizes were grown on the same sapphire wafer. The luminescence emission can be tuned by varying the nanowire size, spacing, and shape in a single epitaxial growth step. We have further developed micro-scale and nano-scale tunable, multi-color LED pixels. We have also demonstrated multi-color nanowire LEDs on sapphire substrate that can exhibit excellent current-voltage characteristics, high power operation, and reduced efficiency droop. The realization of electrically injected RGB InGaN nanowire lasers is being studied and will also be reported.

9748-64, Session 13

Use of tin and indium interlayers for forming low resistance Ti/Al-based ohmic contacts to N-polar n-GaN for high-power GaN-based vertical light-emitting diodes

Tae-Yeon Seong, Sung Ki Kim, Tae Wook Kang, Korea Univ. (Korea, Republic of)

The fabrication of high-efficiency InGaN-based vertical-configuration LEDs (VLEDs) is crucial to the realization of solid-state lighting application. Performance of VLEDs is in part subject to the formation of low resistance and thermally stable ohmic contacts to N-polar n-type GaN as well as low resistance p-type reflectors. Unlike ohmic contacts to Ga-polar n-GaN,
ohmic contacts to N-polar n-GaN are not easy to form. It was shown that the electrical properties of Ti/Al contacts to the N-polar GaN were degraded after annealing even at 400 °C. This electrical degradation was explained by the presence of the complex surface states of the N-polar GaN, consisting of impurities and process-induced donor-like and acceptor-like defects. Thus, it is important to develop thermally stable N-polar n-contact schemes in order to enhance the output power of VLEDs. In this study, the effects of Sn and In interlayers (3 ~ 10 nm thick) on the electrical properties of Ti/Al/Au contacts were investigated. Sn and In were chosen because they have small work functions of 4.12 ~ 4.28 eV. Unlike the Ti/Al/Au contacts, both types of samples were ohmic with contact resistivities of 1.4 ~ 10?4 ~ 4.0 ~ 10?5 ohm-cm2 after annealing at 300 °C. Furthermore, unlike the Ti/Al/Au contact, the Sn and In-interlayered contacts remained thermally stable with increasing annealing time up to 60 min at 300 °C. Based on the X-ray photoemission spectroscopy (XPS) and secondary ion mass spectrometry (SIMS) examinations, the improved behavior of the interlayered contacts is described in terms of the generation of oxygen-related defects.

9748-65, Session 14
High-efficiency blue LEDs with thin AlGaN interlayers in InGaN/GaN MQWs grown on Si (111) substrates (Invited Paper)
Shigey Ki Kimura, Hisashi Yoshida, Toshihide Ito, Aoi Okada, Kenjiro Uesugi, Shinya Nnoue, Toshiba Corp. (Japan)

We demonstrate high-efficiency blue light-emitting diodes (LEDs) with thin AlGaN interlayers in InGaN/GaN multi-quantum wells (MQWs) grown on Si (111) substrates. The peak external quantum efficiency (EQE) of 82% at room temperature and the hot/cold factor (HCF) of 94% have been obtained by using the functional thin AlGaN interlayers in the MQWs in addition to reducing threading dislocation densities (TDDs) in the blue LEDs. An HCF is defined as EQE (85°C) / EQE (25°C).

The blue LED structures were grown by metal-organic chemical vapor deposition on Si (111) substrates. The MQWs applied as an active layer of 8- pairs of GaInAs/AlGaN/In0.15Ga0.85N heterostructures. Thin-film LEDs were fabricated by removing the Si (111) substrates from the grown layers.

It is observed that the 1- nm-thick AlxGa1-xN interlayers, whose Al content is x=0.3 or less, are continuously formed by high-resolution transmission electron microscopy and three-dimensional atom probe analysis. EQE and the HCFs of the LEDs with thin AlxGa1-xN (x=0.075, 0.15) interlayers are enhanced compared with those of the samples without the interlayers, and such enhancement is particularly pronounced in the low-current-density region. The electro-luminescence properties are consistent with the results of band diagram simulation, indicating the change of carrier density distribution by inserting the interlayers. It is also found by the analysis of temperature dependence of time-resolved photoluminescence that the interlayers reduce non-radiative recombination components in InGaN well layers. We discuss the functions of the AlGaN interlayers from the viewpoints of both the band engineering and the crystal qualities.

9748-66, Session 14
GaN-based superluminescent diodes with long lifetime
Antonino Castiglia, Marco Rossetti, Nicolai Matuschek, Raffaele Rezzonico, Marcus Duelm, Christian Vélez, Exalos AG (Switzerland); Jean-François Carlin, Nicolas Grandjean, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We report on the reliability of GaN-based super-luminescent diodes (SLEDs) emitting at a wavelength of 405 nm. Although such devices have gained interest in recent years, no reports on their reliability has been presented so far.

In this work we show the impact of Mg p-type doping on the device output characteristics and on the extended module lifetime achieved by using optimized p-doped layers. The epitaxial structures were grown by metal organic vapour phase epitaxy (MOVPE) on high quality c-plane GaN free-standing substrates and processed into single-mode ridge waveguide SLED structures. After cleaving and facet coating the devices were assembled into standard uncooled TO56 cans.

The optimized p-type layer allowed decreasing the operating voltage from 6 V to less than 5 V for an injection current of 100 mA. Furthermore, a maximum output power of 350 mW (for an injection current of 500 mA) was achieved in continuous-wave operation (cw) at room temperature. Modules with standard and optimized p-type layers were finally tested on lifetime, at a constant output power of 10 mW, in cw operation and at a case temperature of 25 °C. The modules with non-optimized p-type doping showed a fast and remarkable increase in the drive current during the first hundreds of hours together with an increase of the device series resistance. In contrast, no degradation of the electrical characteristics was observed after 2000 h on devices with optimized p-type layers. Under the specific test conditions, the estimated lifetime for those devices was higher than 5000 h.

9748-67, Session 14
Determination of internal quantum efficiency in GaN by simultaneous measurements of photoluminescence and photo-acoustic signals
Takashi Nakano, Kouhei Kawakami, Atsushi A. Yamaguchi, Kanazawa Institute of Technology (Japan)

Internal quantum efficiency (IQE) in III-nitride materials is usually estimated from temperature dependence of photoluminescence (PL) intensity by assuming that IQE at cryogenic temperature is unity. III-nitride samples, however, usually have large density of non-radiative defects, and the assumption is not necessarily valid. Photo-acoustic (PA) measurement is a good method to directly detect the heat generation by non-radiative recombination, and can be a complementary approach to reveal the recombination processes. In this study, we developed a new method to estimate accurate IQE values by simultaneous PL/PA measurement. The IQE values can be estimated by analyzing the correlation between PL and PA signals in nonlinear behavior of their excitation-power dependence, by considering that these signals are proportional to the amounts of light and heat generation in the radiative and non-radiative recombination, respectively. The samples used were a high-quality free-standing GaN substrate and a relatively low-quality GaN film on a sapphire substrate. The IQE value for the high-quality GaN is estimated as 3 % in our method for certain excitation power at room temperature while the value for low-quality one is less than 0.4 %. On the other hand, temperature dependence of PL intensity shows almost similar behavior and the IQE values are estimated as 2-3 % by the conventional method for both the samples. These results show that the conventional method cannot give accurate IQE values for low-quality samples although it can be valid for high-quality samples, and that the simultaneous PL/PA measurement is a promising way to evaluate luminous efficiency.

9748-68, Session 14
Demonstration of uniform and stable GaN ultraviolet p-i-n avalanche photodiode array
Mi-Hee Ji, Jeomoh Kim, Theeradetch Detchprohm, Russell D. Dupuis, Georgia Institute of Technology (United States); Ashok K. Sood, Magnolia Optical Technologies, Inc. (United States); Nibir K. Dhar, U.S. Army Night Vision & Electronic Sensors Directorate (United States); Jay
The study of growth, processing, and characterization of 474 GaN ultraviolet (UV) p-i-n APD arrays was carried out. We demonstrated a high-uniformity and stability of UV-APD arrays with large size of $75 \times 75 \mu m^2$ using optimized high-quality epitaxial layer and device fabrication processing techniques. To obtain the improved material quality, various growth parameters were introduced for a growth on free-standing GaN substrates in MOCVD. For the fabrication of UV-APD arrays, a low-damage mesa etch, an optimized n-type and p-type ohmic contact, a PECVD-SiO2 passivation, accessing via holes using dry etching, and bonding pads for wire bonding were employed. In order to evaluate the uniformity of UV-APD array, the dark current and photocurrent of 16-element of UV-APD array were measured. Neither microplasmas nor premature junction breakdown luminescence was visually observed for reverse-bias voltages up to near an avalanche breakdown. The dark current density of UV-APD array was below ($6\times10^{-7}$) $A/cm^2$ for reverse bias voltages below 50 % of the average avalanche breakdown voltage of UV-APD array. In addition, the average breakdown voltage of 16-element of UV-APD array was $96\pm0.6$ V. These results indicated uniform distribution of leakage current and breakdown voltage of UV-APDs in the array. Also, we confirmed the stability of 474 UV-APD array by performing the multiple reverse-bias I-V scans. With repeated tests, the measured 4-element along the diagonal of the 474 UV-APD array showed closely same dark current density and consistent breakdown voltages. Detailed growth, fabrication techniques, and characterization of GaN UV p-i-n APD array will be presented.

9748-70, Session 14

**Optical, structural, and compositional nano-scale characterization of InGaN/GaN core-shell microrod heterostructures**

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Three-dimensional nitride based microrods are promising candidates to achieve high efficient optoelectronic devices. By taking advantage of the core-shell geometry with a high aspect ratio, the effective light emitting area can be significantly increased in comparison to conventional planar heterostructures.

In this study we report on the correlation of the structural and optical properties with the chemical composition of the InGaN/GaN core-shell microrods using highly spatially resolved cathodoluminescence microscopy (CL) and scanning transmission electron microscopy (STEM).

The core-shell microrods were fabricated by MOVPE on c-plane GaN/sapphire templates covered with a SiO2-mask. The MOVPE process results in the homogeneous selective area growth of n-doped GaN microrods out of the mask openings. On top of the n-GaN core, an InGaN single quantum well encased by GaN barriers was deposited as active region.

Going from the bottom part towards the tip of the single microrod, the InGaN SQW CL emission shows a redshift from 410 nm to 475 nm. STEM investigations of the InGaN SQW reveal a significant increase in thickness from 6 nm at the bottom part to 13 nm at the top part of the microrod. Quantitative analysis of high-angle annular dark-field STEM micrographs shows a slight increase of the Indium concentration along the non-polar sidewall from 11 % to 13 %. Furthermore, we observe locally strong fluctuations of the Indium concentration within the InGaN SQW. The increased quantum well thickness and the higher indium incorporation lead to the observed red shift of the InGaN SQW emission along the non-polar sidewall.
Debye-tail mobility enhancement (DTME) in semiconductors: application to Ga-doped ZnO

David Look, Wright State Univ. (United States); Eric R. Heller, Air Force Research Lab. (United States); Yu-Feng Yao, Chih-Chung Yang, National Taiwan Univ. (Taiwan)

In semiconductor thin films, the decrease of mobility — with decrease of thickness d is a nearly universal phenomenon, usually arising from increased carrier scattering by defects near the film/substrate interface. Recently we found a surprising violation of this effect in Ga-doped ZnO (GZO) grown by MBE on a ZnO buffer, namely, \( \mu = 34.2 \text{ cm}^2/\text{V-s} \) at \( d = 300 \text{ nm} \), and 64.1 \( \text{cm}^2/\text{V-s} \) at 5 nm, the latter likely a world’s record at 5 nm. The theoretical explanation involves three steps: (1) a Poisson analysis to determine the concentration profile \( n(z) \), \( z = 0 \) to \( d \); (2) a mobility calculation to determine \( \mu(d) \) based on \( n(z) \); and (3) a Hall-effect analysis to determine sheet concentration \( n_s(d) \) and \( \mu(d) \) for comparison with experiment: \( \mu(d) = \int_0^d \mu(z)n(z)dz/n_s(d) = \int_0^d \mu(z)n(z)dz \). The theory, with no adjustable parameters, agrees well with experiment for \( d = 5, 25, 50 \) and 300 nm. For the 5-nm layer, the Poisson analysis shows that about 10% of the electrons “leak” into the ZnO buffer. Although this percentage seems small, the much purer ZnO has very much higher mobilities, ranging from 206 \( \text{cm}^2/\text{V-s} \) at the GZO/ZnO interface to 58 \( \text{cm}^2/\text{V-s} \) at a point 2 nm from the interface (theoretical values). These mobilities should be compared to that of bulk-GZO, 34 \( \text{cm}^2/\text{V-s} \). Although our simple 5-nm-GZO/5-nm-ZnO structure has only 10% of the electrons in the ZnO, we propose other structures with up to 43%. Practical applications of DTME include higher conductance and transmittance in current-spreading layers.


The role of yttrium in zinc-oxide and zinc-tin-oxide (Invited Paper)

Rebecca L. Peterson, Wenbing Hu, Univ. of Michigan (United States)

Zinc oxide-based semiconductors are finding an increasing number of applications in electronic and opto-electronic systems. Yttrium has been demonstrated as a promising alloy element to provide enhanced electrical bias stress stability in ZnO and indium zinc oxide. Here we show that the roles of yttrium in different oxide semiconductors may depend on the film crystallinity. In polycrystalline yttrium zinc oxide thin films, yttrium tends to form insulating structures along grain boundaries, hindering charge transport and increasing film resistivity, as observed by scanning spreading resistance microscopy, even for yttrium concentrations of less than 5%. In contrast in amorphous yttrium zinc oxide (Y:ZTO) thin films, which does not have grain boundaries, low concentrations of yttrium slightly enhance thin film transistor electron mobility and ensure enhancement-mode behavior. Yttrium also decreases the dark conductivity of Y:ZTO, increasing the photo-to-dark conductivity ratio.

Growth of highly conductive Ga-doped ZnO and its applications (Invited Paper)

Yu-Feng Yao, Charrong-Gan Tu, Chun-Han Lin, Chieh Hsieh, Chia-Ying Su, Erwin Zhu, Shaoobo Yang, Chi-Ming Weng, Ming-Yen Su, Meng-Che Tsai, Shang-Syuan Wu, Sheng-Hung Chen, Hao-Tsung Chen, Yean-Woei Kiang, Chih-Chung Yang, National Taiwan Univ. (Taiwan)

In this paper, we will first report the conditions for growing highly conductive Ga-doped ZnO (GaZnO) thin films and the vapor-liquid-solid (VLS) method for forming GaZnO nanoneedles (NNs) with RF-plasma assisted molecular beam epitaxy. Their material, electrical, and optical characterization results are discussed. Then, the applications of GaZnO thin films and NNs to the fabrications of core-shell GaN nanorod light-emitting diode (LED), alternating-current LED, and planar LED are reviewed. The superior performances of field emission of the GaZnO NNs, when compared with other nanostructured materials, are also presented. The differences of the behaviors of field emission and LED light extraction between vertical/parallel and randomly-oriented GaZnO NNs are compared. The causes for the improved optical and electrical properties are elucidated. Generally speaking, by using Ag nanoparticles (NPs) of a high planar density (small distances between Ag NPs) as the catalyst in the VLS growth, randomly distributed GaZnO NNs are formed. On the other hand, Ag NPs of a low planar density (large distances between Ag NPs) as the catalyst leads to the formation of vertical and parallel GaZnO NNs. Finally, the growth of Ga-doped MgZnO to serve as a transparent conductor in the UV range will be presented.
The dynamic interplay between intrinsic defects and shallow donor dopants (Al and Ga) in ZnO (Invited Paper)
Klaus Magnus Johansen, Thomas Neset Sky, Lasse Vines, Ymir Kalmann Frodason, Heine Nygaard Riise, Tor Svendsen Bjørheim, Bengt G. Svensson, Univ. I Oslo (Norway)

Donor doping of ZnO, typically by Al or Ga is of high technological importance, however, achieving 100% donor activation has proven difficult. Both passivation and compensation by, e.g., Zn-vacancies have been proposed as mechanisms for the limited activation. We have previously shown that the process of diffusion can be used as a tool to reveal insight about the interaction between the donor dopants and intrinsic defects in ZnO. A review of the results obtained by employing this recently developed reaction diffusion model for Al in ZnO will be given and extended to include Ga. Furthermore, employing such a model makes it possible to extract values from all the involved activated processes taking part in the diffusion (like migration barriers and formation energies) and compare them with results from density functional theory (DFT). These results are in accordance with recent DFT results from hybrid HSE functionals intermixing with 37% exact exchange on Ga related defects, which will also be presented.

Electrical and optical properties of ZnO:Ga bulk crystals with high gallium ions doping amount
Yunfeng Ma, Beijing Univ. of Technology (China) and Lawrence Berkeley National Lab. (United States); Yijian Jiang, Beijing Univ. of Technology (China)

ZnO-based crystal, such as ZnO:Ga, is a multifunctional semiconductor material that combines the characteristics of transparent conduction, ultra-fast scintillation and ultraviolet emission, etc. Compared with the ITO, ZnO-based transparent conductive oxide materials are of the following advantages: (1) abundant resources; low cost; (2) non-toxic, environmental protection; (3) good thermal and chemical stability; (4) wide-band gap, high light transmittance in the visible light region. The lattice distortion resulted from Gallium ions is less than from Aluminum and Indium ions in the case of equal doping amount. So Gallium ions doping can increase the carrier concentration and electrical conductivity of ZnO effectively.

In this study, we grew out cm-sized ZnO:Ga crystals with Ga2O3 doping amount of 0-1wt% by travelling solvent floating zone technique. Hall effect measurements show that the crystal of ZnO doped with 0.5 wt% Ga2O3, compared to other composition, possesses the lowest resistivity 1.08?10-3 ?cm and the highest carrier concentration 1.78?1020cm-3.

The resistivity of pure ZnO, Ga2O3-GaO-0.2wt% and Ga2O3-GaO-0.5wt% crystals as a function of temperature at the range of 90-400K show that their resistivity temperature coefficients are -6.3?10-5?°C/K, 1.27?10-6?°C/K and 7.4?10-7?°C/K respectively, which indicates that the thermal stability of ZnO:Ga crystals improves with increasing Ga doping amount. We have studied Ga doping effects of bulk ZnO:Ga crystal by means of photoluminescence (PL) measurements, which show that the UV peak broadened and blue-shift with increasing Ga doping. The measured decay time of ZnO:Ga crystal is about 0.1 ns, and its variations with Ga doping amount is negligible.

High-performance nano-thin films of transparent conducting oxides by ESAVD (Invited Paper)
Kwang-Leong Choy, Univ. College London (United Kingdom)

Uniform nano-thin transparent conducting oxides with low sheet resistance (<10 ohms/square) and high optical transmittance (>90%) have been deposited by a low cost, scalable and non-vacuum Electrostatic Spray Assisted Vapor Deposition method. They include nanostructured indium tin oxide (ITO) and antimony-doped tin oxide (ATO) thin films. Hydrogen plasma treatment has shown to have significant influence on the optical and conductivity of ITO and ATO films. ITO films fabricated by ESAVD exhibited high thermal stability as compared to sputtered ITO films at 850°C. The thermal effect on the structural, optical and electrical properties of TCO films will be discussed. The efficiency of devices using ITO diffused emitter will also be presented.

Efficient light emission from inorganic/organic semiconductor hybrid structures by energy-level tuning (Invited Paper)
Norbert Koch, Humboldt-Univ. zu Berlin (Germany) and Helmholtz-Zentrum Berlin (Germany)

The fundamental limits of inorganic semiconductors for innovative light emitting and data processing applications might be overcome by combining them with organic semiconductors, which feature fast frequency response and wide color range tunability. Hybrid inorganic/organic structures might thus exploit efficient electrical injection and high excitation density of the inorganic and subsequent energy transfer to the organic semiconductor, provided that the radiative emission yield is high. An inherent obstacle to that end is the unfavorable frontier energy level alignment at such heterostructures, which often facilitates charge transfer that quenches light emission. Technologically relevant methods to optimize heterostructure energy levels by introducing a molecular interlayer are discussed. These adjust the inorganic semiconductor work function, which leads to a proper re-alignment of the organic semiconductor levels. In turn, this directly affects the heterostructure functionality. For ZnO and a tailored ladder-type oligophenylene the heterostructure radiative emission yield could be increased sevenfold. For a molecular p-type semiconductor interfaced with ZnO we reveal interfacial hybrid charge transfer excitations, whose energy can be controlled with molecular interlayers.

Optical properties of GaN fabricated by chemical lift-off using sacrificial ZnO layers (Invited Paper)
Abdallah Ouazzaden, Georgia Tech-Lorraine (France); Cuong Ton-That, Liangchen Zhu, Matthew R. Phillips, Univ. of Technology, Sydney (Australia); A. Rajan, Heriot-Watt Univ. (United Kingdom); David J. Rogers, Nanovation (France); Simon Gautier, Tarik Moudakir, Youssef El Gmili, Georgia Tech-Lorraine (France); Vinod Eric Sandana, Ferechteh H. Teherani, Philippe Bove, Nanovation (France); K. A. Prior, Heriot-Watt Univ. (United Kingdom); Ryan McClintock, Manijeh Razeghi, Northwestern Univ. (United States)
Toward a new generation of white phosphors for solid-state lighting using glassy yttrium aluminoborates powders (Invited Paper)

Alain Ibanez, Pauline Burner, Vinicius Guimaraes, CNRS (France); Lauro J.Q. MAIA, University Federal de Goais (Brazil); Alban Ferrier, Chimie ParisTech, CNRS, UPMC (France); Bruno Viana, Ecole Nationale Supérieure de Chimie de Paris (France); Isabelle Gautier-Luneau, CNRS (France) and University J. Fourier (France)

We present a new family of highly emissive white phosphors for solid-state lighting applications. These phosphors are based on glassy yttrium aluminoborates (g-YAB) compositions and are prepared from solutions, involving non-toxic and low cost precursors by using modified Pechini method and sol-gel process. The resins are then dried and annealed at moderate temperatures, without any melting, and under controlled atmospheres. The photoluminescence (PL) of the resulting amorphous powders arises from structural defects, whose energy levels are widely extended within the large bandgap of these alumino borates materials. One of the main objectives of this work is to enhance the point defect concentrations by accurately controlling the powder annealing (temperature and atmosphere) in order to generate intense and broadband PL. Moreover, these g-YAB powders exhibit good thermal and chemical stabilities and tunable PL properties from bluish to warm white emissions, by adjusting the final annealing temperature. We determined the internal quantum yields of g-YAB powders using near ultraviolet excitations, which reached values above 90%. We quantified the relative amounts of point defects by electronic paramagnetic resonance and their distribution within the bandgap by means of thermally stimulated luminescence and we directly correlated this defect density to the PL properties. Finally, based on these promising lighting properties, a prototype was firstly developed to estimate the lighting performances of this new g-YAB phosphors family.

Efficiency enhancement by growing highly-conductive Ga-doped ZnO nanoneedles on a light-emitting diode

Yu-Feng Yao, Chun-Han Lin, Chieh Hsieh, Chia-Ying Su, Erwin Zhu, Shaobo Yang, Chi-Ming Weng, Ming-Yen Su, Meng-Chie Tsai, Shang-Syuan Wu, Sheng-Hung Chen, Chang-Gan Tu, Hao-Tsung Chen, Yean-Woei Kiang, Chih-Chung Yang, National Taiwan Univ. (Taiwan)

The combined effects of a few mechanisms for emission efficiency enhancement produced in the overgrowth of the transparent conductor layer of Ga-doped ZnO (GaZnO) on a surface Ag-nanoparticle (NP) coated light-emitting diode (LED), including surface plasmon (SP) coupling, current spreading, light extraction, and contact resistivity reduction, are demonstrated. With a relatively higher GaZnO growth temperature (350 degree C), all the Ag NPs are preserved for generating a stronger SP coupling effect. By using a thin annealed GaZnO interlayer on GaN before Ag NP fabrication, the contact resistivity at the GaZnO/p-GaN interface and hence the overall device resistance can be reduced. Although the use of this interlayer blue-shifts the localized surface plasmon resonance peak of the fabricated Ag NPs from the quantum well emission wavelength of the current study (535 nm) such that the SP coupling effect becomes weaker, it is useful for enhancing the SP coupling effect in an LED with a shorter emission wavelength.
Charging/relaxation features and multimodal uses of persistent luminescent materials (Invited Paper)

Cyrille Richard, Elliot Teston, Thomas Maldiney, Bich-Thuy Doan, Daniel Scherman, Suchinder Sharma, Didier Gourier, Bruno Viana, Ecole Nationale Supérieure de Chimie de Paris (France)

A couple of years ago, our lab pioneered the use of persistent luminescence nanomaterials for in-vivo bioimaging applications. In that context, we have shown that NIR-persistent luminescence oxide-based nanoparticles furnish images with high target to background ratio, [1]. The charging and decharging -or relaxation- processes depend on the materials and on the excitation wavelengths. For instance in ZnGa2O4:Cr gallate, it is possible to charge the materials with red photons of low energy while this is not the case in some others hosts. In addition, by working on the composition and the surface modification of such nanoparticles, we have recently observed that they could be co-doped with Gd3+ to get bi-modal imaging agents that could be both observed by optical imaging and MRI [2], but also surface modified for example with mesoporous silica could lead to theranostic agent [3]. We have also design different nanohybrids with both persistent luminescence and superparamagnetic properties to get nanoplatofrms which could be further magnetically guided [4]. These different aspects will be presented with a wide range of characterizations and applications.

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Optical and electrical properties of nanostructured indium tin oxide fabricated by oblique-angle deposition

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Indium tin oxide (ITO) is a material that is widely used in optoelectronics because it is both optically transparent and electrically conductive. In this study, oblique-angle deposition (OAD) technique is used to fabricate ITO thin-films with a porous and columnar nanostructure. We find that the structural, optical, and electrical properties of the ITO films show a strong dependence on the deposition angle which is defined, in an e-beam evaporator system, as the angle between the substrate surface normal and the direction of the vapor flux. First, as the deposition angle increases, the refractive index of the ITO film decreases and the porosity increases. Secondly, as measuring the resistivity of the ITO film at each deposition angle, we find that as the porosity increases, the resistivity of the ITO films increases super-linearly. A theoretical model is presented to describe the relationship between the ITO film’s resistivity and its porosity. Finally, transmittance measurements show that the optical bandgap of the ITO films decreases as the porosity increases. We find that such behavior is associated with the crystal quality parameter of the ITO films examined via X-ray diffraction method.
Research of controlling ZnO nanowire growth using several steps of UV-laser processing

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Zinc oxide (ZnO) is one of the promising and reasonable material for piezoelectric, sensing, field emitting devices, and ultraviolet light emitting diodes (UV-LED). Additionally, ZnO nanowires, which are characterized by their unique configurations and fine structures, can be synthesized by various methods. In our study, ZnO nanowires have been synthesized on sapphire substrates using nanoparticle-assisted pulsed laser deposition (NAPLD). Since it can be achieved without catalyst, more simple and reasonable fabrication can be expected. Recently, we have researched the variations in their crystal structures and selective growth of ZnO nanowires, because it is important to understand crystal growth mechanisms and to control the crystal growth, including their configurations, number densities, and positional control of ZnO nanowires. In this report, the overview of ZnO nanowire growth will be discussed such as the dependence on sapphire substrate-orientations and the effect of surface laser treatment of ZnO buffer layers. C-axis directed ZnO nanowires can be grown on ZnO buffer layers, which were deposited on the various oriented sapphire substrates. Crystal orientations and surface morphologies were investigated by electron back scattering diffraction measurement and field-emitter scanning electron microscopy. Additionally, selective growth of ZnO nanowires using micro laser patterning with four beam interference will be described.

Photoabsorption cross-section in the frame of local plasma frequency model for semiconductor nanoparticles on example of In2O3

Valerie A. Astapenko, Sergey V. Sakhno, Moscow Institute of Physics and Technology (Russian Federation); Mark Kozhusner, Leonid I. Trakhtenberg, N.N. Semenov Institute of Chemical Physics (Russian Federation)

The investigation is based on the spatial and energy distribution of charge in spherical semiconductor nanoparticles calculated from the first principles. It was obtained the dependencies of the densities of conduction electrons from the radius at different temperatures and various radii of the nanoparticles.

We have calculated photoabsorption cross section, based on obtained results, and formula for donor photoionization. All calculations were made for In2O3 nanoparticles. In this case total photoabsorption cross section is equal to sum of three cross sections: by electrons at a donor(1), on free electrons(2) and on the electrons on the oxygen atom surface(3).

(i) and (3) were calculated using cross section for donor photoionization, (2) was obtained using so-called local plasma frequency model and mentioned results on spatial distribution of the charge in the nanoparticle. In this approach the nanoparticle is described by the inhomogeneous distribution of the free electrons with concentration n(r), and to each point into nanoparticle space corresponding to its own local plasma frequency. The resulting dependence has three peaks, each of which corresponds to its own mechanism of photoabsorption: free electron cross section peak has central frequency about 0.08 eV; cross section on donors is much more wider and asymmetrical, with a maximum (0.25 eV) shifted to higher energy; total cross section of the electrons on the surface of the oxygen atom has negligible absolute values in infrared range because of small number of such electrons, but in the visible range it is the main mechanism of forming photoabsorption cross section.

Magnetic Field Effects of Rydberg Excitons in Cu2O (Invited Paper)

Johannes Thewes, Julian Heckötter, Marc Assmann, Dietmar Fröhlich, Technische Univ. Dortmund (Germany); Peter Grünwald, Institut für Physik, Universität Rostock (Germany); Stefan Scheel, Univ. Rostock (Germany); Manfred Bayer, Technische Univ. Dortmund (Germany)

The description of excitons as hydrogen atom-like complexes has turned out to be extremely useful for describing their optical properties. In Rydberg atoms an electron has been promoted into a state with high principal quantum number. Thereby the atom becomes a mesoscopic object with dimensions in the micrometer-range, with which for example the transition from quantum to classical dynamics can be studied. Recently it has been shown that also an exciton can be highly excited by observing states with principal quantum number up to n=25 in high-quality natural cuprous oxide crystals. This corresponds to an average radius of 1.04 µm so that the exciton wave function is extended over more than 10 billion crystal unit cells.

Two examples for results based on high spectral resolution will be given which show in particular that the hydrogen model is not fully appropriate for describing excitons because of the reduction from full rotational symmetry to discrete symmetry in the crystal:

(i) Angular momentum is not a good quantum number in a strict sense in a crystal. As a consequence high angular momentum exciton states become mixed with the dipole allowed P-excitons so that they can be observed in absorption. Moreover, they show a characteristic fine structure pattern.

(ii) In magnetic field manifold Zeeman splittings are observed which bring states belonging to different quantum numbers in resonance. In this regime clear signatures of quantum chaos can be observed in the level statistics. These studies indicate a non-trivial time-reversal symmetry breaking by the external field.

Development of low loss tellurite glass fibers for optical applications in the mid-IR (Invited Paper)

Arturo Chavez-Pirson, NP Photonics, Inc. (United States)

No Abstract Available

Optical and vibrational spectroscopy of (ZnO)kIn2O3 superlattice (Invited Paper)

Samuel Margueron, Univ. de Lorraine (France) and Harvard Univ. (United States) and Univ. de Franche-Comté (France); Stella Skiadopoulou, Jan Pokorn?, Stanislav Kamba, Institute of Physics of the ASCR, v.v.i. (Czech Republic); David R. Clarke, Harvard Univ. (United States)

Zinc oxide superlattices, consisting of single InO2 sheets interspersed every k layers of ZnO, are periodic nanostructures that form spontaneously at high-temperatures. They are of interest as transparent conductors and have good figures of merit for thermoelectric applications at high temperature. In this presentation we describe optical spectroscopy observations using ultraviolet and infrared reflectivity as well as Raman spectroscopy of polycrystalline
samples. Distinct vibrational modes and shifts in the optical absorption edge are observed that are consistent with phonon and electron confinement in the superlattice nanostructures. The most remarkable features, however, are evidence for mode dampings indicative of a strong interaction with charge carriers. After presenting the spectroscopy observations, we describe the properties of the (ZnO)kIn2O3 superlattices in terms of electron-phonon coupling and possible connection to the thermolectric properties.

9749-21, Session 4
Large persistent photoconductivity in strontium titanate single crystals
Violet M. Poole, Matthew D. McCluskey, Washington State Univ. (United States)

Strontium titanate (SrTiO3, or STO) is a complex oxide with a range of interesting properties, including a large, temperature-dependent dielectric constant and superconductivity at low temperatures. In the present work, single crystals were annealed at 1200°C, resulting in the creation of native defects. These annealed samples show persistent photoconductivity at room temperature. When irradiated with sub-gap light, the resistivity drops significantly. After the light is turned off, the increased conductivity persists for days with negligible decay. This unusual effect is attributed to the excitation of an electron from an acceptor defect into the conduction band.

A large barrier for recapture prevents electrons from returning to the defect level. Recent work suggests that optimized annealing conditions result in weakly n-type material prior to illumination, consistent with the acceptor-defect model. After illumination, the sample resistance decreases by several orders of magnitude. Possible applications, such as holographic memory and optically defined circuits, will be discussed.

9749-22, Session 4
Temperature-induced changes in optical properties of thin film TiO2-Al2O3 bi-layer structures grown by atomic layer deposition
Rizwan Ali, Univ. of Eastern Finland (Finland); Muhammad R. Saleem, Univ. of Eastern Finland (Finland) and National Univ. of Sciences and Technology (Pakistan); Seppo Honkanen, Univ. of Eastern Finland (Finland)

We investigate the optical properties and corresponding temperature-induced changes in highly uniform thin amorphous films and their bi-layer stacks grown by Atomic Layer Deposition (ALD). The environmentally driven conditions such as temperature, humidity and pressure have a significant influence on optical properties of homogeneous and heterogeneous bi-layer stacked structures of TiO2-Al2O3 and subsequently affect the specific sensitive nature of optical signals from nano-optical devices. Owing to the super hydrophilic behavior and inhibited surface defects in the form of hydrogenated species, the thermo-optic coefficient (TOC) of ~ 100 nm thick ALD–TiO2 films vary significantly with temperature, which can be used for sensing applications. On the other hand, the TOC of ~ 100 nm thick ALD–Al2O3 amorphous films show a differing behavior with temperature.

In this work, we report on reduction of surface defects in ALD–TiO2 films by depositing a number of ultra-thin ALD–Al2O3 films to act as impermeable barrier layers. The designed and fabricated heterostructures of ALD–TiO2/Al2O3 films with varying ALD–Al2O3 thicknesses are exploited to stabilize the central resonance peak of Resonant Waveguide Gratings (RWGs) in thermal environments. The temperature-dependent optical constants of ALD–TiO2/Al2O3 bi-layer films are measured by a variable angle spectroscopic ellipsometer (VASE), covering a wide spectral range 380 ≤ λ ≤ 1800 nm at a temperature range from 25 to 105 °C. The Cauchy model is used to design and retrieve refractive indices at these temperatures, measured with three angles of incidence (59°, 67°, and 75°). The optical constants of 100 nm thick ALD–TiO2 and various combinational thicknesses of ALD–Al2O3 films are used to predict TOCs using a polynomial fitting algorithm.

9749-23, Session 4
The development of thin film metrology by coherence scanning interferometry (Invited Paper)
Hirokazu Yoshino, Loughborough Univ. (United Kingdom); Daniel Mansfield, Taylor Hobson Ltd. (United Kingdom); Roger Smith, J.ohn M Walls, Loughborough Univ. (United Kingdom)

Scanning White Light Interferometry (SWLI), now referred to as Coherence Scanning Interferometry (CSI), is established as a powerful tool for sub-nanometre surface metrology. The technique provides accurate and rapid 3-D topographical measurements without contacting the surface under measurement. This paper will focus on recent developments of CSI using the HCF function that have extended its use for important thin film measurements. These developments now enable CSI to perform thin film thickness measurements, to derive optical constants (refractive index (n) and extinction coefficient (k)) and to measure the surface profile and the interfacial surface roughness of a buried interface.

9749-24, Session 4
ZnO-based multiple channel and multiple gate FinMOSFETs (Invited Paper)
Ching-Ting Lee, Hung-Lin Huang, Chun-Yen Tseng, Hsin-Ying Lee, National Cheng Kung Univ. (Taiwan)

In recent years, zinc oxide (ZnO)-based metal-oxide-semiconductor field-effect transistors (MOSFETs) have attracted much attention, because ZnO-based semiconductors possess several advantages, including large exciton binding energy, nontoxicity, biocompatibility, low material cost, and wide direct bandgap. Moreover, the ZnO-based MOSFET is one of most potential devices, due to the applications in microwave power amplifiers, logic circuits, large scale integrated circuits, and logic swing. In this study, to enhance the performances of the ZnO-based MOSFETs, the ZnO-based multiple channel and multiple gate structured FinMOSFETs were fabricated using the simple laser interference photolithography method and the self-aligned photolithography method. The multiple channel structure possessed the additional sidewall depletion width control ability to improve the channel controllability, because the multiple channel sidewall portions were surrounded by the gate electrode. Furthermore, the multiple gate structure had a shorter distance between source and gate and a shorter gate length between two gates to enhance the gate operating performances. Besides, the shorter distance between source and gate could enhance the electron velocity in the channel fin structure of the multiple gate structure. In this work, ninety channels and four gates were used in the FinMOSFETs. Consequently, the drain-source saturation current (IDS) and maximum transconductance (gm) of the ZnO-based multiple channel and multiple gate structured FinFETs operated at a drain-source voltage of 10 V and a gate-source voltage of 0 V were respectively improved from 11.5 mA/mm to 13.7 mA/mm and from 4.1 mS/mm to 6.9 mS/mm in comparison with that of the conventional ZnO-based single channel and single gate MOSFETs. This work was supported by the Advanced Optoelectronic Technology Center of the National Cheng Kung University and the Ministry of Science and Technology of the Republic of China under contract no. MOST 103-2221-E-006-004.
Nitrogen diffusion in ZnO (Invited Paper)

Norbert H. Nickel, Nicole Karpensky, Marc A. Gluba, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany)

Zinc oxide (ZnO) is attracting a lot of interest because of its electrical and optical properties for a variety of applications ranging from UV light emitting diodes and lasers to transparent conducting electrodes. However, the major drawback of ZnO is the doping asymmetry naturally favoring n-type conductivity. The fabrication of stable p-type ZnO with reasonable hole concentrations is extremely difficult. Among the group V elements nitrogen is the most prominent candidate for p-type doping.

In this paper, we investigate the diffusion of nitrogen in ZnO. The samples were deposited on sapphire substrates using pulsed laser deposition. N-doping was accomplished by microwave assisted plasma dissociation of N2O or a mixture of N2 and O2. Information on nitrogen incorporation and diffusion were obtained from gas effusion measurements and secondary ion mass spectrometry (SIMS). The gas effusion measurements revealed that the incorporation of N in the ZnO lattice strongly depends on the precursor gas. When N2O is used as the dopant source three N2 peaks are observed at 409 °C, 625 °C, and 870 °C. In addition, atomic oxygen and N2O also exhibit peaks in the effusion spectra at 409 °C and 625 °C. This suggests that nitrogen is mainly forming N2O during the effusion and atomic O and N2 molecules are byproducts that form at the filament of the mass spectrometer. On the other hand, samples doped from a mixture of N2 and O2 only exhibit an effusion peak at ≈583 °C. Based on this observation a sample was deposited where the first 0.5 μm was doped with isotopically enriched 15N and the following 0.5 μm was doped with 14N. According to SIMS measurements the isotopes did not intermix during growth. Effusion measurements show that the flux of 14N2, 14N15N, and 15N2 amounted to 5×10^10 cm^-2s^-1. The observation of a large 14N15N flux and the fact that the two isotopes are confined to different parts of the ZnO sample clearly demonstrates that nitrogen diffuses atomically. Moreover, our results establish that the molecules are formed at the sample surface.

Electrical properties of columnar-structured p-type MgZnO:Sb film grown by metalorganic chemical vapor deposition (Invited Paper)

ByeongHyeeok Kim, Yong-Seok Choi, Jang-Won Kang, Seong-Ju Park, Gwangju Institute of Science and Technology (Korea, Republic of)

ZnO is a promising material for optoelectronic device because it has attractive features such as direct wide band gap and large exciton binding energy. The realization of the full potential of ZnO in optoelectronic device application has been challenged by the availability of high conductive p-type properties. Especially to realize the ZnO ultraviolet LEDs, it is necessary to fabricate p-type MgZnO layer to confine the carriers in the active region and prevent the self-absorption of emission lights from in p-type ZnO layer. In this study, We report on the electrical properties of the columnar-structured p-type MgZnO:Sb layer grown by metalorganic chemical vapor deposition (MOCVD). We characterized the electrical properties of MgZnO:Sb layer in the lateral and vertical directions using the Hall effect and C-V measurements, respectively. The Hall effect measurements show that the columnar-structured MgZnO:Sb film has an acceptor concentration of 3.05×10^17 cm^-3. The C-V characteristic of p+Si/SiO2/MgZnO:Sb metal-insulator semiconductor (MIS) structure reveals that the MgZnO:Sb is a p-type semiconductor and the net ionized acceptor concentration is 9.31×10^17 cm^-3. The difference in electrical properties of columnar-structured p-type MgZnO:Sb indicates that more accurate hole concentration can be obtained by the C-V measurement in the vertical direction than Hall effect measurement in the lateral direction due to the large defect scattering at the grain boundary of columnar structures.

Optical and structural properties of P-doped ZnO microsphere synthesized by pulsed laser ablation

Yuki Fujiwara, Tatsuya Ikebuchi, Takeshi Ueyama, Toshinobu Tanaka, Fumiaki Nagasaki, Mitsuhiro Higashihata, Daisuke Nakamamura, Tatsuo Okada, Kyushu Univ. (Japan)

ZnO is an excellent candidate material for ultraviolet (UV) emitting devices such as UV light emitting diodes and UV lasers. In addition, ZnO nano/microstructures have attracted considerable attention because of their high crystalline quality and unique structures. We have succeeded in synthesizing micro-spherical ZnO crystals by a simple laser ablation method in air. In this method, ZnO microspheres are produced by rapid cool down of ZnO droplets generated by laser ablation and recrystallize into spherical shape by the surface tension. Thus, it is expected that this synthesizing method may accelerate the doping of acceptor impurities in ZnO microspheres. In this study, we succeeded in synthesizing P-doped ZnO microsphere using a ZnO sintered target containing 2 wt% of P2O5, which is one of the prospective material for p-type ZnO. Raman peak of the P-doped ZnO microspheres indicated local vibrational mode of P-O. Room-temperature photoluminescence properties of the microsphere were investigated under laser excitation. P-doped ZnO microspheres showed whispering-gallery-mode (WGM) lasing by optical pumping. In this contribution, we report crystalline and emission characteristics and lasing characteristics of optically-pumped single P-doped ZnO microsphere.
P-type ZnO based films and their optoelectronic applications (Invited Paper)

Chong-Xin Shan, CIOMP, Chinese Academy of Sciences (China)

Besides its large bandgap, one of the most noteworthy properties of ZnO lies in its large exciton binding energy, which ensures that efficient excitonic emission and low-threshold lasing may be realized from this material. Experimentally, ZnO luminescence and lasing have been realized. To realize efficient light-emitting devices (LEDs), pn junction is an indispensable structure. However, ZnO is intrinsically an n-type semiconductor. To construct p-n junction LEDs, p-type doping of ZnO is necessary. To realize reproducible and reliable p-type ZnO has been one of the largest challenges for ZnO-based optoelectronics, and quite a few efforts have been devoted to this issue in recent years. P-type ZnO films have been demonstrated using various dopants such as nitrogen, phosphorous, arsenic, antimony, and lithium, sodium, etc. Nevertheless, the reproducibility and reliability of p-type ZnO is still far below expectation, and the performance of ZnO-based LEDs is still very low.

In this talk, we show that by employing lithium-nitrogen codoping method, p-type ZnO films can be realized. Hall measurement indicates that the ZnO films can maintain p-type conduction for several months, indicating the good stability of the films. X-ray photoelectron spectroscopy was employed to study the doping mechanism of p-type ZnO using Li-N. LEDs fabricated from the p-type ZnO:(Li,N) shows obvious emission under the injection of continuous current. The LEDs can work continuously for around 97 hours under the injection current of 20 mA, revealing the acceptable reliability of the LEDs.

ZnMgO-based UV photodiodes: a comparison of films grown by spray pyrolysis and MBE (Invited Paper)

Adrián Hierro, Gema Tabares, Manuel Lopez-Ponce, Jose Maria M. Ulloa, Alejandro Kurtz, Elias Muñoz, Univ. Politécnica de Madrid (Spain); Vicente Marin-Borras, Vicente Muñoz-Sanjose, Univ. de València (Spain); Jean-Michel Chauveau, Ctr. de Recherche sur l’Hétéro-Epitaxie et ses Applications (France) and Univ. de Nice Sophia Antipolis (France)

In ZnMgO photodiodes the shortest achievable UV cut-off wavelength is a function of the Mg content, which in turn is dependent on the growth technique. Moreover, increasing Mg contents lead to an electrical compensation of the films, which directly impacts the responsivity of the LEDs. We report on high quality, wurtzite MgxZn1-xO epitaxial films grown via pulsed-metal organic chemical vapor deposition (PMOCVD) (Invited Paper)

Fikadu Alema, Oleg Ledyaev, Ross Miller, Valeria Beletsky, Brian Hertog, Andrei V. Osinsky, Agnitron Technology, Inc. (United States); Winston V. Schoefnfeld, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

We report on high quality, wurtzite MgxZn1-xO (MgZnO) epitaxial films grown via PMOCVD method with a record high Mg content up to 51 %. A series of MgZnO films with variable Mg content were grown on ZnO (~30 nm)/Al2O3(0001) and ZnO (~30 nm)/AlN (~25 nm)/Al2O3(0001) substrates. The band gap for the films estimated using UV-visible transmission spectroscopy ranges from 3.24 - 4.50 eV, corresponding to an Mg fraction between x=0.0 to x=0.51, as determined by RBS. The CL measurement showed a blue shift in position of MgZnO, indicating an increase in Mg content. No multi-absorption edge and CL band splitting were observed, suggesting the absence of phase segregation in the as grown films. The phase purity and crystal structure of the films were further confirmed by XRD. The absence of phase segregation is attributed to the fast periodic transition steps in the PMOCVD, creating a non-equilibrium system where radicals that are formed will have insufficient time to reach their energy...
minimum. AFM analysis on the films has shown decreasing surface roughness with increasing Mg content. MSM photodetectors were fabricated on the films to characterize their spectral response. The devices exhibit peak response between 276 and 350 nm, covering a large portion of the solar blind spectrum. Moreover, the Schottky barrier was enhanced by treating the surface with H2O2, reducing the dark current. The PMOCDV method has also been applied to obtain p and n type doped ZnO and MgZnO films and details will also be discussed.

9749-34, Session 6

Exciton localization and large Stokes shift in quaternary BeMgZnO grown by molecular beam epitaxy

Mykyta Toporkov, MD Barkat Ullah, Shoran D. Hafiz, Vitalii Avrutin, Hadis Morkoc, Umit Ozgur, Virginia Commonwealth Univ. (United States)

Owing to wide range tunability of their bandgaps beyond 4.5 eV, the quaternary (Be,Mg)ZnO solid solutions are attractive for a variety of UV optoelectronic applications, inclusive of solar blind photodetectors and intersubband transition devices. Localization effects are well pronounced in such wide-bandgap semiconductor alloys due to large differences in metal covalent radii and the lattice constants of the binaries, resulting in strain-driven compositional variations within the film and consequently large potential fluctuations, in addition to that possibly caused by defects. However, carrier localization may suppress nonradiative channels, and thus, facilitate high-efficiency optoelectronic devices. To investigate potential fluctuations in Zn- and O-polar BexMgyZn(1-x-y)O films grown by plasma-assisted molecular beam epitaxy with up to x = 0.19 and y = 0.52, temperature-dependent absorption and steady-state and time-resolved photoluminescence (PL) measurements were performed. PL transients indicate that emission at low temperature is dominated by recombination of localized excitons, which exhibit decay times as long as 0.45 ns. The localization energy for films having E0=4.0 eV characteristic energy is 160 meV, significantly larger than 60 meV reported for Mg0.2Zn0.79O thin films having χ=0.1 ns and E0=3.90 eV. This relatively high localization energy leads to a strong Stokes shift, which increased with bandgap and was -0.5 eV for the BeMgZnO layers with 4.6 eV bandgap. The results for a wide range of BeMgZnO compositions will be presented.

9749-35, Session 7

Functional oxides for integrated photonics (Invited Paper)

Stefan Abel, Thilo Stöferle, Chiara Marchiori, Daniele Caimi, Lukas Czornomaz, IBM Research - Zürich (Switzerland); Marta D. Rossell, EMPA (Switzerland); Rolf Erni, FEI Co. (Netherlands); Marilyne Sousa, Heinz Siegwart, Bert-Jan Offrein, Jean Fompeyrine, IBM Research - Zürich (Switzerland)

During the last 10 years, the quest for a replacement gate dielectric in field effect transistors has been a powerful driver to investigate the deposition of ultra thin oxide thin films. Replacing SiO2 with HfO2 in transistors was a major breakthrough for the microelectronic industry and generated a lot of know-how. This knowledge is today cross-fertilizing research areas beyond traditional CMOS microelectronics. Controlling the interface between the oxide and silicon has for example always been a key issue. This specific research triggered the development of new deposition processes, enabling researchers to grow high quality, crystalline, complex oxide films onto silicon. Such functional oxides have physical properties that make them very attractive to perform functions that will be required in future Information and Communication Systems. In particular, technologies must be developed that enable a performance scale-up of the full system, while having stagnating data processing capabilities at the chip level. Silicon photonics is emerging as one of the technology of choice for this purpose. Electro-optical oxides are therefore an extremely important area of research to enable the integration of new functionalities in advanced silicon photonics. This presentation will deal with the opportunities and challenges to combine silicon microfabrication techniques with the capability to grow crystalline directly on silicon. It will in particular focus on the use of ferroelectric perovskites for photonic circuits in future systems, and how defect chemistries might play a crucial role.

9749-36, Session 7

Oxide-based flexible flash memories (Invited Paper)

Suting Han, Li Zhou, Ye Zhou, Jiaqing Zhuang, City Univ. of Hong Kong (Hong Kong, China); Zong-Xiang Xu, South Univ. of Science and Technology of China (China) and City Univ. of Hong Kong (Hong Kong, China)

The next-generation electronic systems are expected to be light, flexible and portable for applications in large area displays, integrated circuits (ICs), light emitting diodes (LEDs), radio frequency identification (RFID) tags, solar cells and so on. Memory is an essential part of advanced electronic systems for data processing, storage and communication. In this presentation, the importance of oxide materials for flash memories on plastic substrates for data storage applications will be discussed.

Memory is an essential part of advanced electronic systems for data processing, storage and communication. Among many types of memories such as ferroelectric, electret, resistive and floating gate [1 & 2] memories, floating gate flash memory devices have gained a great deal of attention due to the simple device structure, non-destructive read-out and controlled charge trap capacity [3-5]. On this regard, solution-processable oxides with high dielectric constant (ε) exhibit great potential in the application of gate dielectrics for low-voltage transistor based flash memories. In this presentation, various oxide materials and their charge trapping ability for flash memories will be discussed. In addition, functionalization of such oxide layers and their respective surface chemistry and device properties will be discussed in detail.


9749-37, Session 7

Multifunctional materials for electronics and photonics (Invited Paper)

Federico Rosei, Univ. du Québec (Canada)

The bottom-up approach is considered a potential alternative for low cost manufacturing of nanostructured materials [1]. It is based on the concept of self-assembly of nanostructures on a substrate, and is emerging as
an alternative paradigm for traditional top down fabrication used in the semiconductor industry. We demonstrate various strategies to control nanostructure assembly (both organic and inorganic) at the nanoscale. We study, in particular, multifunctional materials, namely materials that exhibit more than one functionality, and structure/property relationships in such systems, including for example: (i) control of size and luminescence properties of semiconductor nanostructures, synthesized by reactive laser ablation [2]; (ii) we developed new experimental tools and comparison with simulations are presented to gain atomic scale insight into the surface processes that govern nucleation, growth and assembly [3-7]; (iii) we devised new strategies for synthesizing multifunctional nanoscale materials to be used for electronics and photovoltaics [8-25].

References


9749-38, Session 7

Pulsed laser deposited functional oxide thin films from the lab into the fab

Matthijn Dekkers, SolMatES B.V. (Netherlands)

It is well known that Pulsed Laser Deposition (PLD) is a very flexible and versatile technique allowing fast optimization of new thin film materials. Moreover PLD is superior above other deposition technologies for the stabilization of volatile elements and nucleation of complex oxide material systems. However, mainly because of the sample size, developed materials and processes in PLD research tools only just make it into demonstrator devices. In order to make it into commercial applications, next generation PLD equipment is needed to bridge the gap between demonstrator and the prototype – pilot – production stages.

In this contribution the latest performance and specifications of the Solmates’ PLD platforms are addressed. Data on stability and reproducibility of wafer scale deposition of oxide thin films with excellent properties will be presented. Furthermore application examples of which some are close to pilot production will be discussed:

- Electro optic switching in photonics by Pb(Zr,Ti)O3
- Damage free deposition of ITO enabling full transparent OLEDs
- Strain modulation in FinFETs
- Reflective index grading of Al2O3 and ZrO2 for LED efficiency enhancement

These examples demonstrate that PLD is a production worthy technology since processes can be transferred from the lab to the fab.

9749-39, Session 7

Reversible switching of optoelectric and electromagnetic properties of functional oxides using water-infiltrated glass (Invited Paper)

Takayoshi Katase, Hiromichi Ohta, Hokkaido Univ. (Japan)

No Abstract Available

9749-40, Session 7

Structural, magnetic and magneto optical properties of Fe3O4/NiO bilayers on MgO(001) (Invited Paper)

Joachim Wollschläger, Univ. Osnabrück (Germany); Tobias Schemme, Olga Kuschel, Univ. Osnabrück (Germany) and Cener of Physics and Chemistry of New Materials (Germany); Matthäus Witzioek, Univ. Osnabrück (Germany); Timo Kuschel, Bielefeld University (Germany); Karsten Kuepper, Univ. Osnabrück (Germany) and Center of Physics and Chemistry of New Materials (Germany)

Magnetite (Fe3O4) is an interesting material in the field of spintronics due to its halfmetallic character and its 100% spin polarization at the Fermi level. For instance, magnetic tunneling junctions may be formed using Fe3O4 electrodes. For this purpose, however, it is necessary to pin the magnetization of one of the Fe3O4 electrodes. Here, this effect may be caused by the exchange bias effect caused by antiferromagnetic layers, e.g., by NiO layers. Depositing Fe3O4/NiO bilayers on different substrates we address two key points of the exchange bias effect, namely the influence of the interface structure and of strain. For this reason, we study Fe3O4/NiO bilayers on MgO(001) and on SrTiO3(001). While MgO(001) offers the possibility of minimal strain SrTiO3(001) induces strain in the bilayer which may influence its magnetic properties.

Fe3O4/NiO bilayers are built by reactive molecular beam epitaxy where the metal is deposited in diluted oxygen atmosphere. The structural and stoichiometry properties of the surface near regions are characterized in-situ. The structure of the entire is investigated by synchrotron radiation based x-ray reflectometry and diffraction. Here we observe “normal” behavior for growth on MgO(001) while growth on SrTiO3(001) shows anomalous behavior. These differences are also seen for the macroscopic magnetic properties studied by magneto-optic Kerr effect and ferro magnetic resonances. Compared to Fe3O4/MgO(001), the easy in-plane axes of Fe3O4 rotate by 45° if SrTiO3(001) is used as substrate or if the NiO is used as buffer layer.

9749-71, Session 7

Thermoelectric behavior of ZnO and GaN-based wide bandgap semiconductors (Invited Paper)

Bahadir Kucukgok, Purdue Univ. (United States); Ian T. Ferguson, Missouri Univ. of Science and Technology (United States); Na Lu, Purdue Univ. (United States)

The field of green energy generation and hence the thermoelectric (TE) conversion of waste thermal energy into electrical energy have seen pioneering developments over the past 20 years due to increasing worldwide energy demands. A figure of merit ZT, used to measure the efficiency of the TE materials, has been the main focus when investigating new materials and structures that could potential produce higher efficiency TE devices. Various approaches have been taken to increase the efficiency of TE materials such as: electron quantum confinement, and phonon scattering to increase the power factor and decrease the lattice thermal conductivity, respectively. Additionally, high density-of-states (DOS) by size reduction, resonant states by impurity doping, and multi-valley band structure by band degeneracy have been utilized to further enhance ZT value. This work will show that Zinc Oxide (ZnO), a wide bandgap semiconductor oxide, is a promising candidate for high-temperature TE power generation owing to its enhanced chemical stability and mechanical strength, non-toxicity, and superior electrical properties. The impact of doping, and crystallographic

No Abstract Available
defects on electrical and thermal properties on the TE properties of ZnO thin films grown by metal organic vapor deposition (MOCVD) will be compared to GaN-based materials. New approaches for the future development of thermoelectric ZnO thin film for energy harvesting at high temperatures will be discussed.

9749-75, Session 7

RRAM-based hardware implementations of artificial neural networks: progress update and challenges ahead (Invited Paper)
Mirko Prezioso, F. Merrikh-Bayat, B. Chakrabarti, D. Strukov, Univ. of California, Santa Barbara (United States)

Artificial neural networks have been receiving an increasing attention due to their superior performance in many information processing tasks including pattern recognition, clustering, and data compression. Typically, scaling up the size of artificial neural network results in better performance and richer functionality. However, large networks are challenging to simulate and custom hardware development are generally required for their practical implementations.

Indeed, the common major challenge in building artificial neural networks is efficient vector-by-matrix multiplication, which in turn requires compact implementation of synaptic weights. The purely-CMOS circuits are insufficient for meeting these challenges, mostly because CMOS-implemented synapses are way too bulky. One promising solution to process information in analog form using hybrid circuits combining the existing CMOS integrated circuits with crossbar add-ons using resistive switching (“memristive”) devices. Recent experiments and theoretical estimates based on realistic simulations have shown that such hybrid circuits, being scaled down to realistic 15-nm dimensions, may provide a 1,000X increase in speed and energy-efficiency in comparison with similar networks implemented using conventional circuits.

In this presentation, we will discuss our group’s recent efforts on the development of such custom circuits. We will start by reviewing the basics of memristive devices and of hybrid CMOS/memristor circuits, in particular of CMOL variety. We will then discuss our recent progress towards demonstration of hybrid circuits, focusing on the experimental and theoretical results for artificial neural networks based on crossbar-integrated metal oxide memristors. We will conclude presentation with the discussion of the remaining challenges and the most pressing research needs.

9749-30, Session 8

Fabrication of nanoporous p-NiO by chemical lift-off from sacrificial ZnO nanoarray templates
David J. Rogers, Vinod Eric Sandana, Ferechteh H. Teherani, Philippe Bove, Nanovation (France); Ryan McClintock, Manijeh Razeghi, Northwestern Univ. (United States)

Face centred cubic (fcc) nickel oxide (NiO) was one of the first reported p-type TCOs. It has a direct wide bandgap (reported Eg between 3.4 & 4.3 eV), excellent electrochemical stability, an elevated conduction band energy level and a relatively high ionization potential. As a result of the inherent p-type nature, NiO has been investigated for wide range of existing and emerging applications. Of particular interest of late is the adoption of NiO as a p-type semiconductor for electrode for novel tandem dye sensitized solar cells (DSSCs) in which the anode is a photoelectrode based on an n-type semiconductor (usually TiO2) and the photocathode is a sensitized p-type SC. Up till now, mesoporous NiO photocathodes for DSSC applications have usually been synthesized by either solvothermal growth or electrodeposition. With pulsed-laser deposition (PLD) it was found difficult to obtain a sufficiently large surface-to-volume ratio for DSSC applications because a porous nanostructure could not be readily obtained. In this work we examine the use of zinc oxide (ZnO) nanoarrays as a template layer for the NiO which can then be lifted off chemically by preferentially etching away the ZnO to leave a highly porous NiO surface.

References

9749-68, Session 8

Delafossites for p-type dye-sensitized solar cells (Invited Paper)
Yiying Wu, The Ohio State Univ. (United States)
No Abstract Available

9749-70, Session 8

Emerging oxide materials for solar energy conversion applications (Invited Paper)
Andriy Zakutayev, National Renewable Energy Lab. (United States)

Solar energy conversion applications, including photovoltaic energy generation and photoelectrochemical fuel production, require thin film
oxide materials in the device stacks. However, the desired combination of properties, such as optical transparency and p-type conductivity for p-type TCOs, or strong optical absorption and good electronic transport for oxide-based absorbers, is often difficult to achieve in the well-established oxide materials (e.g., ZnO, In2O3, SnO2). In this talk, I will present on our recent work in the area of emerging oxide materials for solar energy conversion applications. The research is performed using thin-film combinatorial experiments supported by high-throughput first-principles calculations. Following a brief summary of the prior work on novel p-type oxides for electrode applications in organic photovoltaics and p-type dye-sensitized solar cells (e.g. Co-based spines), I will focus on the more recent results in the area of oxide-based light absorbers for photovoltaics and photoelectrochemistry. The outcomes of these studies are isovalent but heterostructural metastable alloys based on MnO and SnO, that have both good optical absorption and reasonable carrier transport for solar energy conversion applications.

9749-73, Session 8

Recent progress in p-DSSCs (Invited Paper)
Dirk M. Guld, Friedrich-Alexander-Universitii, Erlangen-
Nürnbeg (Germany)
No Abstract Available

9749-76, Session 8

New electrolytes and semiconductors for dye-sensitized photocathodes (Invited Paper)
Udo Bach, Monash Univ. (Australia) and Commonwealth Scientific and Industrial Research Organization (Australia)

In dye-sensitized photocathodes (p-DSSCs) light absorption is followed by electron transfer from the valence band of a p-type semiconductor to the photoexcited sensitizer. Subsequently the photoexcited dye is oxidized by a redox mediator in the electrolyte, completing the initial charge separation process. Recently p-DSSCs received increasing attention due to the scope of building dye-sensitized tandem solar cells by combining them with conventional photoanodes (n-DSSC) in a simple sandwich device. Such multi-junction devices potentially offer the scope to increase the efficiency of DSC beyond their current efficiency limit. So far such efforts have been hampered by the generally modest performance of p-DSSCs and prevailing current matching requirements in these series-connected devices. Here we will present a more in-depth analysis of the factors affecting the overall performance of p-DSSCs. We will in particular focus on the origin of the generally modest fill factors observed in these devices. Subsequently we will summarize our recent efforts to increase the performance of these devices by introducing novel materials. These will include novel p-type semiconductors such as CuCrO2, as well as transition-metal based complexes such as the tris(1,2-diaminoethane)cobalt(II/III) complex \((\text{Co(en)}_3)^2+/3^+\), resulting in a more then doubling of the energy conversion efficiency compared to iodine-electrolyte based devices. We will further explore more unconventional semiconductor choices for p-DSSCs, such as indium-doped tin oxide.

9749-42, Session 9

Solution synthesis of metal oxide nanoparticles for interfacial contact layers in organic photovoltaics (Invited Paper)
Jian Wang, Yun-Ju Lee, Diego Barrera, Julia W. P. Hsu, The Univ. of Texas at Dallas (United States)

Inserting interfacial contact layers (ICL) at the active layer/electrode interface has been shown to significantly improve organic photovoltaic (OPV) performance. Metal oxide nanoparticle suspensions that can form a uniform thin (~ 20 nm) film are highly desirable because they are compatible with large-area, low-cost manufacturing processes for OPV. Additionally, the electronic properties of the metal oxide nanoparticle films need to meet the band alignment requirement in the device. Here we show three examples: (1) ZnO with tunable bandgap and work functions for electron transport layer (ETL), (2) 1-2 nm n-type MoOx nanoparticles for hole transport layer (HTL), and (3) Cu-based delafossite nanoparticles, CuMIIIO2 (M = Ga or Cr), as p-type HTL. Microwave heating is used for all syntheses because it provides fast and uniform heating and results in smaller size and narrower distribution. N-butanol is the preferred solvent because it wets both hydrophobic and hydrophilic surfaces. Our approach separates materials synthesis from device processing with the possibility of optimization for each. We will show OPV performance comparable to using standard ICL electrode materials.

REFERENCES
Electrodeposition of ZnO-doped films as window layer for Cd-free CIGS-based solar cells

Fabien Tsin, EDF R&D (France); Amélie Vénérosy, Ctr. National de la Recherche Scientifique (France); Thibaud Hildebrandt, EDF R&D (France); Dimitrios Hariskos, Zentrum für Sonnenenergie- und Wasserstoff-Forschung (Germany); Negar Naghavi, Institut de Recherche et Développement sur l’Energie Photovoltaïque (France); Daniel Lincot, Ctr. National de la Recherche Scientifique (France); Jean Rousset, EDF R&D (France)

The Cu(In,Ga)Se2 (CIGS) thin film solar cell technology has made a steady progress within the last decade reaching efficiency up to 21.7% on laboratory scale, thus surpassing the highest efficiency for polycrystalline silicon cells. High efficiency CIGS modules employ a so-called buffer layer of CdS deposited by chemical bath deposition (CBD), which presence and Cd-containing waste treatment present some environmental concern. A second potential bottleneck of the CIGS technology is its window layer based on i-ZnO/ZnO:A1, which is deposited by sputtering requiring expensive vacuum equipment. A non-vacuum deposition of TCO relying on simpler equipment with lower investment costs will be more economically attractive and could increase competitiveness of CIGS modules with the mainstream silicon-based technologies.

In the frame of NovaZOlar project, we have developed a low-cost aqueous solution photo assisted electrodeposition process of the ZnO-based window layer for high-efficiency CIGS solar cells. The window layer deposition have been first optimized on classical CdS buffer layer leading to cells with efficiencies similar to those measured with the sputtered references on the same absorber (14.3%). Then the optimized ZnO doped layered has been adapted to Cadmium free devices where the CdS is replaced by chemically bath deposited Zn(SO) buffer layer. The effect of different growth parameters has been studied on CBDZnS(Zn,S):Se2 plated coevaporated Cu(In,Ga)Se2 provided by ZSW. This optimization work leads, in a first stage, to the fabrication of a 13.9 % cell efficiency on coevaporated Cu(In,Ga)Se2 which has been measured at 15.2 % with a ZnS/sputtered ZnMgO/ZnO:A1 front contact.

Titanium oxide: electron-selective layers for contact passivation of thin-film crystalline silicon solar cells

Yi Liu, Peking Univ. (China); Yusi Chen, Yangsen Kang, Huifang Deng, Jieyang Jia, Li Zhao, David T. LaFehr, Stanford Univ. (United States); Mengyang Yuan, Zheng Lyu, Tsinghua Univ. (China); Daniel DeWitt, Max A. Vilgalys, Kai Zang, Xiaochi Chen, Ching-Ying Lu, Yijie Huo, Stanford Univ. (United States); James S. Harris, Stanford Univ. (United States) and Stanford Univ. (United States) and Stanford Univ. (United States)

Thin-film crystalline silicon (c-Si) solar cells have been intensely studied recently, as they have great potential to substantially decrease the cost and increase the energy conversion efficiency. Despite the decent short-circuit-current (Jsc) due to good photon management, however, overall efficiency of thin-film c-Si solar cells in previous works was well below the theoretically projected efficiency. This is mainly because of the low open-circuit-voltage (Voc) due to the high recombination. As the thickness of c-Si solar cell decreases, the bulk recombination is significantly reduced, while the surface recombination, especially the recombination at metal contacts, becomes the main challenge. Therefore, passivated contacts with carrier-selective layers are important to highly efficient c-Si thin-film solar cells, as they can significantly reduce the minority carrier recombination and improve the majority carrier transport.

In this work, we report the use of atomic-layer-deposited (ALD) TiOx thin films as electron-selective layers, forming metal-insulator-semiconductor (MIS) type contacts. The carrier-selection effect was demonstrated respectively on intrinsic, n-type and n+-type silicon surfaces. Contact recombination current J0c and contact resistivity Rc, two major parameters for evaluating the contact passivation effect, were studied. The J0c was extracted from minority carrier lifetime measurement with Kane and Swanson method, while the Rc was obtained via the transfer length method (TLM). The reduced J0c indicated a possible higher open-circuit voltage for devices, and the low resistivity exhibited improved conductivity. In addition, the effect of rapid-thermal-anneal (RTA) on contact performance was also investigated. This study provides a new path towards achieving high-efficiency thin-film c-Si solar cells.

High-efficiency PTB7-based inverted organic photovoltaics on nano-ridged and planar zinc-oxide electron transport layers

Beau J. Richardson, Xuezhen Wang, Abdulrahman Almutairi, Qiuming Yu, Univ. of Washington (United States)

Inverted organic photovoltaics (OPVs) have gained considerable attention as they offer increased device stability and processing advantages. ZnO serves as an effective electron transport layer (ETL) in inverted OPVs while efficiently blocking holes. In this work, the sol gel precursor concentration, spin coating speed and baking conditions were used to simultaneously control the film thickness and morphology of ZnO ETLs in inverted devices using the active layer of poly thiophene[3,4-b]thiophene/benzodithiophene (PTB7)@[6,6]-phenyl C71-butyric acid methyl ester (PC71BM) bulk heterojunction (BHJ). Nano-ridged and planar structures of ZnO films were obtained simply by dynamically and statically baking the precursor films, respectively. The optical properties for each ZnO condition were measured and used in transfer matrix method (TMM) calculations to evaluate their effect on device performance. The calculated optical field distributions for completed devices are discussed in conjunction with the measured ZnO morphology and thicknesses and active layer conditions. Consistently high FF’s exceeding 70% and PCEs averaging 7.65-8.01% with a maximum PCE reaching 8.32% were achieved on both nano-ridged and planar ZnO films when the active layer was maintained at ~94 nm. This insensitivity of device performance to ZnO variations is discussed in the context of the small device microstructures of the PTB7:PC71BM active layer as well as the rapid intramolecular charge separation and highly efficient photovoltaic function of PTB7. In addition, the need for fine control of the active layer thickness as underlying ZnO layer morphology changes is highlighted as the primary variable for achieving high performance in these devices.
the development and implementation in the production line of Cd-free buffer layers. The CBD-Zn(S,O) remains one of the most studied buffer layer for replacing the CdS in Cu(In,Ga)Se2-based solar cells and has already demonstrated its potential to lead to high-efficiency solar cells up to 20.8%. However one of the key issue to implement a CBD-Zn(S,O) process in a CIGSe production line is the cells stability, which depends both on the deposition conditions of CBD-Zn(S,O) and on a good band alignment between CIGSe/Zn(S,O)/windows layers. The most common window layers applied in CIGSe solar cells consist of two layers: a thin (50–100 nm) and highly resistive i-ZnO layer deposited by magnetron sputtering and a transparent conducting 300–500 nm ZnO:Al layer. In the case of CBD-Zn(S,O) buffer layer, the nature and deposition conditions of both Zn(S,O) and the undoped window layer can strongly influence the performance and stability of cells. The present contribution will be specially focused on the effect of condition growth of CBD-Zn(S,O) buffer layers and the impact of the composition and deposition conditions of the undoped window layers such as ZnMgO or ZnSnO on the stability and performance of these solar cells.

9749-51, Session 10

Comparison between different metal oxide nanostructures and nanocomposites for sensing, energy generation, and energy harvesting (Invited Paper)

Magnus Willander, Hatim Alnoor, Sami Elhag, Linköping Univ. (Sweden); Zafar Hussain, University of Sindh (Pakistan); Eiman Satti Nour, Omer Nur, Linköping Univ. (Sweden)

I will give a review of our recent results on different nanocomposites and nanostructures for different chemical sensing. The second part deals with the same comparison for water splitting. Finally I will take up some recent results on how to use mechanical harvesting for conversion to electrical energy using different nanostructures. The platform is both flexible substrates as well as solid substrates.

9749-53, Session 10

Luminescence thermometry and nanothermometry (Invited Paper)

Miroslav D Dramicanin, University of Belgrade (Serbia)

Temperature is by far the most-measured physical quantity since the precise and reliable assessment of temperature is crucial in many aspects of daily life. Temperature sensors are therefore extensively used, accounting for about 75–80% of the world’s sensor market. With the use of various types of molecular species, nanomaterials, or bulk materials, temperature evolution can be remotely determined by measuring changes in the luminescent properties of the probe, such as absolute and relative emission intensities, lifetime values of excited states, emission rise times, peak positions, and emission bandwidths. What is more, luminescence thermometry is among just a few prospective routes for temperature measurements at the nanoscale. In this lecture an overview of oxide materials suitable for application in luminescence thermometry and nanothermometry is given [1-4]. Different modalities of luminescence thermometry are discussed, such as the use of materials with a single- or multi- emission centers, the selection of the reference emission, and advantages or disadvantages of the emission intensity measurements versus measurements of temporal changes in emission. An emphasis will be given on the use of downconversion and upconversion emission of rare-earth-doped oxides (both bulk and nano) for luminescence thermometry.


9749-55, Session 10

Zinc-oxide optical sensor for highly sensitive refractive index sensing

Jing Liu, Qiankun Zhang, Tianjin Univ. (China)

We propose a Zinc Oxide (ZnO) nanorod based optical sensor for highly sensitive refractive index (RI) detection. The sensor is fabricated by sequentially growing a seed-layer and nanorod array of ZnO at the endface of an optical fiber. The light coupled into the optical fiber is partially reflected at the seed-layer and nanorod array-analyte interface, respectively, generating an interference spectrum. When the RI of the media filling among the ZnO nanorods changes, the light path between the two reflective surfaces changes, resulting in the shift of the interference spectrum. Therefore, by monitoring the interference shift, it can detect the RI change of the analyte. The proposed sensor has several unique advantages: 1) the sensor is highly sensitive, because light travels through the whole ZnO nanorod array, and thus has full interaction with the analyte that fills the gaps among ZnO nanorods; 2) the sensing cavity of the sensor is easily accessible to the analyte and has miniaturized size, which enables it to be easily integrated with microfluidic systems for on-line real-time sensing; 3) the seed-layer and nanorod array of ZnO is fabricated by hydrothermal method which is simple and inexpensive, significantly lowering the fabrication cost. The sensing capability of the sensor is calibrated by integrating it with a micro-fluidic channel and flowing through mixtures of ethanol and DI water with various concentrations ranging from 0.1% to 10% (v/v). The result shows that the sensor can detect a minimum concentration of 17 nM/mL, corresponding to a RI change of 6*10^-5.

9749-54, Session 10

Climate engineering with oxide photocatalysts

Hal Gokturk, Ecoken (United States)

Climate engineering (CE), which can be defined as any scientific intervention that changes the climate towards the better, can be performed on a global scale if solar energy can be utilized for the CE process. Photocatalysts which are activated by sunlight are promising materials to design CE processes such as neutralization of pollutants in the atmosphere or creation of cloud condensation nuclei.

In this research sequestration of CO2 in air with titanium oxide (TiO2) photocatalysts is investigated. Two types of interactions are of interest: (a) CO2 versus the photocatalytic surface, (b) CO2 versus reactive gas species (O2-, OH, OH-) generated by the photocatalyst.

The analysis is carried out with quantum mechanical calculations using the DFT method with B3LYP functional and Pople type basis sets. Atomic models consist of CO2 interacting with an anatase type TiO2 nanoparticle and other gas molecules of interest. The calculation determines positioning of CO2 with respect to the nanoparticle and other gases. Proximity and interaction energy, IE are derived from the result.

CO2 is positioned at 0.24 nm from the TiO2 surface and IE=0.39 eV. CO2 is at 0.25 nm from the superoxide ion (O2-) and 0.22 nm from the neutral hydroxyl molecule (OH); IE=0.30 eV and 0.08 eV, respectively. As for the hydroxyl ion (OH-), CO2 reacts with it to form HCO3-; binding energy is 2.25 eV.

Results indicate that CO2 does not react with the TiO2 surface, but it can be sequestered with negative ions generated by the photocatalyst.
Impact of glycerol on zinc-oxide-based thin film transistors with indium molybdenum oxide transparent electrodes

Mateusz T. Madzik, Elangovan Elamurugu, Raquel Flores, Jaime Viegas, Masdar Institute of Science & Technology (United Arab Emirates)

Metal oxide transistors are widely studied due to their transparency, making them ideal for display and sensor applications. We report the fabrication of thin film transistors with zinc oxide channel and indium molybdenum oxide electrodes by room temperature sputtering, and with channel width and length from 10um to 300um. For process simplification a fixed gate electrode TFT was used. Output and transfer characteristics were extracted to study the performance of created devices. Once the reference data is taken, thin film transistors were then exposed to the presence of glycerol. We observe a large dynamic but temporary effect and a residual permanent change in device performance after immersion of the FET in glycerol. Control structures without the channel material are also used for demonstrating that the effect of saturation current increase is not due to glycerol alone as sugar alcohol is a low conducting medium. The thin film transistors were studied with and without glycerol, with different immersion time and glycerol concentration. Change in saturation current, threshold voltage, turn-on resistance and other important transistor parameters were extracted. Reflectance and ellipsometry data were also collected and compared to pre-soak in glycerol spectra, to quantify optical changes and compare to electronic variations. The experimental data may lead to numerous applications including sensing and performance enhancement by post-fabrication properties modification. The presented results are useful for further integration of photonics and electronics in sensing applications.

Spatially resolved resistance of NiO nanostructures under humid environment

Christopher Jacobs, Oak Ridge National Lab. (United States); Anton V Ivlev, Liam F Collins, Oak Ridge National Labs (United States); Eric S. Muckley, Pooran C. Joshi, Ilia N. Ivanov, Oak Ridge National Lab. (United States)

Production of metal-oxide and/or metal-sulfide thin film sensing devices typically is an energy intensive process relying on high temperatures during both synthesis and sensing.[1] We report here on the development of flexible thin-film sensors produced using low-cost starting materials and low-temperature deposition, reducing the overall energy cost of production. Energy saving originates during the low-temperature nanofermentation synthesis of nanoparticles from starting materials, synthesized by anaerobic metal-reducing bacteria.[2,3] The particles were processed into targets for pulsed laser or rf-sputtering deposition, compatible with large scale production on flexible substrates. Pressure and oxygen concentration during deposition defines the composition of the final film, which can vary from the metal-sulfide to metal-oxide and intermediate/mixed compositions, while concurrently changing the impedance response of the film. Using pulsed laser deposition, we manufactured flexible sensors on polymeric substrates from ZnO and ZnS thin-films synthesized at temperatures as low as 150 °C, using nanofermented nanoparticles as starting material. These sensors were found to be sensitive to UV-light, as well as to gases such as oxygen and humidity. While metal-oxide sensors, such as ZnO and NiO, typically require temperatures around 400 °C to effectively recover from gas adsorption, polymeric substrates cannot handle such high temperatures. Instead, we found that UV irradiation leads to reversible response and increased sensitivity to both humidity and oxygen. Statistical data analysis was used to decipher the sensor response to water and oxygen, and shows different chemical sensing mechanisms under dark and irradiated conditions, and suggests that water and oxygen also have different, but mixed-sensing mechanisms under UV-irradiated conditions.

Low-temperature and UV-irradiation treatments of porous titania-capped silica GNRs for dye solar cells (DSCs)

Sarah Lai, Sonia Centi, Marina Mazzoni, Fulvio Ratto, Consiglio Nazionale delle Ricerche (Italy) and Istituto di Fisica Applicata “Nello Carrara” (Italy); Roberto Pini, Istituto di Fisica Applicata “Nello Carrara” (Italy); Andrea Ilenco, Lorenzo Zani, Gianna Reginato, Consiglio Nazionale delle Ricerche (Italy) and Istituto di Chimica dei Composti OrganoMetallici (Italy)

In the last years, Dye Solar Cells (DSCs) have attracted international interest as new photovoltaic (PV) technologies with the potential of reducing manufacturing costs by exploiting printing techniques for materials deposition. For this particular application transparency in the 500 – 600 nm is a stringent demand that in most cases implied the use a co-sensitizing NIR dye in addition to a dye sensitizer in the visible region. Plasmonic gold nanoparticles (gold nanorods, GNRs) with a thin insulating shell, such as silica, could be incorporated into PV cells to enhance the organic dye adsorption, especially in the far red part of the visible and NIR dye spectra. In this work, we prepared a nanostructured material made of a core of gold nanorods encapsulated into a silica shell. Finally, each silica gold nanorods were coated with a porous titania shell. Titania coating and silica shell were grown by modified self-assembly method in one-step or two-step procedures. The coating of titania on sylanized GNRs should ensure a protection for any variations in shape due to the next sintering treatment. The titania-silica-GNRs films were printed on the glass substrate and two different sintering treatments were applied: Uv-light and thermal (120°C) processing using both a binder-free paste and a formulation containing a hydroxethyl cellulose (HEC). Before and after sintering procedure GNRs coated with silica and titania were characterized morphologically, by TEM, DLS and X-ray diffraction and optically by Uv-Vis spectrophotometry. Preliminary results showed a good retain of nanorods shape and optical properties and a promising efficiency.

Indium oxide-based perovskite solar cells

Qi Dong, Fangzhou Liu, Man Kwong Wong, Aleksandra B. Djuric?, The Univ. of Hong Kong (Hong Kong, China); Zhiwei Ren, Annie Ng, Qian Shen, Charles Surya, The Univ of Hong Kong Polytechnic Univ. (Hong Kong, China); Wai Kin Chan, The Univ. of Hong Kong (Hong Kong, China)

Hybrid organic-inorganic perovskite solar cells have attracted lots of attention in recent years. With the utilization of solid state hole transporting layer (HTL) and optimization of the active layer, the power conversion efficiency reported by now is up to 20%, which is much higher than that of polymer solar cells. Besides, the solution processing reduced the cost greatly compared to conventional silicon photovoltaics. Growth and properties of perovskite layer and its relationship to photovoltaic performance have been extensively studied. Comparably less attention was devoted to the research of the influence of electron transporting layer
9749-58, Poster Session

A novel flexible C2H2 gas sensor based on Ag-ZnO nanorods on PI/PTFE substrate

A. S. M. Iftekhar Uddin, Gwiy-Sang Chung, Univ. of Ulsan (Korea, Republic of)

In this work a novel acetylene (C2H2) gas sensor based on Ag nanoparticles decorated vertical ZnO nanorods (Ag-ZnO NRS) on PI/PTFE substrate has been investigated. The grown structure was synthesized through a simple, rapid, and low-temperature hydrothermal-RF magnetron sputtering method. The successful immobilization of Ag nanoparticles (NPs) onto the surface of ZnO nanorods contributed large effective surface area and facilitated the charge transfer process. The as-fabricated sensor exhibited enhanced C2H2 sensing performances at low temperature (200°C) including a broad detection range (3 - 1000 ppm), and short recovery time (39 sec). Mechanical robustness and device flexibility were investigated at different curvature angle (0 - 90°) and several times bending-relaxing process (0 – 5 • 105 times). The sensor exhibited stable response magnitude with a negligible drift of ~2% for a maximum bending angle of 90° and a response drop of 8% after 5 • 104 bending/relaxing processes. The superior sensing features along with outstanding flexibility to extreme bending stress indicate the sensor a promising candidate for the development of practical flexible C2H2 gas sensors.

9749-59, Poster Session

Highly flexible room temperature NO2 sensor based on WO3 nanoparticles loaded MWCNTs-RGO hybrid

Usman Yaqoob, Gwiy-Sang Chung, Univ. of Ulsan (Korea, Republic of)

Fabrication and evaluation of a flexible NO2 sensor based on tungsten trioxide nanoparticles-loaded multi-walled carbon nanotubes-reduced graphene oxide hybrid (WO3 NPs-loaded MWCNTs-RGO) on a polyimide/polyethylene terephthalate (PI/PET) substrate have been investigated. A viscous gel of the hybrid materials (WO3-MWCNTs-RGO) was prepared with the assistance of ?-terpineol. To observe the physical and crystalline properties of hybrid materials FESEM, TEM and XRD was carried-out. Afterwards, sensor was fabricated by drop casting hybrid solution between two fingers gold (Au) electrodes. Finally, gas sensing properties were taken out in open air environment. The sensor showed excellent sensing performance towards NO2 including a maximum response of 17% (to 5 ppm), a limit of detection (LOD) of 1 ppm, and relatively short response/recovery time (7/15 min). The sensing behaviors of the fabricated flexible sensor were evaluated systematically at different curvature angles (0-90°) and after several times bending and relaxing (0-107). The sensor exhibited excellent mechanical flexibility and sensing properties at room temperature without any significant performance degradation even at a curvature angle of 90° and after 106 times bending and relaxing process. The results indicates that economical, light weight and mechanical robustness of the proposed WO3 NPs-MWCNTs-RGO hybrid based sensor can be a promising building block for the development of high performance flexible NO2 sensors.

9749-60, Poster Session

Effects of palladium nanocrystal morphologies on hydrogen sensors based on palladium-graphene hybrid

Duy-Thach Phan, Gwiy-Sang Chung, Univ. of Ulsan (Korea, Republic of)

In this study, we demonstrate the effects of palladium (Pd) nanocrystal morphologies on hydrogen (H2) sensors based on Pd-graphene (Gr) hybrid nanomaterials. The Pd nanocrystal with different morphologies of nanocube, nanoporous and core-shell structures were synthesized in colloidal state by a chemical route in two-steps (seed-mediated growth) and then, simply reduced into graphene flakes by hydrazine in a simple one-step process. Resulting in H2 sensors based on Pd-graphene hybrid have such advantages of high sensitivity, good selectivity and stability. Especially, Pd nanoporous and Pt/Pd core-shell structures yield a fast response/recovery time and a large detectable range of H2 gas even at room temperature. The different H2 response properties of various Pd morphologies in hybrid with graphene were investigated and emphasized in this work. These Pd nanocrystal will be applied for optical H2 sensor based on surface plasmon resonance (SPR) in future works. The relationship between resistivity-type and optical-type H2 sensor based on Pd nanocrystal-graphene hybrid will be discussed in this work.

9749-61, Poster Session

Performance improvement of ZnO-nanorod-structured pressure sensors using photo-assisted method

Ching-Ting Lee, National Cheng Kung Univ. (Taiwan)

In view of the inherent merits such as nanoscale, wide direct bandgap, large exciton binding energy, high surface-to-volume ratio, and piezoelectric properties, the ZnO nanorod-based materials have been extensively developed as various optoelectronic devices1 and piezoelectric devices2. The ZnO nanorod-based piezoelectric devices were usually built on the basis of piezoelectricity which is a coupling relation between the mechanical and electrical behaviors. During the operation of ZnO nanorod-based piezoelectric devices, the piezoelectric potential drop would be induced along with the straining direction of the ZnO nanorods when a mechanical stress applied on the ZnO nanorods. However, the ZnO nanorods-structured piezoelectric devices may suffer from the low current transportation that influenced the reflected piezoelectric potential per unit pressure. Therefore, to develop the high sensitive pressure sensors, the conductivity of the ZnO nanorods-structured piezoelectric devices should be improved. Generally, when the ZnO nanorod was illuminated by the ultraviolet light with photon energy larger than its energy band gap, a larger conductivity can be resulted owing to the appearance of photogenerated electron-hole pairs in the ZnO nanorod. In this work, a photo-assisted method was applied to ZnO nanorod-structured pressure sensors using photo-assisted method. The ZnO nanorod-structured pressure sensors with photo-assisted method using 365 nm UV illumination exhibited better sensitivity of 7.89 ?A/cm2/mN when the pressure sensor was operated under the applied pressure from 0.15 mN/cm2 to 3.06 mN/cm2. The result was obviously better than the sensitivity of 0.027 ?A/cm2/mN of the pressure sensor without photo-assisted method.

9749-62, Poster Session

Performance improvement of n-type ZnO nanorod-structured pressure sensors using photo-assisted method

Jung-Hoon Yoon, Soomin Kim, Sung-Chul Ahn, Kyung-Dae Lee, Yongsik Yoo, Sung-Man Son, Daeil Kim, Yong-Jin Lee, Gwiy-Sang Chung, Univ. of Ulsan (Korea, Republic of)

The piezoelectric potential generated on the ZnO nanorod surface is proportional to the applied pressure. Therefore, the piezoelectric potential drop would be induced along with the straining direction of the ZnO nanorods when a mechanical stress applied on the ZnO nanorods. However, the ZnO nanorods-structured piezoelectric devices may suffer from the low current transportation that influenced the reflected piezoelectric potential per unit pressure. Therefore, to develop the high sensitive pressure sensors, the conductivity of the ZnO nanorods-structured piezoelectric devices should be improved. Generally, when the ZnO nanorod was illuminated by the ultraviolet light with photon energy larger than its energy band gap, a larger conductivity can be resulted owing to the appearance of photogenerated electron-hole pairs in the ZnO nanorod. In this work, a photo-assisted method was applied to ZnO nanorod-structured pressure sensors using photo-assisted method. The ZnO nanorod-structured pressure sensors with photo-assisted method using 365 nm UV illumination exhibited better sensitivity of 7.89 ?A/cm2/mN when the pressure sensor was operated under the applied pressure from 0.15 mN/cm2 to 3.06 mN/cm2. The result was obviously better than the sensitivity of 0.027 ?A/cm2/mN of the pressure sensor without photo-assisted method.
9749-62, Poster Session

**Integration of ZnO-based surface acoustic wave devices on steel substrates through use of an insulating a-SiO2 underlayer**

David J. Rogers, Vinod Eric Sandana, Philippe Bove, Ferechtah H. Teherani, Nanovation (France)

ZnO is well-known as a piezoelectric material for use in surface acoustic wave (SAW) devices in delay lines, filters, sensors, resonators in wireless communications & signal processing. Steel is a potentially interesting substrate of choice due to the potential for straightforward integration of acoustic elements with ubiquitous steel structures. In this study, we investigate the possibility of integrating SAW devices on steel by introduction of an amorphous SiO2 underlayer which suppresses current leakage into the steel when a voltage is applied between interdigit transducers.

9749-64, Poster Session

**Oxide nano-ions for carbon dioxide sequestration**

Hal Gokturk, Ecoken (United States)

Among various options which are being studied to combat global warming, the most viable solution is conversion of carbon dioxide (CO2) to a beneficial product, because such a solution can be deployed worldwide, even in emerging economies, to extract the economic value. One such approach is mineralization of CO2 generated during combustion of fossil fuels to carbonates which can be utilized in construction materials like cement. CO2 and water vapor (H2O) which serve as reactants for the carbonate are both available in the exhaust gas. However, the reaction (CO2 + H2O -> H2CO3) does not proceed rapidly due to an activation barrier. What is proposed in this research is lowering of the barrier by adding oxide nanoions to the mineralization process. Nanoions chosen for the study are sulphate (SO4), phosphate (PO4) and silicate (SiO4) carrying a negative charge of -2 to -4, respectively. The reaction barrier is investigated by quantum mechanical calculations using the DFT method with B3LYP functional and Pople type basis sets. Atomic models consist of the selected nanoions surrounded by H2O. CO2 is the second nearest neighbor of the nanoion. Calculated value of the reaction barrier without any ion is 2.0 eV. This barrier is lowered to zero in the presence of the nanoions and the reactions yield H2CO3 with sulfate, HCO3- with phosphate and CO3-- with silicate ions. These results are promising for rapid mineralization of CO2 by incorporating oxide nanoions into the exhaust gas.

9749-65, Poster Session

**Enhancement in optical and structural properties of Zn0.85Mg0.15O nanorods over thin films synthesized by hydrothermal chemical treatment**

Punam Murkute, Shantanu Saha, Sushil Pandey, Indian Institute of Technology Bombay (India); Anwesha Chatterjee, Jadavpur Univ. (India); Dipanjan Datta, Heritage Institute of Technology Bombay (India); Subhananda Chakrabarti, Indian Institute of Technology Bombay (India)

In this paper we report a detailed investigation of ZnO thin films deposited on Si(100) substrate using dielectric sputter followed by annealing in oxygen ambient at temperature 700, 800 and 900° C for 10 seconds to reduce oxygen vacancies defects. Deposited thin film annealed at 900 °C (sample A) measured highest peak intensity and it was subjected to controlled hydrothermal bath conditioning for forming hexagonal nanorods. Four samples were dipped in 2 different solutions with variable molar ratio of zinc acetate hexahydrate and hexamethionine for 2 and 3 hrs respectively. Samples processed in solution 1 (1:1) ratio for 2 and 3 hrs were namely B & C and those in solution 2 (2:1) were D & E respectively. Photoluminescence measurement at 18K demonstrates excitonic near-band-edge (NBE) emission peak at 3.61eV from Zn0.85Mg0.15O sample A whereas other samples exhibited slight blue shift along with bimodal peaks. The other peak observed at lower energy 3.43eV corresponds to transitions due to presence of ZnO phase in Zn0.85Mg0.15O. All samples compared to sample A exhibited more than 10 times increment in peak intensities with sample B producing the highest (~ 20 times). Nanorods formation was confirmed using crosssectional SEM imaging. X-ray diffraction measurements revealed that all Zn0.85Mg0.15O samples had (002) preferred crystal orientation with peak position at 34.7 °. All nanorods samples measured lower reflectance compared to sample A indicating high absorption in nanorods due to high scattering of light at the nanorods surface. DST, NCPRE and IITBNF are acknowledged.

9749-66, Poster Session

**Influence of oxygen partial pressure on optical and structural properties of RF sputtered ZnO thin films**

Punam Murkute, Shantanu Saha, Sushil Pandey, Indian Institute of Technology Bombay (India); Anwesha Chatterjee, Jadavpur Univ. (India); Dipanjan Datta, Heritage Institute of Technology Bombay (India); Subhananda Chakrabarti, Indian Institute of Technology Bombay (India)

In this paper we report a detailed investigation of ZnO thin film properties deposited on Si<100> substrate at 400°C using RF sputtering. To reduce oxygen induced vacancies and interstitial defects in samples, variable oxygen flow rate during deposition followed by post growth annealing in an oxygen ambient were carried out. Four samples were deposited under constant temperature condition but with variable oxygen partial pressure of 0%, 20%, 50% and 80% in Argon and Oxygen mixture, namely sample S1, S2 , S3 and S4 respectively. Deposted films were further annealed at 700, 800, 900 and 1000 °C in oxygen ambient for 10s. Photoluminescence (PL) measurements carried at low temperature (18K) demonstrated near band edge emission peak of ZnO at 3.37eV. Increment in PL intensity was observed with increasing annealing temperature and a particular sample S4 annealed at 900 measured narrowest full width half maxima (FWHM) of ~0.1272eV. Increasing oxygen percentage in growth ambient resulted in improvement of PL spectrum thereby reducing oxygen vacancies defects along with improving film stoichiometry. Defects peaks observed at lower energies were suppressed with increasing oxygen flow and post growth annealing, indicating improvement in film quality. From HRXRD measurement it was observed S4 sample annealed at 900 °C has the highest peak intensity and narrowest FWHM compared to other samples. Highest XRD peak intensity measured at 34.5° corresponds to (002) crystal orientation reveals that the films were highly c-axis oriented. AFM results show increase in grain size with increasing oxygen flow and annealing temperature which ensures improvement in morphological properties of the film.DST, India, IITBNF and SPM Physics, IIT Bombay are acknowledged.
9749-67, Poster Session

**Temperature sensing using a Cr:ZnGa2O4 new phosphor**

Bruno Viana, Suchinder K. Sharma, Didier Gourier, Ecole Nationale Supérieure de Chimie de Paris (France)

The optical measurement of the temperature is of great interest for applications which include, among others, bioimaging and medical application, industrial process control, environmental control and so on. Several advantages of optical sensing include contactless sensor not requirement for electrical connections, and these sensors are insensitive to magnetic fields. The work presents a new thermographic phosphor based on trivalent doped Zinc Gallate (Cr:ZGO or Cr:ZnGa2O4). The emission of has a strong temperature dependence, which makes this material well suitable for temperature sensing. In this work the luminescence emission decay was investigated in detail in a broad temperature range, as well as the shape of the emission spectrum. The results obtained with these two measuring techniques are compared with the other Cr3+ based temperature sensors. In the future, due to the insensitivity of the sensing properties to the immobilization matrix, this material can be easily incorporated in the most appropriate matrix depending on the applications. The high sensitivity which can be achieved with this material, together with its high stability, demonstrates that this phosphor is most suited for the design of a sensitive, inexpensive and robust optical temperature sensor.
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9750-1, Session 1

Less is more: extreme optics with zero refractive index (Invited Paper)
Eric Mazur, Harvard School of Engineering and Applied Sciences (United States)

Nanotechnology has enabled the development of nanostructured composite materials (metamaterials) with exotic optical properties not found in nature. In the most extreme case, we can create materials which support light waves that propagate with infinite phase velocity, corresponding to a refractive index of zero. This can only be achieved by simultaneously controlling the electric and magnetic resonances of the nanostructure. We present an in-plane metamaterial design consisting of silicon pillar arrays, embedded within a polymer matrix and sandwiched between gold layers. Using an integrated nano-scale prism constructed of the proposed material, we demonstrate unambiguously a refractive index of zero in the optical regime. This design serves as a novel on-chip platform to explore the exotic physics of zero-index metamaterials, with applications to super-coupling, integrated quantum optics, and phase matching.

9750-2, Session 1

high-performance silicon photonics devices fabricated by using ArF immersion lithography technology (Invited Paper)

Tsuyoshi Horikawa, National Institute of Advanced Industrial Science and Technology (Japan); Daisuke Shimura, Seok-Hwan Jeong, Masatoshii Tokushima, Keizo Kinoshita, Tohru Mogami, Photronics Electronics Technology Research Association (Japan)

Optical integrated circuits using silicon photonics technology have been expected as a solution to overcome bandwidth bottlenecks in both data transmission among LSIs. In the fabrication of the silicon photonic devices, the most important issue is the reduction of fabrication errors, such as line edge roughness (LER) and deviation from designed width in optical silicon waveguides, because the LER in waveguide causes scattering loss of propagating light and deviations in waveguide dimension result in the degradation of optical device performance due to random optical phase error. We established a fabrication platform for the optical IC based on 40-nm-node CMOS technology with 300-mm silicon-on-insulator wafers and high-resolution ArF immersion lithography, and verified superior performance of fabricated devices.

Silicon wire-waveguides with a cross-section of 440 nm ? 220 nm showed a world-record low propagation loss of less than 0.5 dB/cm in TE single mode propagation for all wavelength range of C band, due to the suppression of scattering in the waveguides with small sidewall roughness obtained by using the ArF immersion lithography technology. Fabricated 16-channels AWGs showed a low crosstalk of 23 dB in their transmission spectra, and 5th order CROWS exhibited resonant peaks with flat top shape, indicating the well suppressed random phase error in these devices. These multi/demultiplexers also showed a small spectral variation of around 2 nm within a whole 300-mm wafer.

The above results showed that our precise fabrication platform is superior in ensuring optical device performance and its wafer-level reproducibility. This research is partly supported by NEDO.

9750-3, Session 1

Low-loss polymer optical waveguides with graded-index perfect circular cores for on-board interconnection

Yuki Saito, Takaaki Ishigure, Keio Univ. (Japan)

Using the Mosquito method, we fabricate a low-loss multimode polymer optical waveguides with graded-index (GI) perfect circular cores for the applications to on-board optical interconnection. We already developed the Mosquito method utilizing a microdispenser, as a fabrication technique for GI circular core polymer waveguides. In the Mosquito method, a liquid-state core monomer is dispensed from a syringe needle into a liquid-state cladding monomer while the needle horizontally scans. Originally we used siloxane based monomers. In this paper, novel organic-inorganic hybrid materials (SUNCONNECT®) are selected to confirm the applicability of wide-range polymers. Here, a dip is observed on the upper perimeter of the obtained core cross-sections particularly when a viscous (~50,000 cPs) core monomer is dispensed. Such a core-shape deviation could increase the coupling loss with circular-core optical fibers. So, the flux of core and cladding monomers while dispensing the core with the needle scanning is visually observed. It is confirmed that the edge of the “straight” needle chips off the upper perimeter of the core when the core monomer is dispensed, leading to the dip. Therefore, the straight needle is replaced for a curved one to change the dispensing direction for eliminating the dip. It is experimentally found that an almost circular core (50-um diameter with 0.98-circularity) is formed when the curved angle is in a range of 15-20-degree and needle I.D./O.D. are 150/300 um. Finally, we successfully demonstrate a 0.93-dB lower loss in a 5-cm long waveguide compared to the one having the core with a dip.

9750-4, Session 1

Strip-loaded waveguides and strip-loaded structures on lithium niobate thin films

Matthieu Roussey, Univ. of Eastern Finland (Finland); Petri Karvinen, Finnlitho Ltd. (Finland) and Univ. of Eastern Finland (Finland); Markus Häyrinen, Markku Kuittinen, Seppo Honkanen, Univ. of Eastern Finland (Finland)

Lithium niobate (LiNbO3, LN) is one of the most interesting materials in optics due to its unique physical properties. This material possesses a high refractive index, a strong anisotropy, thermo-, acousto-, and electro-optic properties and is transparent from the visible till the mid-infrared. This makes lithium niobate a perfect support material for optical telecommunications as well as photonic sensing and bio-sensing.

For several years, LN has also been used in micro- and nanophotonics. However, the fabrication of small structures in this material is extremely challenging, because LN is chemically inert and only mechanical etching or milling can be used for structuration. It has been shown that even this type of patterning is difficult due to the hardness of LN. We present a way to perform optical devices on LN substrates, without patterning the material, via the use of strip-loaded waveguides.

A strip-loaded waveguide is composed of a slab waveguide allowing the confinement in the vertical direction (here, LN thin films) and a thin layer of another material deposited on top of the slab. This additional layer is structured to the desired shape. It increases the effective index of the modes in the slab allowing a confinement in the horizontal direction. A waveguide can then be easily created without any etching of lithium niobate. We have chosen titanium dioxide as the strip material, especially...
ZnO-diffused lithium niobate waveguide polarization controller

James E. Toney, Andrea Pollick, Jason Retz, Vincent E. Stenger, SRICO Inc. (United States); Jay V. DeLombard, Institute for Materials Research, The Ohio State University (United States); Sri Sriram, SRICO Inc. (United States)

The linear electro-optic effect in lithium niobate is capable of realizing a variety of polarization transformations, including TE-to-TM and left-to-right circular polarization conversion. While most LiNbO3 components are designed for operation in the third telecommunications window around 1.55 micron wavelength, current interest in quantum information processing and atomic physics, where the wavelengths of interest are in the visible and near-infrared, has placed new demands on endless polarization control devices.

At short wavelengths, traditional Ti-diffused LiNbO3 waveguides suffer from photorefractive degradation at optical power levels as low as 1 mW or less. Proton exchanged waveguides have much higher power handling capability but can only guide light polarized parallel to the optic axis, and therefore are not applicable to polarization control.

Zinc oxide diffusion is an alternative waveguide fabrication technology that can guide both e- and o-waves with much higher power handling capability than Ti-diffused. ZnO/LiNbO3 waveguides exhibit a highly circular mode field with lower anisotropy than Ti-diffused waveguides. We report on the modeling, fabrication and testing of X-cut, Z-propagating and Z-cut, periodically poled (PPLN) polarization control devices in Zn-doped lithium niobate. TE-to-TM conversion of visible and near-infrared light has been demonstrated with a figure of merit of approximately 40 V.cm.

Birefringence measurement of glass ion-exchanged waveguides: burying depth or cover layer influence

Damiem Jamon, Jean Philippe Garay, Univ. de Lyon (France); Elodie Jordan, François Parsy, Elise Ghibaudo, IMEP-LAHC (France); Sophie Neveu, Sorbonne Université, UPMC Paris 6, CNRS, Lab PHENIX. (France); Jean-Emmanuel Broquin, IMEP-LAHC (France) and Univ. Grenoble Alpes (France)

The fabrication of on-chip optical isolators to protect the integrated optical sources is one of the major challenges of research in integrated optics. Their operation principle is based on the control of the guided wave polarization and the most common structures are composed of a polarization splitter, a non-reciprocal rotator based on the Faraday effect, and a reciprocal rotator. In this work, we propose the fabrication of a reciprocal rotator fabricated by two cascaded ion-exchanges on a glass substrate. Our structure is based on modulated mode evolution and the rotation principle consists in twisting the optic axes by 45° along the waveguide. Two field-assisted ions exchanges are required. The first one creates a high refractive index waveguide core while the second one modifies the geometry of the waveguide to achieve the rotation of its optic axes. In this paper, we will present the design of the function including its technological tolerancing, its realization and last but not least its characterization. Finally, the perspectives of this work concerning the integration of the reciprocal rotator with a non-reciprocal one will be addressed.

Due to polarization dependent losses (PDL) and modal birefringence, almost all integrated components exhibit polarization dependence. For low loss integrated devices, the polarization behavior is characterized essentially by the measurement of the modal TE/TM birefringence. Such measurements have been led in different waveguides using a local, precise, and nondestructive experimental method. It is based on a high resolution polarimeter associated to an ellipsometric-type calibration which allows to determine the full state of polarization of the output light. A magneto-optic perturbation is also added to generate TE/TM mode beating. Thus, the birefringence can be determined through the whole phase shift of the guide and/or through the beating length.

Surface or buried glass ion-exchanged waveguides have been measured through this method as a function of the diffusion aperture width. The results show that the value of the birefringence is decreasing when the burying depth increases (from about 10-3 to 10-5) and can even reach zero. Depending on the burying depth, the behavior can be different with an
increase or a decrease as a function of the diffusion aperture width. It can be explained in terms of a competition between geometric and intrinsic anisotropy.

In selectively buried waveguide the local variation of the birefringence has been evidenced through the study of the mode beating. Finally, the birefringence of hybrid structures obtained with a dielectric cover layer has been compared to that of the initial surface guides.

9750-10, Session 3

Modeling plasmonic nanoresonators with methods from integrated optics (Invited Paper)

Carsten Rockstuhl, Karlsruher Institut für Technologie (Germany); Shakeeb B. Hasan, Jing Qi, Falk L.ederer, Thomas Kaiser, Angela Klein, Michael Steinerst, Matthias Falkner, Christoph Menzel, Thomas Pertsch, Friedrich-Schiller- Univ. Jena (Germany)

Surface plasmon polaritons emerge in two different guises; either as propagating or localized plasmons. Recentiy, optical nanoantenna theory has been merging in both realms. Optical nanoantennas essentially can be understood as finite plasmonic resonators in which propagating plasmons bounce back and forth. A resonance occurs at the frequency where the phase accumulated due to propagation and reflection at the termination of the plasmonic resonator is a multiple of 2π per round trip. This reasoning opened the opportunity to understand localized plasmons sustained by optical nanoantennas with the methodology from integrated optics.

In this contribution, we wish to summarize and highlight our latest contributions that developed this understanding and suggest possible applications. Foremost, this concerns the demonstration of the ability to describe localized plasmon resonances in the quasi-static regime by means of integrated optics. We also show how nanoantennas can be designed to enhance nonlinear processes, i.e. by sustaining resonances at multiple wavelengths involved in the nonlinear interaction. Eventually, we also show that resonances of circular nanoantennas can be easily understood by similar means and demonstrate strategies developed in the context of guided modes to enhance the resonance strength, i.e. to incorporate Bragg-like elements. Even though our contribution emphasises the modelling aspects, we demonstrate in proof-of-principle experiments the applicability of the modelling tools to describe actual optical nanoantennas. Their properties are experimentally probed either in the far-field using spectroscopic techniques or in the near-field using a scanning near-field optical microscope or a photoemission electron microscope.

9750-11, Session 3

Hybrid-plasmonic three-terminal travelling-wave modulator with dynamic reconfigurability

Charles Lin, Amr S. Helmy, Univ. of Toronto (Canada)

The trade-off between extinction ratio (ER) and insertion loss (IL) is a key bottleneck when designing travelling-wave optical modulators. In this work, we report a dynamically reconfigurable modulator architecture that can provide ER and IL attainable only in plasmonic-based and dielectric-based waveguide platforms respectively. This is achieved through: (1) Design of non-resonant, coupled-plasmonic waveguide that supports modes with long-range propagation. (2) Utilization of epsilon-near-zero effect that allows minute change in the permittivity of the active layer to not only induce strong carrier absorption, but also disturb the field symmetry responsible for long-range mode propagation, rendering the otherwise low-loss waveguide highly absorptive. (3) Triode-like biasing scheme that enables further manipulation of field symmetry and consequently independent control of the amplitude and phase of the optical signal.

Specifically, numerical analysis shows that a Si/ITO/HfO2/Al/HfO2/ITO/ Si waveguide can provide amplitude modulation with ER = 4.83 dB/um and IL = 0.03 dB/um, thus requiring active device length and energy-per-bit of 622 nm and 14.8 fJ respectively. This provides at least an order of magnitude improvement in the modulator figure-of-merit and power efficiency compared to previously-proposed ITO-based designs. Moreover, we show that the same waveguide can be reconfigured for phase and 4-quadrature-amplitude modulation, with actively device length of only 5.53 and 17.78 um respectively. Although demonstrated with ITO, our waveguide structure is suitable for a wide range of material platforms and fabrication processes. Overall, the proposed architecture may inspire the design and optimization of other photonic components, where mitigation of IL and device reconfigurability are critical.

9750-12, Session 3

Integrated angular tracking and plasmonic membrane surfaces for a point of a care refractive index sensor

Andrea Dunbar, Rolf Eckert, Eric Grenet, Ross P. Stanley, Edo Franz, Harry Heinzelmann, Ctr. Suisse d’Electronique et de Microtechnique SA (Switzerland)

Nano-hole arrays in metallic membranes have been extensively studied for sensing applications [1], from complex multi-fluidic lab on chip systems [2], through to simplified lens free systems [3]. A key systems issue is the need to maintain sensitivity whilst reducing cost and complexity. The advantages of these plasmonic nano-hole arrays are their strong enhancement and straightforward design due to the symmetry of the surrounding material; moreover they are naturally adapted to microfluidic flow-through allowing kinetic measurements.

Here we design an optical system which integrates a plasmonic membrane sensor and an angular tracking system to enable a compact refractive index measurement system with disposable detection surfaces for point of care diagnostics. The system uses a high angular numerical aperture illumination with a monochromatic source such that a refractive index change at the surface results in a change in the angle of the transmitted light. The membranes are designed using an in-house mode matching model. The transmission of resonant membrane structures is highly dependent on the angular illumination and good agreement is shown between experiment and theory for different angular illuminations. CSEM has designed an embedded angular tracking system based on a commercial detector; the accuracy is 1-10mdeg. Current measurements show a 0.01 change in refractive index results in a shift of 0.7deg of the transmitted light giving an expected detection of [delta]n = 10^-4 to 10^-5. This maintains standard basic refractive index measurements sensitivity whilst allowing functionalization of the plasmonic disposable membrane surface in a portable system with flow kinetic potential.


9750-13, Session 3

Near Infrared Plasmonic Sensor Based on Fano Resonance

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We propose a novel plasmonic gas sensor that operates efficiently in the near infrared spectral range, which is interesting for a variety of applications. The sensor consists of a gold layer, a metal-insulator-metal waveguide and a rectangular cavity that acts as a resonator. The gas to be detected occupies the MIM waveguide and the cavity, where a small change of the gas refractive index can be detected through the shift of a sharp Fano resonance. The small footprint of the sensor matches it with the trend of lab on chip applications. The properties of the Fano resonance are controlled by varying the rectangular cavity dimensions. The Fano profile observed in the transmittance spectrum of the sensor is the result of the interference between two resonant cavity modes. The sensor possesses a wide operational range (0.7-3.5µm), covering the entire near infrared range. The spectral sensitivity of the sensor increases with the Fano resonance wavelength position which high reaches 1500nm/RIU around 1.55µm.

The proposed sensor can be simply tuned to work at any specific wavelength at the telecom wavelength where equipment and NIST-traceable calibration gases and fluids are broadly available.

9750-14, Session 3
Unidirectional reflectiveness propagation in plasmonic waveguide-cavity devices
Yin Huang, Central South Univ. (China); Georgios Veronis, Louisiana State Univ. (United States); Changjun Min, Shenzhen Univ. (China)

Recently, unidirectional reflectionless has been demonstrated in classical photonic structures at optical exceptional points. It has been recognized that there is a close analogy between the Hamiltonian matrix in quantum mechanics and the optical scattering matrix. By engineering the quantum Hamiltonian, its eigenvalue branches merge, and parity-time symmetry breaks down with the appearance of exceptional points. Similarly, in a two-port photonic system, by manipulating the elements of the scattering matrix, the two eigenvalues can become degenerate and form exceptional points. This leads to unidirectional reflectionless propagation in either the forward or the backward direction. In this paper, we introduce a non-parity-time symmetric plasmonic waveguide-cavity device consisting of two metal-dielectric-metal stub resonators side coupled to a metal-dielectric-metal waveguide. In several previous studies periodic modulation of the refractive index profile, which requires careful tuning of the constituent materials, was used for synthesizing parity-time symmetric optical structures. Here, we instead tune the geometric parameters of the structure to obtain the exceptional point, and realize unidirectional reflectionlessness at the optical communication wavelengths. The contrast ratio between the forward and backward reflectivities almost reaches unity. We show that the presence of material loss plays a crucial role in the realization of such a unidirectional phenomenon in the proposed plasmonic system. We investigate the properties of the realized plasmonic exceptional point as well as the associated physical effects of level repulsion, crossing and phase transition. We also show that by properly cascading the plasmonic waveguide-cavity structures we can design a wavelength-scale unidirectional plasmonic waveguide perfect absorber.

9750-15, Session 4
Microwave and RF Applications for Micro-resonator Frequency Combs (Invited Paper)
David J. Moss, Arnan Mitchell, RMIT Univ. (Australia); Roberto Morandotti, Institut National de la Recherche Scientifique (Canada); Thach Nguyen, Mehrdad Shoeiby, RMIT Univ. (Australia); Alessia Pasquazi, Marco Peccianti, Univ. of Sussex (United Kingdom); Sai Tak Chu, City Univ. of Hong Kong (China); Brent E. Little, Xi’an Institute of Optics and Precision Mechanics (China)

Photonic integrated circuits that exploit nonlinear optics in order to generate and process signals all-optimally have achieved performance far superior to that possible electronically - particularly with respect to speed. Although silicon-on-insulator has been the leading platform for nonlinear optics for some time, its high two-photon absorption at telecommunications wavelengths poses a fundamental limitation. We review the recent achievements based in new CMOS-compatible platforms that are better suited than SOI for nonlinear optics, focusing on Hydrox glass. This material system, together with silicon nitride, has opened up many new capabilities such as on-chip optical frequency comb generation and ultrafast optical pulse generation and measurement. This paper focuses on the potential of these devices for photonic RF and microwave applications. Many applications, including radar mapping, measurement, imaging as well as the realization of advanced modulation formats for digital communications, require the generation, analysis and processing of analogue RF signals. In these applications, both the amplitude and phase of the signals are critically important. Photonic implementations of RF and microwave filters have been demonstrated that have achieved very high performance over a very wide bandwidth. Furthermore, these devices can offer immunity to electromagnetic interference, while being compatible with fiber remote distribution systems and parallel processing. We review our recent results in a number of areas related to the use of micro-resonator combs and nonlinear photonic chips to RF and microwave signal generation, measurement and processing.

9750-16, Session 4
Densely-aligned multilayered polymer optical waveguide with low interchannel crosstalk
Yusuke Kogo, Keio Univ. (Japan)

In this paper, we fabricate graded-index (GI) circular core polymer waveguide with a densely-aligned multilayered structure utilizing the Mosquito method maintaining low interchannel crosstalk for on-board optical interconnects.

For the application to optical printed circuit boards, we developed the "Mosquito method," as a fabrication technique for GI circular core polymer optical waveguides utilizing a microdispenser. In the Mosquito method, a liquid-state core monomer is dispensed into a liquid-state cladding monomer from a syringe needle while the needle scans horizontally, by which circular cores are formed. Here, after the needle scans repeatedly, multiple core alignment is realized. The core and cladding monomers are cured after forming the whole waveguide structure. Therefore, the needle scanning over a layer of cores in the cladding before curing enables to fabricate even multilayered waveguides very easily. However, we previously found that the interchannel crosstalk to the vertical neighbor cores was much higher than the crosstalk to the horizontal ones in the multilayered waveguides, which should be a crucial problem in high-density interconnects.

In this paper, we find that the high crosstalk to vertical neighbor cores stems from the "UV exposure-induced vestige" formed beneath the core during the UV curing process. The vestige with a refractive index slightly higher than cladding makes a bridged structure of vertically aligned cores. However, a new UV exposure method allows to eliminate the vestige, resulting in very low crosstalk (<40 dB). We demonstrate densely aligned multilayered polymer waveguides with low loss and crosstalk.
**9750-17, Session 4**

**Functionalization of UV-curing adhesives for surface-integrated micro-polymer optical fibers**

Bechir M. Hachicha, Ludger Overmeyer, Leibniz Univ. Hannover (Germany)

Polymer optical waveguides are increasingly being used for short distance communication, as well as for sensing applications. The achievement of a working communication route still requires different and sequential realized steps. Generally these steps are the packaging of semiconductor beam senders and receivers, the fabrication of the optical waveguide, the preparation of its end-facets, the alignment of the different elements along their optical axis and the integration into the desired communication route. The development of a process which integrates these steps together for planar surfaces offers a reduction in production time and an increase in flexibility. Furthermore, this allows a fusion between the optical system and the end-product-surface.

A sub-step toward this automated system is the integration of optical waveguides into the planar surface. In this context, we are investigating the use of a micro-dispensing process to realize this integration step. We functionalize UV-curing adhesives as cladding for micro-optical cores as well as for inherent bonding to the substrate surface.

For this purpose, an optical characterization of the adhesives was necessary for an adequate core and cladding material combination. A rheological characterization was also relevant to analyze the used dispensing process and the flow behavior of the selected adhesive. Finally, a mechanical characterization was done to test the adhesion of the core to the adhesive, as well as the adhesive to the substrate surface.

In this paper we present a summary of the realized optical and mechanical characterization of selected polymers. Based on experiment results, we infer limits and opportunities which this method offers.

**9750-19, Session 4**

**Monolithic integration of GaAs/AlGaAs waveguides**

Zhongfa Liao, Univ. of Toronto (Canada); Muhammad Z. Alam, California Institute of Technology (United States); James S. Aitchison, Univ. of Toronto (Canada)

In this paper we describe a vertical integration approach in the III-V material system, AlxGa1-xAs, which allows for the integration of multiple elements with different band gaps. GaAs has emission wavelength of 850 nm that can find applications in warehouse-sized intra-datacenter transceivers and optical biosensors. Multiple vertically integrated guiding layers can be designed into a single chip which allows for the integration of materials with different band gaps. As a first step towards demonstrating this approach to monolithic integration in GaAs, we have designed and fabricated a two layer chip consisting of a lower layer acting as a spot size converter, and an upper layer for high contrast waveguides for on-chip signal processing. The wafer consists of five AlxGa1-xAs/GaAs layers. As the lateral dimensions of the top waveguide are tapered down, the mode is adiabatically transformed to the large mode in the lower layer. Simulation shows 95% conversion efficiency. The fabrication involves only one single epitaxial growth followed by electron beam lithography and etching. To precisely control the etch depth in the taper section, a highly selective wet etch has been used and selectivity of over 100 measured. Waveguides supporting the tightly confined TE mode have been fabricated using wet etch, showing only 4 dB/cm propagation loss. It demonstrates AlxGa1-xAs as a viable material platform for building compact three dimensional optical chips.

**9750-52, Session 4**

**Integrated-optic tunable chromatic dispersion compensator composed of lattice-form circuit with interleave filter**

Koichi Takiguchi, Ritsumeikan Univ. (Japan)

Although digital coherent optical transmission is being vigorously investigated, optical signal processing technology is important in order to realize future all-optical networks. A tunable optical dispersion compensator (TODC) is one of significant optical signal processing devices. An integrated-optic lattice-form TODC, which is composed of cascaded Mach-Zehnder interferometers (MZIs) and has 2 x 2 input-output configuration, is one of candidates for use in the all-optical networks because it has such merits as a small footprint, good stability, and a high-speed response with a thermo-optic effect. However, as the lattice-form TODC alternately generates the same absolute value and opposite sign dispersion with respect to each half of the free spectral range (FSR), nearly half bandwidths are inoperable. To solve this problem and improve the characteristics, I propose and demonstrate a lattice-form TODC integrated with a lattice-form interleave filter, whose FSR is the same as the TODC. The interleave filter alternately divides signal bandwidths into two different input ports of the TODC with respect of each half of the FSR. As the TODC transfer matrix is unitary, two pairs of input-output ports in the TODC provide signals in the adjacent frequency range with the same absolute and sign dispersion. Thus, the TODC produces the same dispersion with respect to each half of the FSR and can remove the wasted bandwidths by fully utilizing the two pairs of input-output ports. The proposed TODC was fabricated with a silica-waveguide with relative index difference of 1.2 %. The number of asymmetrical MZIs in the TODC and interleave filter was designed to be nine and six, respectively. The chip size and fiber-to-fiber loss were 27 mm x 44 mm and 5.6 dB, respectively. The dispersion of ~321 to 299 ps/nm was experimentally obtained over 40 GHz bandwidth with a period of 50 GHz.

**9750-20, Session 5**

**Monolithic integration of a microlaser with a passive waveguide via selective quantum well etching**

Hwi-Min Kim, Hoon Jang, Yong-Hee Lee, KAIST (Korea, Republic of)

Photonic integrated circuit has been actively studied for the next generation data processing. In optical data processing, light sources and waveguides are essential components. Therefore, the demand for dense integration of optical elements has been increasing as to replace electrical counterparts and to keep up with the increase of data traffic. III-V semiconductor compound has become an established host material of the light sources at telecom wavelength. As a compact optical device, small light sources and waveguides need to be merged in a single host membrane; however, in a standard wafer growth and fabrication process, it is challenging to integrate lasers and waveguides in a single epitaxial wafer due to the horizontally uniform active layers. Therefore, heterogeneous integration in a horizontal direction has been sought after. So far, several works have been reported including metal-organic chemical vapor deposition regrowth, adhesive bonding methods, and quantum well (QW) intermixing. In this work, we propose and demonstrate a lattice-form TODC integrated with a lattice-form circuit with interleave filter, whose FSR is the same as the TODC. The interleave filter alternately divides signal bandwidths into two different input ports of the TODC with respect of each half of the FSR, nearly half bandwidths are inoperable. To solve this problem and improve the characteristics, we propose a new method that monolithically combines active/passive optical devices by employing a selective QW etching technique. Here, wet-etching of InGaAsP QW is deterministically controlled. This enables mass production by taking advantage of a standard complementary metal-oxide-semiconductor fabrication process including epitaxial growth of wafers. Besides, position of the active and passive parts can be tailored during the fabrication process. Here, we demonstrate the integration of a photonic crystal laser and a passive waveguide. A coupling efficiency is calculated numerically by finite difference time domain method and the efficiency can be 90% with our proposed design. Also, we optically characterize the laser emission extracted at the end of the waveguide.
Controllable red and blue bandgap energy shifted LEDs and modulators on InGaAsP quantum well platform

Parinaz Aleahmad, Univ. of Central Florida (United States); Thamer Tabbkha, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Demetrios N. Christodoulides, Patrick L. LiKamWa, Univ. of Central Florida (United States)

Exploiting a controllable technique for red and blue shifting of quantum well's bandgap energy, we have fabricated LED sources accessing a wide frequency spectrum along with all-optical phase modulator devices. We demonstrate bandgap tuning of InGaAsP multiple quantum well structures by utilizing an impurity free vacancy diffusion technique. Substantial modification of the bandgap energy toward the red and blue part of the spectrum has been observed using SiO2 / SiOyNx / SiNx capping layers and by controlling the associated oxygen and nitrogen content. The resulting degree of tuning, up to 120nm red-shift and 140nm blue-shift of the band to band wavelength emission, has been studied using room temperature photoluminescence, in agreement with the emission spectra obtained from semiconductor LED devices fabricated on this platform. The phase modulator devices have been fabricated along with LED sources compatible for the selected frequency, designed to reach minimum material losses and residual amplitude modulation.

Realization of back-side heterogeneous hybrid III-V/Si DBR lasers for silicon photonics

Jocelyn Durel, STMicroelectronics (France) and CEA-LETI (France); Thomas Ferrootti, STMicroelectronics (France) and CEA-LETI (France); Alain Chantre, Sébastien Cremer, STMicroelectronics (France); Julie Harduin, CEA-LETI (France); Jean-Emmanuel Broquin, IMEP-LAHC (France); Badhise Ben Bakir, CEA-LETI (France)

In this paper, the simulation, design and fabrication of a back-side coupling (BSC) concept for silicon photonics which targets heterogeneous hybrid III-V/Si laser integration is presented. While various demonstrations of a complete SOI integration of passive and active photonic devices have been made, they all feature multi-level planar metal interconnects, and a lack of integrated light sources. This is mainly due to the conflict between the need of planar surfaces for III-V/Si bonding and multiple levels of metallization. The proposed BSC solution to this topographical problem consists in fabricating lasers on the back-side of the Si waveguides using a new process sequence. The devices are based on a hybrid structure composed of an InGaAsP MQW active area and a Si-based DBR cavity. The emitted light wavelength is adjustable within a range of 20 nm around 1.31µm thanks to thermal heaters and the laser output is fiber coupled through a Grating Coupler (GC). From a manufacturing point of view, the BSC approach provides the advantages of allowing the use of thin-BOX SOI instead of thick one; as well as of shifting the laser processing steps with their non CMOS-friendly materials to the far back-end areas of fabrication lines. Moreover, the BSC concept not only solves the technological integration issues, but also offers several new design opportunities for active and passive devices (heat sink, Bragg gratings, grating couplers enhanced with integrated metallic mirrors, tapers,...). These building boxes are explored here theoretically and experimentally and will be presented.
Background-free phase-preserving upconversion of faint near-infrared light

Sergey V. Polyakov, Yu-Hsiang Cheng, Tim O. Thomay, Glenn S. Solomon, Alan L. Migdall, National Institute of Standards and Technology (United States)

We demonstrate statistically background-free upconversion of near-infrared light with high efficiency at a single-photon level in periodically polled lithium niobate waveguides. In our experiment, we used a 1550 nm pump to up-convert a signal at 920 nm, i.e. corresponding to a wavelength of self-assembled InGaAs quantum dots. We obtained 20% up-conversion efficiency, limited by the available pump power. We measured the background generated by the up-converting process by blocking the signal altogether, and obtained -1(2) photons per second. This is because the pump is far detuned from the signal, and noise generated by the pump at the signal wavelength, i.e. through a Raman effect, is expected to be negligible even at a single-photon level. The uncertainty, which is the lowest reported in similar measurements (to our knowledge), is limited by the detector’s dark counts. In addition, we demonstrate faithful preservation of coherence in up-converting faint states of light, using a multi-color up-converting mach-zhender interferometer. We used two up-converting waveguides in each of the arms of the interferometer and measured the visibility of the up-converted states, we obtained 98(1)% for a range of input powers (all the way down to 10^-5 input photons per second). This work enables faithful up-conversion of faint states of light, including single-photon states and entangled states. Combined with darkcount-free detectors of visible light, this work extends background-free light detection to the infrared.

9750-26, Session 6

Background-free phase-preserving upconversion of faint near-infrared light (Invited Paper)

Sergey V. Polyakov, Yu-Hsiang Cheng, Tim O. Thomay, Glenn S. Solomon, Alan L. Migdall, National Institute of Standards and Technology (United States)

We demonstrate statistically background-free upconversion of near-infrared light with high efficiency at a single-photon level in periodically polled lithium niobate waveguides. In our experiment, we used a 1550 nm pump to up-convert a signal at 920 nm, i.e. corresponding to a wavelength of self-assembled InGaAs quantum dots. We obtained 20% up-conversion efficiency, limited by the available pump power. We measured the background generated by the up-converting process by blocking the signal altogether, and obtained -1(2) photons per second. This is because the pump is far detuned from the signal, and noise generated by the pump at the signal wavelength, i.e. through a Raman effect, is expected to be negligible even at a single-photon level. The uncertainty, which is the lowest reported in similar measurements (to our knowledge), is limited by the detector’s dark counts. In addition, we demonstrate faithful preservation of coherence in up-converting faint states of light, using a multi-color up-converting mach-zhender interferometer. We used two up-converting waveguides in each of the arms of the interferometer and measured the visibility of the up-converted states, we obtained 98(1)% for a range of input powers (all the way down to 10^-5 input photons per second). This work enables faithful up-conversion of faint states of light, including single-photon states and entangled states. Combined with darkcount-free detectors of visible light, this work extends background-free light detection to the infrared.
the combination of SNSPDs on two waveguides at the output of 50:50 splitters. These circuits enable on-chip correlation measurements with fast and efficient readout and small footprint. Our demonstration of traveling wave SNSPDs on diamond waveguides is an important step towards the full integration of single photon sources, photonic circuitry and single photon detectors on a single chip.

9750-28, Session 6

Engineering reconfigurable laser-written circuits for practical quantum metrology

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Quantum metrology uses effects such as entanglement to gain an enhancement in precision over classical measurement techniques. One ubiquitous measurement task in quantum metrology is the estimation of an optical phase. Such a measurement requires an extremely stable interferometer with a tunable phase. These requirements make waveguide interferometers fabricated in bulk glass using the (FLDW) technique prime candidates due to their stability against temperature fluctuations and vibrations. The 3D capability of the technique allows for further gains in precision by adding extra arms to the interferometer. Implementing multiple phase shifters in such a device allows for the phase relationships between each arm to be controlled in order to maximize the precision.

We have identified a writing regime in which two-and three port directional couplers may be reliably fabricated with minimal tolerance. These are then cascaded in series to form two and three-arm interferometers. The 3D inscription allows for individual waveguides to be brought to shallower depths in order to selectively interact with nichrome heaters deposited on the glass surface. Cross-talk between the implemented phase shifters is reduced by machining contours in the glass surface using picosecond laser ablation to separate the raised waveguides.

An unknown phase for estimation can be introduced to the interferometer by machining a microfluidic channel adjacent to an interferometer arm so that the evanescent field of the waveguide mode penetrates into the sample occupying the channel. Channels have been machined parallel to individual waveguides within distances of 6 - 10 μm, allowing for interaction with the waveguide mode with additional losses of less than 0.5dB.

9750-29, Session 7

Faraday polarisation mode conversion in semiconductor waveguides incorporating periodic garnet claddings (Invited Paper)

David C. Hutchings, Cui Zhang, Barry M. Holmes, Univ. of Glasgow (United Kingdom); Prabesh Dulal, Andrew D. Block, Bethanie J. H. Stadler, Univ. of Minnesota, Twin Cities (United States)

The nonreciprocal optical effect of Faraday rotation is widely exploited in optical isolators to suppress back-reflections protecting optical sources and other devices from injection noise, or in optical circulators routing counter-propagating signals in a single physical channel to different ports. To date, these devices are assembled manually from bulk components, with consequences due to assembly costs and yields when scaling-up the number of implemented devices. Consequently, the prospect of a monolithically integrated on-chip, waveguide based isolator defined by lithography is attracting considerable attention. Our approach to the development of a waveguide isolator capable of being integrated is to use an evanescent interaction in conventional semiconductor photonic platforms with a magneto-optic iron garnet (with lower refractive index) as an upper cladding. A quasi-phase-matching (QPM) approach where the upper cladding alternates either between a magneto-optic cladding and a non-magneto-optic cladding, or between magneto-optic claddings of opposite sign, can accommodate the birefringence inherent in a planar format. We have recently investigated deposition of bismuth- and cerium-substituted terbium iron garnet (Bi:TIG, Ce:TIG), and cerium-substituted yttrium iron garnet (Ce:YIG on a MgO buffer layer) on silicon-on-insulator waveguides by multi-target RF sputtering in an oxygen atmosphere, with subsequent lift-off and annealed to form the garnet phase elements. The application of a longitudinal magnetic field saturates the magnetisation of the samples. A non-reciprocal polarisation-mode conversion was observed over a phase-matching bandwidth centred on the wavelength defined by the QPM grating period.

9750-30, Session 7

Monolithic on-chip nonreciprocal photonics based on cerium/bismuth substituted yttrium iron garnet thin films (Invited Paper)

Juejun Hu, Massachusetts Institute of Technology (United States); Xueyin Sun, Massachusetts Institute of Technology (United States) and Harbin Institute of Technology (China); Qingyang Du, Massachusetts Institute of Technology (United States); Taichi Goto, Toyohashi Univ. of Technology (Japan); Mehmet Onbasli, Caroline A. Ross, Massachusetts Institute of Technology (United States)

Monolithic integration of nonreciprocal optical devices on semiconductor substrates has been a long-sought goal of the photonics community. One promising route to achieve this goal is to deposit high quality magneto-optical (MO) oxide thin films directly on a semiconductor substrate. In this talk, we will review our ongoing progress in material development and device engineering towards enabling a monolithically integrated, high-performance magneto-optical nonreciprocal photonics platform. Our recent work has led to a new pulsed laser deposition (PLD) technique of Ce or Bi substituted yttrium iron garnet (YIG) thin films with reduced thermal budget, simplified growth protocols and improved magneto-optical characteristics. These materials were incorporated in monolithic resonator and interferometer based isolator devices to demonstrate on-chip optical isolation with improved device figure of merit. Challenges and opportunities for monolithic magneto-optical devices will be discussed in the context of our latest material and device performance metrics. The prospect of extending the operation wavelengths of these devices to the visible and mid-infrared wavelength regimes will also be analyzed based on dispersion measurements in these MO oxide materials.

9750-31, Session 7

Nanocomposite magnetic material embedded on TiO2 pillars to realize magneto-optical resonant guided-mode gratings

Bobin Varghese, Emilie Gamet, Damien Jamon, Lab. Hubert Curien (France); Sophie Neveu, UPMC Sorbonne Univ. (France); Loïc Berthod, Olga Shavdina, Stéphanie Reynaud, Lab. Hubert Curien (France); Isabelle Verrier, Colette Veillas, Université de Lyon, CNRS UMR5516,
Laboratoire Hubert Curien (France); François Royer, Lab. Hubert Curien (France)

Periodic structuration of magnetic material is a way to enhance the magneto-optical behavior of optical devices like isolators. It is useful to reduce the footprint of such integrated devices or to improve their features. However, the structuration and/or integration of efficient magnetic materials on photonic platforms is still a difficult problem, because classical magneto-optical materials require an annealing temperature as high as 700°C. A novel wafer-scale approach is to incorporate that material into an already structured template through a single step deposition at low temperature.

Using the dip-coating method, a magneto-optical thin film (~300nm) of CoFe2O4 nanoparticles in silica matrix prepared by sol-gel technique was coated on a 2-D grating structure of TiO2. The periodicity of the host structure is 1μm in both spatial directions and the pillar dimensions are 200nm height and 300nm width. It was confirmed by Scanning Electron Microscopy that the magneto-optical composite completely occupies the voids of the 2-D structuration showing a good compatibility between both materials. Our composite in thin film form shows a typical specific Faraday rotation of 200°cm⁻¹ at 1.5μm for 1% of volume fraction of nanoparticles. Spectral magneto-optical measurements evidence that this effect remains after the deposition on the dielectric grating considered.

This approach permits to realize magneto-optical gratings in few steps on conventional substrates. The further work will be focused on the realization of an optimized resonant grating based on the phenomenon of Guided-Mode Resonances to reach the enhancement of the magneto-optical effect.

9750-32, Session 8
High-efficiency subwavelength index engineered fibre-chip couplers for photonics integration and sensing (Invited Paper)

Pavel Cheben, Danxia Xu, Jens Schmid, Siegfried Janz, Shurui Wang, Martin Vachon, National Research Council Canada (Canada); Gonzalo Wanguemert-Perez, Robert Halir, Alejandro Ortega-Monux, Itxigo Molina-Fernández, Univ. de Málaga (Spain); Milan Dado, Daniel Benedikovic, Jarmila Müllerová, Univ. of Žilina (Slovakia); Carlos Alonso Ramos, Univ. Paris-Sud 11 (France); Martin Papes, Vladimir Vasinek, V2B-Technical Univ. of Ostrava (Czech Republic); Yves Painchaud, Marie-Josee Picard, Martin Guy, TeraXion Inc. (Canada); Mohamed Rahim, National Research Council Canada (Canada)

We report our recent advances in development of subwavelength engineered fiber-chip couplers. This unique NRC patented technology allows synthesis of magneto-optic materials in an unprecedented control of material properties, constituting a powerful tool for a designer of photonic integrated circuits. We have demonstrated a number of subwavelength engineered devices operating at telecom wavelengths, including fiber-chip couplers, waveguide crossings, WDM multiplexers, ultra-fast optical switches, athermal waveguides, evanescent field sensors, polarization rotators, transceiver hybrids and colorless interference couplers. The subwavelength metamaterial concept has been adopted by industry (IBM) for fiber-chip coupling and subwavelength structures are likely to become key building blocks for the next generation of integrated photonic circuits. Here we demonstrate an unprecedented control over the light coupling between optical fibers and silicon chips by constructing several types of subwavelength index engineered couplers operating at telecom (1.557μm) and datacom (1.37μm) wavelengths. Specifically, we report a surface grating coupler with measured fiber-chip coupling efficiency of -1.3 dB, the highest efficiency achieved to date in 220-nm silicon-on-insulator (SOI) without high-index overlays or bottom mirrors. We also report on a subwavelength engineered surface grating coupler with bottom mirror, in which a sub-decibel (0.69 dB) experimental coupling efficiency is demonstrated for the first time for a single etch process in a 220-nm SOI. Finally, we report on a polarization independent fiber-chip edge coupler with a coupling efficiency of 92% (0.32 dB) and polarization independent operation for a broad spectral range exceeding 100 nm. Implementations in photonics hybrid integration and evanescent field waveguide sensing will be presented.

9750-33, Session 8
Compact two-mode (de)multiplexer based on MMI couplers with different core thickness on InP Substrate

Guo Fei, Dan Lu, Ruikang Zhang, Huitao Wang, Chen Ji, Institute of Semiconductors (China)

A novel design structure of two-mode (de) multiplexer based on MMI couplers on the InP substrate is proposed. The phase difference is achieved by tuning the core layer thickness of the phase shifter waveguide. Rather than other phase shifter structures, the device is highly insensitive to the phase shifter length, being able to relax the fabrication tolerance notably. In addition, the total length of the device is as small as 549 μm (does not include inputs and outputs), much shorter than other mode (de) multiplexers based on InP wafer. Furthermore, this new structure is easy to couple with fibers and monolithically integrate with other devices base on InP substrate. Three-dimensional Beam Propagation Method (3D-BPM) is used to simulate the properties of the two-mode (de) multiplexer. The simulations show that, the two-mode (de) multiplexer crosstalk is below -20 dB and the insertion loss lower than 0.7 dB both of the fundamental mode and the first order mode within the whole C band wavelength range (1530 nm-1565 nm). This proposed device has the advantage of compact size, high fabrication tolerance, large optical bandwidth, easy to couple with fibers and monolithically integrated with other devices base on InP substrate, making it a promising candidate in the MDM system and MDM+WDM systems.

9750-35, Session 8
Design and fabrication of adiabatic vertical couplers for hybrid integration by flip-chip bonding

Jinfeng Mu, MESA+ Institute for Nanotechnology (Netherlands); Mustafa Akin Sefunc, Optical Sciences Group, MESA+ Institute for Nanotechnology, University of Twente (Netherlands); Bojian Xu, NanoElectronics Group, MESA+ Institute for Nanotechnology, University of Twente (Netherlands); Meindert Dijkstra, Sonia M. García-Blanco, MESA+ Institute for Nanotechnology (Netherlands)

One of the key challenges in hybrid integration of different platforms remains the design and fabrication of low-loss and large fabrication tolerance vertical couplers for transferring light between different waveguides. Efficient couplers would allow on-chip scale integration of active components such as lasers and amplifiers for applications in optical interconnects and photonic sensors.

In this paper, we present a methodology for the efficient design of adiabatic vertical couplers based on 2D mode field overlap calculations. We apply this method to the design of a vertical coupler between a Si3N4 waveguide and an intermediate SU-8 waveguide, which will be ultimately be utilized for the integration of erbium doped KY(WO4)2 waveguides amplifiers and lasers with passive platforms. To ensure low-loss coupling, both waveguides are adiabatically tapered. The 110 nm thick Si3N4 waveguide taper (on the bottom) was fabricated with angles ranging from 0.3° to 1.5°. The ~0.6 μm thick SU-8 waveguide taper (on the top) was designed with a fixed taper angle of 0.25°. The 2D mode field overlap results for the vertical couplers show less than 0.5 dB loss for the different angles and less than 1 dB loss for ± 1 μm lateral misalignment. Such results are in agreement with 3D
9750-36, Session 8

Ferroelectric-oxide-based slot waveguides monolithically integrated on silicon for optoelectronics

Sebastien Cueff, Regis Orobtchouk, Pedro Rojo-Romeo, Baba Wague, Xuan Hu, Romain Bachelet, Philippe Régreny, Bertrand Vilquin, Guillaume Saint-Girons, Institut des Nanotechnologies de Lyon (France)

Photonic devices enabling light modulation and switching are a cornerstone of integrated optics. Their performances directly impact both the speed of data transmission and energy consumption. In that field, silicon-based electro-optic modulators are widely investigated because of their direct compatibility to CMOS fabrication processes. However, the trade-off between modulation speed and power consumption?characteristic of the plasma dispersion effect used in Si based modulators?intrinsically limits the performances of these devices. To overcome such limits, ferroelectric oxides with naturally strong electro-optical coefficients could be ideal candidates for high-speed modulators. It would therefore be of particular interest to implement such materials on silicon based photonic platforms.

However, it is challenging to seamlessly implement ferroelectric oxides on silicon, both in terms of material growth and optoelectronic design. In this communication, we will present methods to monolithically integrate BaTiO3 (BTO) and Pb(Zrx,Ti1-x)O3 (PZT) on silicon and to design devices that leverage their strong Pockels coefficient for efficient and fast electro-optical modulation. Specifically, we report on the epitaxial growth of thin films of these materials on silicon, using a SrTiO3 template. We then design slot waveguide photonic devices and RF electrodes to both confine the optical mode and maximize the electro-optical overlap within the active ferroelectric layer. We will show how our designs and technologies enable the fabrication of low-loss BTO slot waveguides, compatible with the requirements for large-scale integrated devices. We further discuss on the latest experimental results, expected performances and future devices.

We acknowledge funding from the European Commission under project FP7-ICT-2013-1-619456 SITOGA.

9750-38, Session 9

Integrated optofluidic label-free biosensors using a silicon-nitride-based coupled-resonator optical waveguide (Invited Paper)

Jiawei Wang, Zhanshi Yao, Andrew W. Poon, Hong Kong Univ. of Science and Technology (Hong Kong, China)

We report our recent progress in silicon nitride (SiN)-based optofluidic label-free biosensors using a coupled-resonator optical waveguide (CROW) in the visible wavelengths. Our CROW-based biosensor enables pattern-recognition-based biosensing in the spatial domain. The working principle is based on far-field imaging of the CROW mode-field intensity distributions at a fixed probe wavelength. The imaged pattern changes reflect a minute change in the refractive index of the upper cladding or real-time analyte binding information around the waveguide near-surface. The key merit of our CROW-based sensing technique is the simple setup configuration, which only requires a fixed-wavelength laser diode as a light source, with the probe wavelength within the relatively wide CROW transmission band, and a low-cost silicon charge-coupled device/CMOS camera for recording the light scattering patterns.

In our on-going experiments, we study both one-dimensional (1D) and two-dimensional (2D) SiN microring-based CROW biosensors. We employ nitrogen-rich SiN using plasma-enhanced chemical vapor deposition to minimize the waveguide propagation loss in the visible wavelength. We study the bulk refractive index sensing using NaCl and glucose solutions. We report label-free protein detection using surface functionalized SiN CROW. In the case of protein detection, we employ a standard biotin-avidin/streptavidin system to detect the protein concentration. We also report a control sensing experiment using bovine serum albumin to prove the sensing specificity. We numerically model the 1D and 2D CROW biosensors considering designed non-uniform parameters to further optimize the sensing performance, namely better uniformity of the sensitivity profiles and high sensitivities.

9750-39, Session 9

Integrated optics for sensing applications in lithium niobate based microfluidic systems

Cinzia Sada, Giacomo Bettella, Gianluca Pozza, Annamaria Zaltron, Univ. degli Studi di Padova (Italy); Mathieu Chauvet, Blandine Guichardaz, Univ. de Franche-Comté (France)

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. Recently lithium niobate has been also proposed as candidate for application in opto-microfluidic technology thus combining the tools typical of microfluidics with the potentialities offered by this material. In this work we will present recent results on the realization of a LiNbO3 substrate a T-shaped and cross-junction droplet generators respectively where optical stages are integrated on the same substrate in a monolithic configuration. This opto-fluidic platform aims to perform on-site optical sensing processes such as those required in chemical and biological analyses. In particular, by illuminating the droplets with integrated optical waveguides, we will show how to get a optimised refractive index sensor able to count the droplets and analyse their content. As a matter of fact, the spectral fluorescence selectivity can be obtained by integrating holographic grating on the output waveguide thanks to the photorefractive property of the material when locally doped with iron. Finally, perspectives regarding on-chip droplet enhanced fluorescence emission for low concentration of fluorescent constituents will be proposed as well as the integration of tailored optical stage to widen the applications of the LiNbO3 platforms to plasmonics based sensing.

9750-40, Session 9

Complex manipulation of single microparticles in air by fiber-based compact optical tweezers

Sudipta K. Bera, Avinash K. Gupta, Souvik Sili, Tanumoy Saha, Ayan Banerjee, Indian Institute of Science Education and Research Kolkata (India)

Optical tweezers are routinely used in complex micromanipulation of mesoscopic particles in liquid environments. Micromanipulation in air is more challenging due to the low viscosity which requires larger optical forces to confine particles. We have developed a fiber based compact optical tweezers that can confine and manipulate absorbing toner particles employing photophoretic forces generated by light. We demonstrate, for the first time, the trapping of particles using a multi-mode optical fiber (core diameter 125 microns) where the spatial modes of light are entirely superposed and the resultant mode profile arbitrary. The trapping region is created inside a chamber by focusing the light using a 25 mm focal length lens that is integrated with the fiber mount, and the entire assembly
is placed on a motorized rotating stage so that the trap can be rotated in circular orbits controllably. We achieve circular particle trajectories of diameter a few mm with the rotating trap. We also achieve very efficient trapping by generating higher order transverse spatial modes (TE01/TEM00) out of a commercial single mode optical fiber that is optimized to be single mode at a wavelength higher (980 nm) than the trapping wavelength (670 nm). We generate very stable Hermite-Gaussian modes in this fashion and are able to trap particles at about 20 mW of laser power where the trapped particles are again manipulated in circular and linear trajectories over millimeters. This method has the capability to extend the capabilities of optical tweezers in air to a large variety of absorbing particles including metal nano-particles.

9750-41, Session 10

Design and optimization of silicon photonic devices (Invited Paper)

B. M. Azizur Rahman, City Univ. London (United Kingdom)

When the dimensions of an optical waveguide are much smaller than the operating wavelength, unique materials and structural dependent properties can be observed and these recently have been receiving much attention. In this regard, silicon has been particularly attractive as the low-cost and mature CMOS fabrication technology widely used in the electronics industry can be exploited. The high index contrast of silicon allows light confinement in submicron size waveguides, along with the creation of very compact bends, to allow increased functionality of photonic integrated circuits. However, strong spatial field variation and high field at the dielectric interface demands a full-vectorial approach must be used. A rigorous H-field based full-vectorial modal analysis has been carried out, which can more accurately characterize the abrupt dielectric discontinuity of a high index contrast optical waveguide. As a result, the full-vectorial H and E-fields and the Poynting vector profiles are shown in detail. The modal solutions of silicon nanowires and vertical and horizontal slot waveguides will be presented. Rigorous design optimization of silicon power splitters, mode splitters, polarization splitters, polarization rotators, biosensors and spot-size converters will also be presented.

9750-42, Session 10

Wave interaction in photonic integrated circuits: Hybrid analytical / numerical coupled mode modeling (Invited Paper)

Manfred Hammer, Univ. Paderborn (Germany)

Computational tools are indispensable in the field of photonic integrated circuits, for specific design tasks as well as for more fundamental investigations. Difficulties arise from the usually very limited range of applicability of purely analytical models, and from the frequently prohibitive effort required for rigorous numerical simulations. Hence we pursue an intermediate strategy. Typically, an optical integrated circuit consists of combinations of elements (like straight and curved waveguide channels, cavities) the simulation and design of which is reasonably well established, usually through more or less mature numerical eigenproblem-solvers. What remains is to predict quantitatively the interaction of the waves (modes) supported by these elements. We address this task by a quite general, “Hybrid” variant (HCMT) of a technique known as Coupled Mode Theory. Starting point is a physically reasonable field template. Typically this consists of a few known, most relevant modes of the optical channels in the structure, superimposed with coefficient functions of the respective — in principle arbitrary and possibly different — propagation coordinates. Also the resonant eigenfields of optical cavities can be included, multiplied by single unknown coefficients. Methods from the realm of finite-element numerics then lead to good quantitative, reasonably low-dimensional, and easily interpretable models in the frequency domain. Spectral scans can be complemented by the direct computation of supermode properties (spectral positions and linewidths, coupling-induced phase shifts). This contribution describes the theoretical background, explains its limitations, hints at implementational details, and discusses a series of examples that illustrate the versatility of the technique. The examples include composites of straight and curved waveguides, and circuits with localized resonances (a waveguide crossing, ring- and disk-resonator filters, a coupled-resonator-optical-waveguide configuration, a photonic molecule), and first tentative results of a 3-D HCMT implementation.

9750-43, Session 10

Leaky waveguides for low k-measurement: From structure design to loss evaluation

Christoph A. Wächter, Riccardo Rizzo, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Francesco Michelotti, Sapienza Univ. di Roma (Italy); Peter Munzert, Norbert Danz, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

For high quality optical coatings the knowledge of the losses of the deposited materials is essential. Loss figures of \\[\text{Im}(\text{n})\leq 10^{-4}\] can still be determined by spectrophotometry, whereas the precise measurement of losses of \\[\text{Im}(\text{n})\leq 10^{-6}\] with methods like laser-calorimetry or laser-induced deflection is restricted to wavelengths where high power lasers are available, and which might differ from the intended operating wavelength. Low loss figures can be determined in waveguide configurations due to a significantly increased light-sample interaction length. In a sliding prism configuration this is trivially accomplished for a thin film of high index material but impractical for low refractive index materials. Remarkably, the analysis of leaky waves turns out to be a suitable means in case of H-L-stacks, generally. In this case, the angle-dependent reflection curve of an appropriate stack exhibits at least one dip which indicates a leaky wave resonance, and resonance depth and angular width allow to deduce \\[\text{Im}(\text{n})\] of the layer materials, at least in principle. Numerical investigations reveal that different leaky wave schemes, e.g. Bragg-Bloch- and Anti-resonant-Reflecting waveguides, comply differently with practical requests like strong discrimination of the losses of the different materials, adaptability to loss magnitude as well as a minimum number of layers within the stack. After deposition and measurement the loss data need to be extracted from the angular reflection curve, finally. Design data or data from in-situ monitoring of the layer deposition serve as reasonable initial values for the solution of the inverse problem. Nevertheless, ambiguity and limits of measurement accuracy require peculiar attention, and suitable constraints for layer data and a proper merit-function construction have to be used. In the talk different designs and numerical analysis of the corresponding experimental data will be discussed.

9750-44, Session 10

Modeling graphene based surface plasmon waveguides and devices

James Pond, Federico Duque-Gomez, Ahsan Alam, Roberto Armenta, Jens Niegemann, Dylan McGuire, Adam Reid, Numerical Solutions, Inc. (Canada)

Graphene is different from most optical materials in that it is a thin material layer with a thickness as small as one atom. Graphene layers can be incorporated into optical simulations using either a surface conductivity material model or a volumetric permittivity material model; however, introducing graphene through a volumetric permittivity is computationally inefficient because it requires very fine discretization grids. We have recently developed a more efficient approach that enables the use of comparatively coarse grids by formulating a discretization of Maxwell’s equations (in the time or frequency domains) that combines a surface...
vertical coupled resonator waveguide systems will be presented together with integrated detectors. Recent progress in fabrication of horizontal and light source and silicon can be used itself for realization of homogeneous systems allow for the realization of transparent low loss waveguides in the 800nm to 900nm range where low-cost VCSEL lasers can be used as a light source and silicon can be used itself for realization of homogeneous siliconoxynitride represent an interesting alternative to more common silicon based ones for realization of photonic biosensors. Indeed, both material configurations with air cover show that a certain asymmetry can well be achieved for symmetric system, here realized by slab waveguides with a silicon core guiding layers at different elevation levels in a 3-D integrated optical chip, the step structures. One obtains a configuration that optically connects guiding layers at different elevation levels in a 3-D integrated optical chip, without radiation losses, over “large” distances, and reasonably broadband. We show rigorous quasi-analytical results for typical high-contrast Si/SiO2 structures. Although the “theoretical” full-transmission effect requires a symmetric system, here realized by slab waveguides with a silicon core sandwiched between thick silica substrate and cover layers, simulations for configurations with air cover show that a certain asymmetry can well be afforded.

WGM resonator based integrated optical circuits for lab-on-chip sensors at ~0.85 micron (Invited Paper)

Georg Pucker, Fondazione Bruno Kessler (Italy); Alina Samusenko, Fondazione Bruno Kessler (Italy) and Univ. degli Studi di Trento (Italy); Mher Ghulinyan, Laura Pasquardini, Fondazione Bruno Kessler (Italy); Tatiev Chalyan, Romain Guider, Davide Gandolfi, Univ. degli Studi di Trento (Italy); Andrea Adami, Leandro Lorenzelli, Fondazione Bruno Kessler (Italy); Lorenzo Pavesi, Univ. degli Studi di Trento (Italy)

Whispering gallery mode based optical circuits in silicon nitride and/or siliconoxynitride represent an interesting alternative to more common silicon based one for realization of photonic biosensors. Indeed, both material systems allow for the realization of transparent low loss waveguides in the 800nm to 900nm range where low-cost VCSEL lasers can be used as a light source and silicon can be used itself for realization of homogeneous integrated detectors. Recent progress in fabrication of horizontal and vertical coupled resonator waveguide systems will be presented together with a detailed review of the properties of the waveguides, directional couplers, and integrated detectors. The optical circuit allows to measure refractive index changes smaller than 10^-6 refractive index units (RIU).

Finally, we will review results on the use of these sensors for sensing of Aflatoxin M1 in milk, a potent carcinogen. Aflatoxin M1 is a metabolite of Aflatoxin B1, produced by the ubiquitous fungus Aspergillus flavus, which can contaminate feedstock. Fast sensing of Aflatoxin is important for dairy industry to avoid destruction of large batches of milk and dairy products. The lab on a chip sensor allowed the sensing of Aflatoxin M1 down to ~10 nanomolar, which means that in principle it is possible to sense aflatoxin M1 in milk for the limits required by European regulations, after sample preparation and some preconcentration.

9750-45, Session 10

Oblique incidence of semi-guided waves on step-like folds in planar dielectric slabs: Lossless vertical interconnects in 3D integrated photonic circuits

Andre Hildebrandt, Samer Alhaddad, Manfred Hammer, Jens Förstner, Univ. Paderborn (Germany)

Semi-guided light propagation across linear folds of slab waveguides is being considered. Radiation losses vanish beyond certain critical angles of incidence, as can be understood by arguments resembling Snell’s law. One thus realizes lossless propagation through 90-degree corner configurations, where the remaining guided waves are still subject to pronounced reflection and polarization conversion. A step-like system of two of these sharp corners can then be viewed as a system akin to a Fabry-Perot interferometer, with two partial reflectors at a distance given by the vertical separation of the slab cores. The respective resonance effect enables full transmission of semi-guided, laterally plane waves through the step structures. One obtains a configuration that optically connects guiding layers at different elevation levels in a 3-D integrated optical chip, without radiation losses, over “large” distances, and reasonably broadband. We show rigorous quasi-analytical results for typical high-contrast Si/SiO2 structures. Although the “theoretical” full-transmission effect requires a symmetric system, here realized by slab waveguides with a silicon core sandwiched between thick silica substrate and cover layers, simulations for configurations with air cover show that a certain asymmetry can well be afforded.

9750-46, Session 11

Waves - BSW) at the surface of one dimensional photonic crystals were demonstrated as a practical route to enhanced resolution and constitute an attractive alternative to surface plasmon polaritons (SPP).

Oblique incidence results include electrical simulations of graphene and demonstrates how both optical and electrical simulations can be combined to produce a complete model of a graphene based device. For each example, we compare with previously published results, including experimental results.

9750-47, Session 11

Label-free and fluorescence biosensing platform using one-dimensional photonic crystal chips (Invited Paper)

Francesco Michelotti, Alberto Sinibaldi, Aleksei Anopchenko, Sapienza Univ. di Roma (Italy); Peter Munzert, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Stefan Schmiede, Fraunhofer IWS Dresden (Germany); Rona Chandrawati, Subinoy Rana, Imperial College London (United Kingdom); Frank Sonntag, Fraunhofer IWS Dresden (Germany); Agostino Occhicone, Sapienza Univ. di Roma (Italy); Lucia Napione, Univ. degli Studi di Torino (Italy); Molly M. Stevens, Imperial College London (United Kingdom); Norbert Danz, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The increasing demand for non-invasive early detection of diseases drives the efforts to develop more and more sensitive techniques to detect disease biomarkers in extremely low concentrations. Among other techniques, optical label-free bio-sensing is considered to be the most promising tool for high throughput detection of biomolecules. Surface Plasmon resonance (SPR), operating in a variety of configurations, is commonly used in biology and pharmaceutical laboratories. Among other label-free optical approaches those based on the excitation of electromagnetic modes (Bloch Surface Waves - BSW) at the surface of one dimensional photonic crystals were demonstrated as a practical route to enhanced resolution and constitute an attractive alternative to surface plasmon polaritons (SPP).

The main advantages of BSW for bio-sensing, in comparison to SPR, lie in the favorable properties of the 1DPC such as the small absorption of the dielectric materials and the tunability of the layer thicknesses to operate in any wavelength range. Besides, the use of BSW in fluorescence-based bio-sensing does not suffer from quenching of the fluorophores emission at the 1DPC surface.

Here we report on the development of BSW biochips operating in both label-free and fluorescence modes and demonstrate their use for the detection of clinical biomarkers related to angiogenesis and early cancer development. We describe the design and fabrication of BSW biosensors and the layout of the optical reading instrument. Surface functionalization and methods for effective immobilization of proteins on the biochips are discussed. Experimental results of the assays are presented.

9750-48, Session 11

Fabrication of scattering source for an optical fiber sensor using femtosecond laser internal processing

Naoki Chinen, Masahiko Shiraishi, Soka Univ. (Japan); Kenji Goya, National institute of Advanced Industrial Science...
and Technology (Japan); Atsushi Seki, Kazuhiro Watanabe, Soka Univ. (Japan)

Micro-processing by using an ultrashort pulsed laser has been previously reported and developed in the past decade for fabricating micro devices. Using tightly focused short pulse laser beam, the laser intensity easily can reach more than 1013 W/cm^2. Under such conditions non-linear phenomena are attractively triggered and multiphoton ionization and self-focusing are notably induced especially in a transparent medium. Femtosecond laser enables micro-fabrication without critical heat damage owing to extremely shorter pulse width and very fast multi-photon absorption at the laser focal point, compared with longer pulse. In this report, a micro-voids array was created in optical fiber line by using a femtosecond laser to produce sensing area only at local micro-region of the fiber line. At sensing portion consisted of the voids array, transmitted light was partially scattered by voids after that the leaked light could be reflected on the interface of cladding and outsides, which held the incident angle depending on structures of the micro-voids array. Voids array played as a role of scattering sources to transmitted light and consequently it was expected that the transmitted light can be broadly leaked out from the fiber core to the cladding. Furthermore, optical losses attributed to the creation of micro voids were quantitatively obtained so as to figure out the sensor characteristics. Consequently the reflection region which was considered as a sensing area showed the re-coupling rate of 0.04 dB (3.03%) to insertion loss of 1.32 dB, and the incident angle existed between 67.2 – 71.9°.

9750-49, Session 11

**Enhanced electro-optical Fano-based photonic crystal-on-fiber E-field sensor**

Maria-Pilar Bernal, Abdoulaye Ndao, Wentao Qiu, Venancio Calero, Roland Salut, Nadège Courjal, Fadi I. Baida, FEMTO-ST (France) and Ctr. National de la Recherche Scientifique (France)

Electro-optical (EO) electric field sensors with high sensitivities and large bandwidth are very interesting since they are capable of detecting small electric fields without distorting the field to be measured due to the absence of metallic parts. Most of EO electric field sensors are based on Mach-Zehnder configurations fabricated on LN. In the work presented here, we increase the sensibility by using a LN photonic crystal (PC) with a Fano resonance that is tuned by the EO effect of LN. The tunability is greatly enhanced due to the photonic crystal geometry. The dielectric material is a thin film lithium niobate air suspended membrane of only 700 nm thickness. Furthermore, the LN PC membrane is attached to a cleaved end of single mode fiber couplers and, the resulting device is a small and robust reflection based sensor. Temperature and electric field sensing will be demonstrated theoretically and experimentally.

9750-50, Session 11

**On-chip spectrometer based on an evanescently coupled multimode spiral waveguide**

Brandon Redding, U.S. Naval Research Lab. (United States); Seng Fatt Liew, Raktim Sarma, Yaron Bromberg, Hui Cao, Yale Univ. (United States)

The development of a high-resolution chip-scale spectrometer is essential to low-cost, portable sensing applications and could add functionality to lab-on-a-chip systems. However, the spectral resolution of a spectrometer depends on the spread in the optical pathlengths through a dispersive medium, which is difficult to achieve on-chip where the footprint is inherently limited. Here, we present a novel spectrometer design based on a multimode waveguide patterned in a spiral geometry. Interference between the modes of the waveguide forms a wavelength-dependent speckle pattern which can be used as a fingerprint to identify the input wavelength. The spectral resolution scales with the length of the multimode waveguide but can be improved by introducing evanescent coupling between neighboring waveguide arms. This evanescent coupling increases the spread of optical pathlengths in the spiral, thereby improving the spectral diversity. Experimentally, we show that an evanescently coupled spiral spectrometer with 500µm diameter can resolve two lines separated by 0.01 nm at λ = 1520nm. The ability to achieve such high resolution with low loss in a compact footprint could enable applications in low-cost portable sensing or add functionality to lab-on-a-chip systems.

9750-51, Session 11

**Whispering gallery modes in self-assembled bottle microresonators coupled to planar waveguide**

Immacolata A. Grimaldi, Istituto per il Rilevamento Elettromagnetico dell’Ambiente (Italy); Simone Berneschi, Istituto di Fisica Applicata “Nello Carrara” (Italy); Genni Testa, Istituto per il Rilevamento Elettromagnetico dell’Ambiente (Italy); Francesco Baldini, Gualtiero Nunzi Conti, Istituto di Fisica Applicata “Nello Carrara” (Italy); Romeo Bernini, Istituto per il Rilevamento Elettromagnetico dell’Ambiente (Italy)

Optical WGMs microresonators, with their unique properties of high Q factors, long photons storage in small volumes and high light – matter interaction, meet an always increasing interest in many fields of Physics and Technology. In last years, several different microresonator geometries, each one with associated unique characteristics, are reported in the literature, such as planar microring, microsphere, microtoroid and micro-bottle. In particular, bottle resonators support non-degenerate WGMs which propagate, by successive total internal reflections close to the resonator surface and all along its axis, between two turning points (the so called “bottle-necks” points).

In the present work, we present a simple, self-assemble process for bottle microresonators fabrication in SU-8 polymer. The photopolymeric material is dispersed onto a fiber stem, and is photo-polymerized by an UV lamp. The simultaneous superposition between the SU-8 surface energy and the SU-8 – glass fiber surface tension confers the bottle – like shape at these resonant microstructures. Planar single-mode SU-8 based waveguides, realized on polymethylmethacrylate (PMMA) as substrate, are chosen for exciting the micro-bottle resonators by evanescent wave. We demonstrate the possibility to modulate their geometrical sizes (diameter and neck-to-neck distance) by changing the SU-8 resist content with a good repeatability. WGMs, obtained by coupling these microstructures with single mode SU-8 ridge waveguides around 1.5 µm wavelength, are observed. The highest Q factor measured is about 3.8 x 10^4, close to the maximum reachable simply considering the material losses.

9750-18, Poster Session

**Switchable ferroelectrically-fixed refractive index structures in nonlinear photonic crystals**

Mousa Ayoub, Hannes Futterlieb, Jörg Imbrock, Cornelia Denz, Westfälische Wilhelms-Univ. Münster (Germany)

Several studies have demonstrated the capability of induction of refractive index structures in electro-optic crystals with very low intensities. This provides an important tool for optical data storage. However, for these applications, it is desirable to have fixed structures. For that, fixing methods
were proposed, based on structuring the ferroelectric domains, using the screening effect. In those methods, ferroelectric domains are switched through locally increasing of the sum of the externally applied field and the local space-charge field. In this contribution, we investigate alternatively switchable fixed refractive index structures in an electro-optical strontium barium niobate crystal (SBN), utilizing the switching feature of the ferroelectric domain structures, which are parallel and antiparallel to the crystallographic c-axis. An electric field is applied along the c-axis of an unpoled SBN stepwise until the coercive field is exceeded. During the poled process, a 1D refractive index channel is induced by a laser beam (532nm). The field is then applied in the other direction and a second 1D channel is simultaneously written at a different place. The sample is then probed by poling and repoling it several times without illuminating with the writing beam under the phase-contrast microscope. The results show that the two refractive channels switched alternatively “on”/“off”, i.e. the sign is locally switched, in correspondence to the field direction they were written with. Furthermore, the switching field does not lead to lose the structures. Our results allow to switch the refractive index profiles in a controllable way that is important for optical switching.

9750-54, Poster Session

High-precision opto-mechanical lens system for space applications assembled by innovative local soldering technique

Pol Ribes Pleguezuelo, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Charlie Koechlin, SODERN (France); Thomas Burkhardt, Marcel Hornaff, Diana Burkhardt, Andreas Kamm, Steffen Gramens, Erik Beckert, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Guillaume Fiault, SODERN (France); Ramona Eberhardt, Andreas Tünnermann, Fraunhofer IOF (Germany)

Solder joining using metallic solder alloys is an alternative to adhesive bonding. Laser-based soldering processes are especially well suited for the joining of optical components made of fragile and brittle materials such as glasses due to a localized and minimized input of thermal energy. This so-called Solderjet Bumping technique is used to assemble a beam expander used for molecular and particle based back-scattering and atmosphere analysis at the ESA EarthCare Mission. Flexures are designed in the mounts to accommodate the difference of thermal expansion between titanium and the SQ1 glass. The lens will be then locally soldered using Solderjet Bumping. The assembly and integration processes will have to meet several requirements:
- high stability and non-deformation of the optical shape,
- high cleanliness - (molecular: level A Mil- STD-1246 <0.05·10-6 g/cm2; particles: < 50 ppm; inorganic).

At the same time the opto-mechanics have to operate reliably in harsh environments leading to the following demands:
- long life time (20-30 years),
- thermal cycling range: ± 40 °C/+60 °C,
- compatibility with vacuum and radiation,
- high joint strength (~ 100 g).

After the demonstrators assembly several tests have been carried out in order to verify that the devices meet the specified requirements. Initial tests (residual stress measurements, wave front errors (WFE) in transmission, lens depolarization measurements, etc.) have been performed to verify an adequate optical behavior of the components; followed for a test campaign to validate that the lens array can operate in those harsh environments (humidity, thermal cycle, vibration and shock).

9750-55, Poster Session

An LSPR fiber optic sensor based on in-line micro-holes fabricated by a second harmonic 400-nm femtosecond laser

Masahiko Shiraishi, Kenji Goya, Soka Univ. (Japan); Atsushi Seki, Kazuhiro Watanabe, Soka University (Japan)

In this study, we have proposed a novel type of localized surface plasmon resonance (LSPR) fiber optic sensor based on in-line/pico-liter micro-holes which can be experimentally fabricated into the fiber waveguide by using a second harmonic 400 nm femtosecond laser. A repetitive pulse train of 1 kHz with a pulse width of 350 fs was irradiated onto a MMGI fiber optic to make three holes that penetrate through the fiber core and work as spectroscopic-microfluidic flow cells. In order to induce the interaction between transmitted light and gold nanoparticles (GNPs) adhered on the inner surface of the flow cells, micro-holes were designed to be the width of approximately 40 micrometer, along a direction perpendicular to an optical axis of an optical fiber. GNPs with approximately 100 nm of particle diameter adhered onto the inner surface according to 3-aminopropyliethox silane treatment. The transmitted light through the micro-holes was obtained by optical instruments consisted of a white light source and an optical spectrum analyzer. In order to obtain the reference spectrum, the optical spectrum was acquired before dipping the sensor into the GNPs solution. After 30 min of immersing the sensor portion into the GNPs solution, the optical spectrum was also obtained. The reference spectrum which was considered as the baseline, was set to zero and then, the absorbance spectrum was calculated. The absorbance peak at a wavelength of 537 nm occurred in an air condition in the sensing area, which seemed like the resonance peak based on the LSPR.

9750-56, Poster Session

Quadrature phase-shifted integrated optical current sensors based on polymer waveguide MMI coupler

Sung-Moon Kim, Woo-Sung Chu, Min-Cheol Oh, Pusan National Univ. (Korea, Republic of)

Optical current sensors (OCSs) measure the electric current by detecting the phase difference of lights with an interferometer. In sensing fiber coil around a conductor, small circular birefringence is occurred by magnetic field, which is called Faraday effect. In order to acquire good sensitivity and linearity in sinusoidal interference signal, several researches about biasing technique has been investigated. This paper reports on the study of a quadrature phase-shifted OCSs with polarization rotated reflection interferometer (PRRI). The PRRI consists of sensing coil and integrated polymer waveguide chip. In order to convert circular birefringent to linear birefringent, the sensing coil was comprised of a fiber QWP, a spun fiber and a fiber mirror. The phase difference can be measured from interference signals produced by integrated polymer waveguide chip, which is consisting of TE/TM polarization converter, TE-pass polarizer, thermo-optic phase modulator and MMI coupler. of the 2 x 4 MMI coupler produces output interference signals with phase differences of 90°. By comparing the output signals with 90 phase difference, without applying the quadrature point bias in the optical interferometer, we measured the current induced phase change. In the experiment of electrical current measurement, the optical signal exactly followed the 4kA, 60Hz sinusoidal waveform source current. Single chip integration reduces the complexity of the interferometry and enables mass-production of low-cost high performance optical CT.
Tunable channel-drop filters with tilted Bragg reflector and mode sorting branch

Tae-Hyun Park, Jin-Soo Shin, Guanghao Huang, Min-Cheol Oh, Pusan National Univ. (Korea, Republic of)

Optical transceiver is one of the key components in wavelength division multiplexing and it is important to realize the device with low-cost and small-foot print. In this work, tunable channel drop filter with tilted Bragg grating is demonstrated based on thermo-optic polymer waveguide. In an ordinary Bragg reflection device, the filtered signal is reflected backward to the input optical waveguide. Hence, an external magneto-optic circulator is necessary to separate the filtered signal from the input waveguide. It increases the size of the device and the cost. To extract the filtered signal into another output port, tilted Bragg reflectors and a mode sorting asymmetric Y-branch are employed. The asymmetric Y-branch exhibits good mode sorting efficiency with large fabrication tolerance and tilted Bragg reflector operates as a mode converter. The maximum reflectivity of Bragg reflectors was over 90% for a 6-mm long Bragg grating. The 3-dB and 20-dB bandwidths were 0.3 nm and 3 nm, respectively. The side mode suppression ratio was less than -17 dB. The crosstalk in the mode sorting asymmetric X-branch was less than -20 dB. The wavelength tuning was over 10 nm at the applied thermal power of 192 mW.

Advances in spun multicore fiber technology

Andrew Webb, Laurence J. Cooper, Mark D. Hill, Aurélien Bergonzo, Fibercore Ltd. (United Kingdom)

In recent years there has been a surge of interest in multicore fiber (MCF) to fulfil a wide range of applications from data transmission to optical sensing. The placement and composition of the waveguides is critical to the fibers performance and needs to be tailored to the specific deployment so as to ensure tight control on parameters such as optical loss and cross-talk between wave-guiding channels. Furthermore, in MCFs that are used for optical sensing there is a pre-requisite for the cores to be highly doped, either to provide high photosensitivity for the inscription of fiber Bragg gratings (FBG) or to enhance the fundamental optical effects that enable small perturbations in the shape of the fiber to be detected.

Owing to the vast amount of possible applications and configurations for MCF, Fibercore has developed an industrialized and flexible MCF manufacturing platform by building on our experience and proven 4-core fiber technology. This allows the flexibility to customize the composition (e.g. passive or active dopants such as Erbium), the refractive index profile (step or graded index), the size (single mode or multimode), and the position of the cores to an exacting specification.

We will report on the advances in design and manufacturing of spun 7-core MCF at Fibercore which has been specifically tailored for shape-sensing applications. The placement of wave-guiding elements in our 7-core has been successful in minimizing the cross-talk whilst increasing the modal confinement that allows FBGs to be written without the need for hydrogen loading.

Design of a silicon polarization grating with a sub-wavelength anisotropic structure

Koji Anju, Hiroyuki Tsuda, Keio Univ. (Japan); Hisato Uetsuka, National Institute of Advanced Industrial Science and Technology (Japan)

Polarization gratings, which have the important properties of being highly efficient for first order diffraction and having high polarization sensitivity, can be applied to beam splitters, displays, spectro-polarimeters, and so on. Usually, polarization gratings are fabricated utilizing the periodic anisotropy of liquid crystal molecules. However, high tolerance to light, heat, and humidity is required, in particular, for optical communication applications. Therefore, a polarization grating based on an inorganic material is more suitable than one based on an organic one. We propose a silicon polarization grating with form birefringence. It is induced by an anisotropic surface microstructure that has features shorter than the wavelength of light (sub-wavelength anisotropic structure), allowing the birefringence to be controlled through the selection of periodic structural dimensions. In this paper, we describe the design of sub-wavelength structures of half wave plates using a thin film of silicon. By optimizing the line width, the line spacing, and the thickness of the film, a transmittance of more than 99% was obtained at an incident wavelength of 1550 nm. A polarization grating based on this half wave plates was designed. The orientation of the half wave plate structure was rotated in a particular direction. Furthermore, we evaluated the wavelength dependence and the incident angle dependence of the diffraction efficiency using a finite-difference time-domain method.

Polymer waveguide tunable filters with a surface relief apodized grating

Guanghao Huang, Jin-Soo Shin, Won-Joon Lee, Tae-Hyun Park, Woo-Sung Chu, Min-Cheol Oh, Pusan National Univ. (Korea, Republic of)

Optical communication systems have evolved to use multiple channels with independent wavelength carriers to increase their capacity for data transmission. When a wavelength-multiplexed optical signal arrives at its destination, it is necessary to demultiplex or extract a certain wavelength by using a wavelength filter. The wavelength filters for WDM application have been investigated in various fields, such as silicon photonics, MEMS, and polymer devices. Compared to other technologies, Polymeric Bragg grating devices based on a fluorinated acrylate polymer have demonstrated important progress. Because polymer material has a highly efficient refractive index tuning capability based on its large thermo-optic (TO) effect and low heat conductivity. The tunable filter developed for WDM applications should have strong reflectivity and a proper bandwidth to filter a certain wavelength from 0.8-nm spaced multiplexed wavelength signal. In this work, to produce a narrow-bandwidth wavelength filter, an apodized grating structure is incorporated in the polymer waveguide Bragg grating device. To form the apodized structure in polymeric surface relief gratings, we propose a shadow mask method during the plasma etching of the polymer grating pattern. Then, the depth of the surface relief grating could be gradually varied along the propagation direction. Tunable wavelength filter with wide tuning range and a flat top passband was demonstrated. The fabricated polymer grating exhibits a 3-dB bandwidth of 0.36 nm and a 20-dB bandwidth of 0.72 nm with a 95% reflection. The reflection wavelength is tunable over 14 nm for an applied thermal power of 500 mW.

A novel high-sensitive laser diode sensor based on micro-cavity

Hong-Seung Kim, Daegu Gyeongbuk Institute of Science & Technology (Korea, Republic of); Jung-Min Park, Sung-Bok Kim, Electronics and Telecommunications Research Institute (Korea, Republic of); Chil-Min Kim, Daegu Gyeongbuk Institute of Science & Technology (Korea, Republic of); Kwang Ryong Oh, Electronics and Telecommunications Research Institute (Korea, Republic of)
Silicon photonics is of first choice while designing integrated optoelectronic devices, because of low loss, high bandwidth transmission and highly matured fabrication techniques, but diffraction limit of light puts a lower limit on the device cross-section. Light can be guided below the diffraction limit and propagate at metal-dielectric interface by means of SPP, but it incurs heavy loss, which puts an upper limit on device length. In this effort, an attempt is made to make use of both worlds, i.e. low footprint and low loss simultaneously and study its performance in packet based data switching network.

A compact and high-speed optical switch at telecommunication wavelength based on lumped-type electro-optic MZI in push-pull configuration is theoretically studied. Both the arms of MZI utilize plasmonic-slot waveguide (PSW) and input-output 3dB couplers utilize silicon-photon waveguide. PSW (Metal-Dielectric-Metal interface) is used because of two reasons: (a) both metals can also be used as electrodes on which RF field can be applied, thus omitting the need of any external electrode, (b) mode can be confined inside the slot of size much lower than operating wavelength, which gives a very high interaction factor between optical and RF fields. The mode profiles of optical and RF fields and their interaction are calculated by using COMSOL multiphysics. Nano-size tapered waveguide structure is used to couple the photonic and plasmonic waveguides and more than 85% coupling efficiency is achieved. The slot of PSW is a 2nd order non-linear organic material having large electro-optic coefficient to achieve low V_{mL}. Final response time, extinction ratio, packet switching rate and the bandwidth limitations due to rise-time of switch are discussed.

9750-64, Poster Session

**Packaged integrated opto-fluidic solution for harmful fluid analysis**

Timothée Allenet, Davide Bucci, Jean-Emmanuel Broquin, IMEP-LaHC (France); Fabien Geoffray, Fabrice Canto, Laurent Couston, Commissariat à l’Energie Atomique (France); Elsa Jardinier, IMEP-LAHC (France)

Advances in nuclear fuel reprocessing have led to a surging need for novel chemical in-line analysis tools.

We present a packaged lab-on-chip approach with co-integration of optical and micro-fluidic functions on a glass substrate as a solution. A chip was built and packaged to obtain light/liquid interaction in order for the entire device to make spectral measurement using the photospectroscopy absorption principle.

The interaction between the analyte solution and light takes place in a waveguide fabricated by ion-exchanged cores which is combined with a fluid nano-channel. This 120±4 nm deep nano-channel was obtained with Reactive Ion Etching.

Other micro-scale fluidic channels established on the same glass substrate act as reservoirs for the nano-scale channel. They were elaborated with a lithography procedure and HF etching resulting in 150±8 μm deep channels. They are compatible with industrial fluidic interfaces/chip mounts. This allows for analyte fluid in external capillaries to be pumped into the nano-channel through the micro-channels, hence solving issues of fluid injection resistance through nano-scale channels.

In order to produce this complex structure, two substrates were bonded. A study of direct wafer-to-wafer molecular bonding was carried out to improve detector sturdiness and durability and put forward a bonding protocol with a surface energy of ≥5.0±0.9 J/m^2.

The input and the output of the nano-channel waveguides were pigtailed with standard single mode optical fibers at 780 nm. Detector viability was shown by obtaining optical mode measurements and detecting traces of neodymium (Nd) in a 0.01 M and pH 2 nitric acid (HNO3) solution by obtaining an absorption peak specific to neodymium at 794 nm.

As a next step this fully packaged device will be tested for future industrial measurements with a fully automatic acquisition system and lower pH solutions.
9750-65, Poster Session

**Ferrofluid-based optical fiber magnetic field sensor fabricated by femtosecond laser irradiation**

Yang Song, Lei Yuan, Liwei Hua, Clemson Univ. (United States); Qi Zhang, Jincheng Lei, Clemson University (United States); Jie Huang, Missouri Univ. of Science and Technology (United States); Hai Xiao, Clemson Univ. (United States)

Optofluidic system has been more and more attractive in optical sensing applications such as chemical and biological analysis as it incorporates the unique features from both integrated optics and microfluidics. In recent years, various optofluidic based structures have been investigated in/on an optical fiber platform which is referred to as “lab in/on a fiber”. Among those integrated structures, femto-second (fs) laser micromachining technique plays an important role due to its high precision fabrication, flexible design, 3D capability, and compatible with other methods such as chemical etching, etc.

Here we present a ferrofluid based optical fiber magnetic field sensor fabricated by femtosecond (fs) laser irradiation and subsequent selective chemical etching. With the help of fs laser micromachining technique, a built-in micro-reservoir inside a singlemode optical fiber could be fabricated. The micro-reservoir functions as a fiber inline Fabry-Perot (FP) cavity which is filled by ferrofluidic liquid. The refractive index of the ferrofluid varies as the surrounding magnetic field strength changes, which can be optically probed by the FP interferometer. A fringe visibility of up to 30 dB can be achieved with a detection limit of around 0.4 Gauss. Due to the assembly-free fabrication, multiple cascaded micro-reservoirs can be fabricated inside an optical fiber and distinguished through a microwave-photonic interrogation system. A quasi-distributed magnetic field sensing application has been demonstrated with a high spatial resolution of around 10 cm.

9750-66, Poster Session

**Integrated all-polymer Mach-Zehnder interferometers without interaction window in asymmetric configuration**

Yanfen Xiao, Meike Hofmann, Ziyu Wang, Stanislav Sherman, Hans Zappe, Pei Li, Univ. of Freiburg (Germany)

Integrated Mach-Zehnder interferometers (MZI) based on semiconductors or glasses have been widely used as evanescent field sensors for the monitoring of liquid or gas concentrations. In these systems the upper cladding of the sensing arm is removed partially to form an interaction window by means of subtractive fabrication techniques like etching. The use of polymer materials implicates new options and challenges. Polymers are tunable in terms of refractive index and viscosity offering a great flexibility in design and fabrication in a certain range. They enable a cost-efficient and large-scale roll-to-roll manufacturing of integrated optics on flexible foils as substrate material. The foils can be pre-patterned for example by hot-embossing. Additive steps such as printing a pattern or dispensing a homogeneous layer of liquid monomer material followed by a UV induced polymerization can be used to define the optical structure. However, when a large scale fabrication is required, the reliable production of small lateral structures and thin layers is challenging. Thus the fabrication according to the classical MZI design including an interaction window is difficult so that new design approaches are required.

We present here the design and systematic evaluation of MZI sensors without interaction window based on polymer materials. The phase shift at the recombining Y-splitter of the MZI upon a refractive index change of an analyte, which serves as upper cladding of the entire system, is generated by a geometrical asymmetry of the MZI. The waveguides in the sensing and the reference arm have different width leading to different effective refractive indices and sensitivities. We consider theoretically the expected interference signal and show results from numerical simulations of the whole system using commercial software. The simulations include the material as well as propagation losses. The interference signal as a function of the overall MZI length modulates within an envelope which is mainly determined by the MZI sensitivity and the losses. The maximum of this function gives the optimum interferometer length for generating the largest signal change for a given refractive index step. By means of this systematic evaluation a comparison between different MZI designs is done.

The designed interferometers are fabricated by hot-embossing waveguide grooves into a PMMA-foil serving as lower cladding. The core layer consists of a custom-made liquid co-monomer composition and is applied by spin-coating followed by a polymerization step using UV-light under nitrogen atmosphere forming inverted rib waveguides with a total height of 2.7 μm and widths between 2 and 3.5 μm. For a proof of concept we apply water and a water glucose solution in different fractions as analyte. From the measured signal steps at 852 nm we determine the interference curve and compare it with the theoretical predictions.

9750-68, Poster Session

**Enhancing the resonance stability of a high-Q micro/nanoresonator by an optical means**

Xuan Betty Sun, Rui Luo, Xi-Cheng Zhang, Qiang Lin, Univ. of Rochester (United States)

High-quality optical resonators underlie many important applications ranging from optical frequency metrology, precision measurement, nonlinear/quantum photonics, to diverse sensing such as detecting single biomolecule, electromagnetic field, mechanical acceleration/rotation, among many others. All these applications rely essentially on the stability of optical resonances, which, however, is ultimately limited by the fundamental thermal fluctuations of the devices. The resulting thermo-refractive and thermo-elastic noises have been widely accepted for nearly two decades as the fundamental thermodynamic limit of an optical resonator, limiting its resonance uncertainty to a magnitude 710-14 at room temperature.

Here we report a novel approach that is able to significantly improve the resonance stability of an optical resonator. We show that, in contrast to the common belief, the fundamental temperature fluctuations of a high-Q micro/nanoresonator can be suppressed remarkably by pure optical means without cooling the device temperature, which we term as temperature squeezing. An optical wave with only a fairly moderate power launched into the device is able to produce strong photothermal backaction that dramatically suppresses the spectral intensity of temperature fluctuations by five orders of magnitudes and squeezes the overall level (root-mean-square value) of temperature fluctuations by two orders of magnitude. The proposed approach is universally applicable to various micro/nanoresonator platforms and the optimal temperature squeezing can be achieved with an optical Q around 106-107 that is readily available in various current devices. The proposed photothermal temperature squeezing is expected to have profound impact on broad applications of high-Q cavities in sensing, metrology, and integrated nonlinear/quantum photonics.
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9751-1, Session 1

Silicon photonics: some remaining challenges (Invited Paper)
Graham T. Reed, Optoelectronics Research Ctr. (United Kingdom)

This paper discusses some of the remaining challenges for silicon photonics, and how we at Southampton University have approached some of them. Despite phenomenal advances in the field of Silicon Photonics, there are a number of areas that still require development. For short to medium reach applications, there is a need to improve the power consumption of photonic circuits such that inter-chip, and perhaps intra-chip applications are viable. This means that yet smaller devices are required as well as thermally stable devices, and multiple wavelength channels. In turn this demands smaller, more efficient modulators, athermal circuits, and improved wavelength division multiplexers. The debate continues as to whether on-chip lasers are necessary for all applications, but an efficient low cost laser would benefit many applications. Multi-layer photonics offers the possibility of increasing the complexity and effectiveness of a given area of chip real estate, but it is a demanding challenge. Low cost packaging (in particular, passive alignment of fibre to waveguide), and effective wafer scale testing strategies, are also essential for mass market applications. Whilst solutions to these challenges would enhance most applications, a derivative technology is emerging, that of Mid Infra-Red (MIR) silicon photonics. This field will build on existing developments, but will require key enhancements to facilitate functionality at longer wavelengths. In common with mainstream silicon photonics, significant developments have been made there is much left to do. Here we summarise some of our recent work towards wafer scale testing, passive alignment, modulator integration, and MIR silicon photonics technology.

9751-2, Session 1

Schematic-driven silicon photonics design (Invited Paper)
Lukas Chrostowski, The Univ. of British Columbia (Canada)

Electronic circuit designers commonly start their design process with a schematic, namely an abstract representation of the physical circuit. In integrated photonics on the other hand, it is very common for the design to begin at the physical component level. In order to build large integrated photonic systems, it is crucial to design using a schematic-driven approach. This includes simulations based on schematics, schematic-driven layout, layout versus schematic verification, and post-layout simulations. This presentation will describe such a design framework implemented using Mentor Graphics and Numerical Solutions design tools.

9751-3, Session 1

Design considerations for silicon micro-ring modulators (Invited Paper)
Andrew P. Knights, Edgar Huante-Ceron, McMaster Univ. (Canada)

The talk will discuss the development of new material structures for fast detection and modulation at extended wavelengths in a pure silicon platform. The emphasis of the presentation will be the need for materials development required to continue the advance of photonic systems in a “Moores Law” type paradigm.

9751-4, Session 2

Nanolasers and related issues for integrated photonics applications (Invited Paper)
Cun-Zheng Ning, Arizona State Univ. (United States)

On-chip photonic integration requires light sources of small footprint, high bandwidth, and high energy-data-rate efficiency. Currently lasers meeting all these requirements are still need to be developed. In this talk we will describe our efforts in the last few years in developing metallic cavity nanolasers. Issues such as energy data rate efficiency, modulation speed, noise, thermal performance, as well as their relationship with device size will be described. Recent results on new generation of nanolaser design and fabrication will be also presented including metallic cavity nano-membrane lasers.

9751-5, Session 2

Nano-antennas from the visible to the mid-infrared: material considerations and applications (Invited Paper)
Stefan A. Maier, Imperial College London (United Kingdom)

The light harvesting properties of nanoantennas composed of different materials such as metals, semiconductors, and polar dielectrics are evaluated. A particular focus lies on applications in surface enhanced spectroscopies and optoelectronics, for frequencies spanning from the visible to the mid-infrared.

Optical nanoantennas based on metallic nanostructures enable the controlled focusing of light from the far field to highly confined volumes below the diffraction limit, and have spurred a renewed interest in the field of plasmonics. Here, we present an overview over plasmonic antenna designs operating in the visible part of the spectrum, and investigate how a change in materials to hybrid structures, semiconductors, polar dielectrics, and anisotropic van der Waals crystals enables us to overcome the disadvantages of plasmonics for certain application areas, mainly related to the associated optical losses.

Firstly, hybrid nanoantennas composed of both metallic and in this case transition metal oxides are shown to be a viable and highly efficient platform for higher harmonic generation. Specifically, dipolar Au antennas with a 20 nm ITO disc in the feedback exhibit an enhancement of third harmonic generation by about six orders of magnitude.

Dielectric nanoantennas composed out of semiconductors instead of metals also enable controlled near-field localization, without heating losses and the possibility to also manipulate the magnetic field distribution in a controlled manner. We evaluate this behaviour in terms of applications in surface enhanced spectroscopie, and show that Si dimers are a promising platform for low-loss, zero-heat surface enhanced Raman spectroscopy in the visible part of the spectrum.

Finally, we turn our attention to the mid-infrared part of the electromagnetic spectrum, where polar dielectrics enable nanofocusing due to the excitation of surface phonon polaritons. Specifically, nano forests composed out silicon carbide nanopillars show Purcell factors up to 107 due to the combination of low-loss phonon modes and ultra-small mode volumes. Going one step further, the combination of polar behaviour with anisotropy due to van der Waals interactions in adjacent crystal planes allows the occurrence of hyperbolicity in natural materials such as hBN. This enables truly three-dimensional nanophotonic confinement, with a high promise for applications in the mid-infrared.
9751-6, Session 2

**Efficient optical coupling into ultra-compact plasmonic slot waveguide using dipole nanoantennas (Invited Paper)**

Qian Gao, Fangzheng Ren, Alan X. Wang, Oregon State Univ. (United States)

As the number of transistors per chip continues to increase according to Moore’s law, photonic integrated circuits (PICs) are becoming smaller and denser, and their speed is expected to exceed 100Gbit/s in the near future. In order to build functional chip-scale PICs, it is vital to develop key circuit elements with ultra-small footprints and high energy efficiency. One of the most promising directions for miniaturizing photonic devices is using surface plasmon polaritons (SPPs). SPP waves can overcome the fundamental diffraction limit of light, and the sizes of future PICs based on SPP waves could be reduced to a few square micrometers or even smaller. However, one of the great challenges is how to efficiently couple light into a sub-wavelength SPP waveguide. Recently, nanoantennas have been used as nanocouplers due to their ultra-compact size, easy fabrication, and highly efficient conversion efficiency from free space into plasmonic waveguides. In this paper, we designed and characterized various nanoantennas to efficiently couple light into ultra-compact plasmonic slot waveguides from high numerical aperture optical fibers. Our simulation and experimental results show that the couple-in efficiency from the optical fiber is lower than the couple-out efficiency from the plasmonic slot waveguide. We attribute this discrepancy to the mismatch of the incident light profile with respect to the radiation pattern from the dipole nanoantennas. Moreover, we experimentally characterized the dependence of the couple-in efficiency to the size of the incident light spot and measured the propagation loss of the plasmonic slot waveguide.

9751-7, Session 2

**Ultrafast generation and relaxation of non-equilibrium carriers in plasmonic nanostructures (Invited Paper)**

Prineha Narang, California Institute of Technology (United States) and Northrop Grumman Corp. (United States)

Despite more than a decade of intensive scientific exploration, new plasmonic phenomena continue to be discovered, including quantum interference of plasmons, observation of quantum coupling of plasmons to single particle excitations, and quantum confinement of plasmons in single-nm scale plasmonic particles. Simultaneously, plasmonic structures find widening applications in integrated nanophotonics, biosensing, photovoltaic devices, single photon transistors and single molecule spectroscopy. Decay of surface plasmons to hot carriers is a new direction that has attracted considerable fundamental and application interest, yet a theoretical understanding of ultrafast plasmon decay processes and the underlying microscopic mechanisms remain incomplete.

Recently we analyzed the quantum decay of surface plasmon polaritons and found that the prompt distribution of generated carriers is extremely sensitive to the energy band structure of the plasmonic material. A theoretical understanding of plasmon-driven hot carrier generation and relaxation dynamics at femtosecond timescales is presented here. We report the first ab initio calculations of phonon-assisted optical excitations in metals, which are critical to bridging the frequency range between resistive losses at low frequencies and direct interband transitions at high frequencies. We also present calculations of energy-dependent lifetimes and mean free paths of hot carriers, accounting for electron-electron and electron-phonon scattering, lending insight towards transport of plasmonically-generated carriers at the nanoscale. We will discuss calculations for multiplasmon and nonlinear processes in the ultrafast regime from the mid-IR to visible and in different geometries. Employing a Feynman diagram approach here has been critical to determine the relevant processes.

9751-8, Session 3

**Polarization diversity circuit for a silicon optical switch using silica waveguides integrated with photonic crystal thin film waveplates**

Koki Sugiyama, Keio Univ. (Japan); Takafumi Chiba, Takayuki Kawashima, Shojiro Kawakami, Photonic Lattice Inc. (Japan); Hiroshi Takahashi, Sophia Univ. (Japan); Hiroyuki Tsuda, Keio Univ. (Japan)

Recently, silicon photonics has been studied intensively since it enables dense integration and low cost fabrication of optical functional circuits. However, silicon waveguides have large polarization dependence. Therefore, polarization diversity is absolutely imperative. Here, we proposed a compact polarization diversity circuit using silica waveguides and photonic crystal waveplates. By setting this circuits at the front and the rear of the silicon devices, the polarization dependence of the silicon optical circuits can be suppressed. The employed photonic crystal is considered an artificially designable crystal by nanolithography. Therefore, the retardation and the orientation of the photonic crystal waveplate can be locally varied in one-chip. This enables to dramatically cut down size of the polarization diversity circuit which consists of a 1x2 multimode interference (MMI) coupler, two arm waveguides with quarter-waveplates, a 2x2 MMI coupler, and output waveguides with half-waveplates. The input light including transverse electric (TE) and transverse magnetic (TM) modes is split by a 1x2 MMI coupler. The optical axes of 125 µm-spaced two quarter-waveplates are set orthogonally, so that the phases of TE modes in two arm waveguides should differ by 90 degrees, and those of TM modes should differ by -90 degrees. The TE mode and the TM mode are separated at the 2x2 MMI coupler outputs and the polarization of one of the output light is aligned to the other output by the half-waveplate. In this paper, we designed 4x8 polarization diversity circuit for a 4x4 silicon optical switch.

9751-9, Session 3

**Resolving the controversy in the physical origin of enhanced optical gain/absorption in micro/nano waveguiding dielectric or plasmonic structures in photonic integrated circuits via the concept of geometrical energy velocity (Invited Paper)**

Seng-Tiong Ho, Xi Chen, Northwestern Univ. (United States); Yingyan Huang, OptoNet, Inc. (United States)

The concept of mode confinement factor in the computation of optical gain or absorption for an optical beam propagating in “beam-confined
optical structures” that include dielectric optical waveguides, photonic bandgap (PBG) structures, plasmonic waveguides, and complex optical meta-materials in photonic integrated circuits is of broad interest. It has been observed that in many of these beam-confined optical structures, the optical gain or absorption per unit propagation length can be altered (e.g. enhanced) sometime quite strongly. Such gain/absorption enhancements also enhance the nonlinear optical response, and can lead to substantially more compact photonic devices such as compact lasers or modulators. Several forms of such mode confinement factor has been discussed in the literature, including one based on power-flow, another based on field overlapping integral multiplied by the group velocity, and another based on energy velocity.

The observation that optical gain or absorption is related to group velocity has lead one to think for example that the physical origin of the enhancement is due to the slowing down of the photons in the beam. Such interpretation, however, is fundamentally problematic as optical gain/absorption coefficient is a “single frequency” parameter. Group velocity, however, requires the refractive index of more than one frequency point to be known or sensed by the beam. We have resolved the issue and show that the physical origin of the gain/absorption change is due to photon’s geometrical path alteration that can be described by the concept of geometrical energy velocity that is akin to but clearly different from the physical group velocity.

9751-10, Session 3

Development of broadband antireflection of high-index substrate using SiNx/SiO2
Kim Peng Lim, Keh Ting D. Ng, Qian Wang, A*STAR - Data Storage Institute (Singapore)

Broadband antireflection coatings are commonly required in many silicon or III-V compound semiconductor based optoelectronic devices such as solar cells, photodetectors, and image sensors so as to enhance light conversion efficiency. Conventional approach using a single-layer antireflection coating is simple and commonly used in industry but it has a limited working bandwidth. To achieve broadband or even omni-directional characteristics, structures using thick graded refractive index (GRIN) multilayers or nanostructured surfaces which have equivalent graded refractive index profile have been proposed and demonstrated. In this paper, we will show our development of broadband antireflection for high index substrate using double-layer SiNx/SiO2 via inductively coupled plasma chemical vapour deposition (ICP-CVD). Global optimization of thin-film broadband antireflection coating using adaptive simulated annealing is presented. Unlike the conventional optical coating design which uses the refractive index of available materials, the optimization approach used here decides the optimal values of the refractive index as well as the thickness of each layer. The first thin-film material optimization is carried out on the ICP-CVD machine operating at low temperature of 250°C by tuning the SiH4/N2 gas ratio. The double layer thin film has the respective refractive index of 2.56 and 1.54 with respective thickness of 63.1 nm and 109.1nm. With this coating, we have resolved the issue and show that the physical origin of the gain/absorption change is due to photon’s geometrical path alteration that can be described by the concept of geometrical energy velocity that is akin to but clearly different from the physical group velocity.

9751-45, Session 3

Bandgap engineering of InGaAsP/InP laser structure by photo-absorption-induced point defects
Mohammad Kaleem, COMSATS Institute of Information Technology (Pakistan); Sajid Nazir, London South Bank Univ. (United Kingdom); Nazar Abbas Saqib, Computer Engineering Department, CE&ME, National University of Sciences and Technology (NUST) (Pakistan)

The advancements in optoelectronic and photonic integrated circuits are playing an important role in defining future optical communication systems and provide an impetus for a variety of research directions. To realize a photonic integrated circuit (PIC), numerous monolithic fabrication approaches are being investigated. Two well-known techniques are Selective regrowth and Selective area epitaxy. The regrowth techniques require expensive fabrication facilities such as metal-organic vapor phase epitaxy (MOVPE) but the yields are generally low during the entire fabrication process. Similarly, Selective area epitaxy using silica masking allows areas with different band-gaps to be created across the same wafer in a single growth step, but again it does not allow full control of the band-gap. Post growth quantum well intermixing (QWI) is an attractive alternative technique to control the band-gap of quantum well (QW) semiconductors such that the absorption edge is externally changed by blending the wells and barriers of the multiple quantum well structure. The QWI technique depends upon creation of point defects by UV-Laser irradiation process followed by rapid thermal annealing treatment. This allows post growth wafer level fabrication of multiband-gap QW laser structure for monolithically integrated applications. In this paper, we present experimental results and detailed analysis of the wavelength blue-shifted InGaAsP/InP QW laser structure obtained after the combination of UV-Laser irradiation and rapid thermal annealing treatment. The results demonstrate better performance of UV-laser quantum well intermixing technique to blue-shift the band-gap edge of InGaAsP/InP QWs laser structure over 140nm which is imperative for monolithically integrated photonic circuit applications.
9751-13, Session 4
Integration of two-dimensional semiconductors with photonic structures (Invited Paper)
Vinod Menon, The City College of New York (United States)
Transition metal dichalcogenides (TMDs) have emerged as an attractive class of two-dimensional (2D) semiconductors that show unprecedented strength in its interaction with light. Here we will discuss the integration of these two-dimensional semiconductors with photonic structures such as one-dimensional microcavities, photonic crystals, waveguides and metamaterials. The possibility to exploit effects such as valley polarization and valley coherence seen in these TMDs for optoelectronic applications will also be discussed.

9751-14, Session 4
Ultra-thin oxide interlayer wafer bonding for heterogeneous III-V/Si photonics integration
Chee-Wei Lee, A*STAR - Institute of Materials Research and Engineering (Singapore); Ying Shun Liang, Keh Ting D. Ng, Yi Yang, Hnin Yu Yu Ko, Qian Wang, A*STAR - Data Storage Institute (Singapore)
Ultrathin oxide interlayer bonding can bring III-V layers to silicon for photonic subsystem on chip. As compared to direct III-V/Si bonding, it eliminates the need for fabricating outgassing structures on the substrate and also the use of hazardous chemicals such as Piranha and hydrofluoric acid etc. However, the oxide interlayer should be thin enough for an efficient optical coupling between III-V and Si.

We report a low-temperature covalent bonding of InP-based epitaxy substrate to silicon through a thin thermal oxide interlayer of around 20 nm. Detailed optical simulation and experimental characterizations show the 20 nm thin oxide is sufficient as the outgassing medium and the bonding has minimal effect on the transferred epitaxy layer.

9751-15, Session 4
All-optical SR flip-flop based on SOA-MZI switches monolithically integrated on a generic InP platform
Stelios Pitis, Christos Vagionas, Ctr. for Research and Technology Hellas (Greece) and Aristotle Univ. of Thessaloniki (Greece); George T. Kanellos, Ctr. for Research and Technology Hellas (Greece); Tolga Tekin, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); Ronald Broeke, Bright Photonics B.V. (Netherlands); Nikos Pleros, Ctr. for Research and Technology Hellas (Greece) and Aristotle Univ. of Thessaloniki (Greece)
At the dawn of the exaflop era, High Performance Computers are foreseen to exploit integrated all-optical elements, to overcome the speed limitations imposed by electronic counterparts. Drawing from the well-known Memory Wall limitation, imposing a performance gap between processor and memory speeds, research has focused on developing ultra-fast latching devices and all-optical memory elements capable of delivering buffering and switching functionalities at unprecedented bit-rates. Following the master-slave configuration of electronic Flip-Flops, coupled SOA-MZI based switches have been theoretically investigated to exceed 40 Gb/s operation, provided a short coupling waveguide. However, this flip-flop architecture has been only hybridly integrated with silica-on-silicon integration technology exhibiting a total footprint of 45x12 mm2 and intra-Flip-Flop coupling waveguide of 2.5cm, limited at 5 Gb/s operation.

Monolithic integration offers the possibility to fabricate multiple active and passive photonic components on a single chip at a close proximity, bearing promises for fast all-optical memories. Here, we present for the first time a monolithically integrated all-optical SR Flip-Flop with coupled master-slave SOA-MZI switches. The photonic chip is integrated on a 6x2 mm2 die as a part of a multi-project wafer run using library based components of a generic InP platform, fiber-pigtalled and fully packaged on a temperature controlled ceramic submount module with electrical contacts. The intra Flip-Flop coupling waveguide is 5 mm long, reducing the total footprint by two orders of magnitude. Successful flip flop functionality is evaluated at 10 Gb/s with clear open eye diagram, achieving error free operation with a power penalty of 4dB.

9751-16, Session 5
Broadband SLED-based light source and spectrometer
Yonathan Dattner, Orly Yadid-Pecht, Luxmux Technology Corp. (Canada)
A small footprint, low power, cost effective single mode fiber coupled broadband light source is presented. It is based on Super Luminescent Diode (SLED) devices and a compact design enables coverage of the 1250nm-1750nm region with a total power of 50mW at the output of the fiber. This Broad Spectrum Tunable Super Luminescent (BeST SLED) light source can operate at temperatures ranging from -40C to 60C, and resides in a custom designed 26-pin package. The fiber is a standard SMF-28 fiber with FC/PC connector at the output. A polarization maintaining version was developed as well. The light source is coupled to an all Solid State spectrometer, the Nano-Spect that provides a reliable (high Signal to Noise Ratio) based output in real time. Current application results for Steam Quality measurement in oil production show improved resolution and faster response (full spectrum scan in 100 micro seconds, compared to alternative technologies which require several seconds for one spectrum). Other applications in different fields such as air quality and food allergen detection are being sought and developed.

9751-17, Session 5
Lasing characteristics of integrated lasers with whispering-gallery mode microresonator (Invited Paper)
Yong-Zhen Huang, Xiu-Wen Ma, Yue-De Yang, Jin-Long Xiao, Yun Du, Institute of Semiconductors (China)
Whispering-gallery mode (WGM) microlasers, which can be fabricated by planar technique processing, are potential light sources for photonic integrated circuits. In addition to the microdisk lasers with a circular resonator, polygonal resonators can also support high-Q WGMs for realizing directional emission microlasers. Directional emission circular and polygonal resonator microlasers have been fabricated by directly connecting an output waveguide to the microresonators. In this talk, we will report the characteristics of integrated lasers consisting of a Fabry-Pérot cavity with one side connected to a WGM microresonator. As the WGM microresonator can result in a modulated reflectivity for the Fabry-Pérot cavity, single mode lasing is expected for the integrated laser. The integrated lasers with different types of WGM microresonators are fabricated and compared experimentally. Single mode lasing with the side mode suppression ratio higher than 40 dB and narrow far-field divergence angle is realized for the
integrated laser with the Fabry-Pérot cavity length of 300 μm. In addition to the lasing characteristics of single mode operation, we will also report the high speed modulation characteristics of the integrated lasers. Furthermore, we can deposit antireflection mirror on the cleavage facet of the Fabry-Pérot cavity, and obtain the integrated laser as a WGM microcavity with an optical amplifier with better single mode characteristics.

9751-18, Session 5
Integration of mode-locked diode lasers (Invited Paper)
Ann C. Coleman, The Univ. of Texas at Dallas (United States); John H. Marsh, Lianping Hou, University of Glasgow (United Kingdom)

Monolithic mode-locked semiconductor lasers are attractive sources of short optical pulses with advantages over more conventional sources in compactness, robustness, performance stability, power consumption, and cost savings. The mode-locking frequency is determined by the cavity round trip time and therefore is inversely dependent on the cavity length. Consequently, lasers mode-locking at 10 GHz have relatively long cavities (~4.4 mm). Long cavities can lead to degradation of the emitted pulses through their interaction with carriers in the gain region. Furthermore it can be desirable to introduce some control on the output spectrum of the pulses. Distributed Bragg reflectors (DBRs) are indispensable for controlling the spectral bandwidth, the center wavelength, while additionally providing tuning possibilities of the pulse repetition rate. The DBR requires a wider bandgap than the active region, to reduce the direct interband absorption, which is usually obtained by selective etching and regrowth processes. An alternative approach is to etch the gratings into the surface of the laser, a post growth process which does not require costly regrowth. A wider bandgap can be achieved by using quantum well intermixing (QWI) in the region of the DBR and QWI can also reduce the interaction of the pulses with the carriers. QWI is a post growth process based on the interdiffusion of lattice components between the quantum wells and barriers that make up the active region of the laser. The use of QWI in the fabrication of mode-locked semiconductor lasers with integrated DBRs and their performance will be presented.

9751-19, Session 5
Ultra-high-Q silicon nitride microresonators for on-chip frequency comb generation (Invited Paper)
Minghao Qi, Yi Xuan, Yang Liu, Xiaoxiao Xue, Andrew J. Metcalf, Pei-Hsun Wang, Jian Wang, Ben Niu, Kyunghun Han, Min Teng, Daniel E. Leaird, Andrew M. Weiner, Purdue Univ. (United States)

Silicon nitride (SiN) micro-resonators offer the potential of integration with integrated circuits and other silicon photonics components, and therefore are the material choice of many integrated photonic devices. In addition to a high quality factor (Q), for frequency comb (FC) generation a film thickness of 600-800 nm is required for near zero dispersion. Such a thickness is typically too thick for stoichiometric SiN due to the large stress. In this work, ~600 nm thick stoichiometric LPCVD SiN film was grown in three installments of 166-200 nm each on patterned 3.5 micron thick thermal oxide islands on a Si wafer at 800 °C using dichlorosilane and ammonia as precursors. A race-track like resonator with multiple turns was designed to fit the resonator with an effective diameter ~2 mm inside an electron beam (EB) lithography exposure field (~1 mm²). 1 micron thick oxide was deposited after the resonator is patterned and etched. The finished chip went through a high temperature annealing at 1250 °C for 4 hours. We utilize two independent methods to accurately determine the Q of the SiN resonators. First, we measured the FWHM of the resonance by slowly scanning a single-mode laser at low power through the resonance and measuring the transmission spectrum. There were three resonant modes, and we identified the TE00 mode through fitting the FSR. Transmission measurements at resonance wavelengths of 1553.697 nm and 1553.8958 nm showed high extinction (> 15 dB), which indicates that the resonator is near critical coupling. The loaded Q (Qi) and intrinsic Q (Qi) factors are calculated to be Qi=6.93 (Qi=16.6) million and Qi =8.32 (Qi =16.7) million, respectively. We then independently verify the Qs using a cavity ring down measurement. The pump light was quickly turned on and off, and the transient of the same pump light after passing through the resonator was measured with a high speed photodiode. The loaded quality factor can be calculated directly by the time constant of the exponential decay of the transient light. This method results in the Qs of Qi=8.06 (Qi=17.2) million for the 1553.697 nm resonance and Qi =9.34 (Qi =17.4) million for the 1553.8958 nm resonance. Such high Q resonators lead to low power for the onset of frequency combs. We observed an on-chip pump power as low as 2.8 mW for the onset of nonlinear frequency generation. This is the lowest reported for SiN microresonators.

9751-20, Session 6
Generic heterogeneously integrated III-V lasers on silica with metal-coated high-reflectance etched mirror (Invited Paper)
Chee-Wei Lee, Keh Ting D. Ng, Qian Wang, Min Ren, Yuan Hsing Fu, Anthony Yew Seng Kay, Jing Pu, Vivek Krishnamurthy, Ai Ling Tan, Fabijana Tjiptoharsono, Soo Bin Choo, A*STAR - Data Storage Institute (Singapore)

Heterogeneous III-V/Si laser devices and integration allow us to combine the best of III-V semiconductors in efficient optoelectronic functionality and silicon in dense photonic integration to realize a functional subsystem on chip. While there have been many advances in this field, majority of the host substrates are still based on silicon-on-insulator (SOI) substrate, which requires challenging light coupling between SOI and III-V photonic layers and also restricts the choice of substrate used. In our work, we demonstrated electrically pumped AlGaNAs-based multiple quantum wells (MQW) Fabry-Perot (FP) lasers bonded on silica-on-Si substrate. There are three key features of the device: (i) the metal-coated etched-facet ensures the lasers can be used as on-chip light source and provides high reflectance without adding in any extra fabrication steps; (ii) the bonded III-V on SiO2 promises a flexible host substrate provided that a high quality SiO2 buffer layer is deposited, and (iii) the laser mode is sufficiently close and overlaps with the SiO2 bonding layer, and this enables more effective optical coupling design with passive waveguides and optical devices. The laser devices demonstrated have the lowest threshold of 50 mA, a maximum output power of ~9 mW and a differential quantum efficiency of 27.6%, which is much higher than other heterogenous integrated lasers reported so far. One promising application for this laser-on-silica with metal-coated high-reflectance etched mirror is for high-density magnetic recording (HAMR) technology. It enables us to integrate laser, waveguide and transducer on slider for fully-integrated light delivery system solution.

9751-21, Session 6
Patterned semiconductor inverted quantum-dot photonic devices (Invited Paper)
James J. Coleman, The Univ. of Texas at Dallas (United States)

In many cases, the utility of quantum dot lasers and other photonic devices would be enhanced by ordered distributions of uniform, or better yet
engineered distributions of arbitrary, quantum dots. We have successfully applied selective area epitaxy or wet chemical etching using a patterned oxide mask for the formation of quantum dot layers. This has led to a novel inverted quantum dot structure – sometimes called a nanopore – which consists of an InGaAs quantum well, that has been periodically perforated on a scale of tens of nanometers. The pores thus formed are then filled with the higher bandgap GaAs barrier material. This structure exhibits a unique quantized energy structure something like a planar atomic bond structure. Strong coupling between unit cells results in the formation of allowed and forbidden energy bands instead of highly localized, fully discrete states. In addition, the periodicity of the etched “lattice” affects the nature of higher order states and can result in large increases in carrier lifetimes in higher order states.

Here we describe in detail the growth, processing and characteristics of inverted quantum dot structures that exhibit interesting and potentially important effects arising from the introduction of nanoscale features (<50 nm) in the active medium. Methods for forming these patterned quantum structures by etching or patterned selective area epitaxy are outlined and the resultant optical characteristics are presented.

9751-22, Session 6

Tunable on-chip light sources using III-N nanowire arrays and two-dimensional atomic crystals (Invited Paper)
Zetian Mi, Songrui Zhao, Yong-Ho Ra, Xianhe Liu, Binh Le, Renjie Wang, McGill Univ. (Canada)

Electrically injected, tunable on-chip light sources are in demand for a broad range of applications, including chip-level optical communications, smart lighting, displays, and chemical and biochemical sensing. The performance of conventional III-V devices on Si, however, has been fundamentally limited by the presence of extensive dislocations, due to the large lattice mismatch. In this context, we have investigated the epitaxial growth, fabrication, and characterization of coherent light sources on Si with the use of III-nitride nanowire arrays and two-dimensional MoS2 atomic crystals. In this work, catalyst-free III-nitride nanowire arrays were grown directly on Si substrate or GaN template using a plasma-assisted molecular beam epitaxial growth system. The nanowires are vertically aligned on the substrate. Micron and nano-scale LEDs and lasers were fabricated using standard e-beam and photolithography, etching and contact metallization techniques. We have demonstrated electrically injected, color tunable single InGaN nanowire light sources. Multi-color LEDs and lasers are realized in a single epitaxial growth step by controlling the nanowire diameters using the selective area growth process. Such color tunable nanoscale light sources are ideally suited for ultrahigh-resolution projection displays and on-chip optical interconnects. By exploiting the Anderson localization, we have also demonstrated nanowire lasers on Si that can exhibit relatively low threshold current (~ 300 A/cm2) at room-temperature. The direct integration of III-nitride nanowires with two-dimensional MoS2 atomic crystals and the realization of integrated nanophotonic circuits on a Si platform will also be reported.

9751-43, Poster Session

Compact transverse-magnetic mode-pass polarizer based on one-dimensional photonic crystal waveguide
Dong Wook Kim, Moon Hyeok Lee, Yudeuk Kim, Inha Univ. (Korea, Republic of); Kyong-Hon Kim, Inha Univ (Korea, Republic of)

Silicon photonics based on the silicon-on-insulator (SOI) platform have been recognized as an important technology to realize compact photonic integrated circuits (PICs) because of the beneficial property of the silicon’s high refractive index. However, nano-silicon waveguides of the high refractive index contrast with respect to their clad counterpart and of the conventional rectangular-shape cross sectional geometry cause large polarization mode-dispersions (PMDs) due to their structural birefringence. Polarization-control devices based on the nano-silicon waveguides, such as polarizer, polarization beam splitter, and polarization rotator, are indispensable to overcoming the PMD problems. Planar-type polarizers of highly polarization isolating properties are also very important to such a purpose.

Various types of polarizers have been proposed and demonstrated. Transverse-electric (TE) mode-pass polarizer based on a shallowly etched silicon waveguide is demonstrated. Theoretical prediction to the polarizer indicates an extinction ratio of >60 dB with a device length of about 1000 μm. Transverse-magnetic (TM) mode-pass polarizers have been demonstrated with a 9–7μm long subwavelength-grating-waveguide-type TM mode-pass polarizer of measured extinction ratio of about 27 dB.

In this paper, we have proposed a simple and compact TM mode-pass polarizer based on rectangular-shape one-dimensional photonic-crystal silicon waveguide providing an extremely high extinction ratio of > 35 dB in a compact device size of ~ 4.5 μm. The polarizer has been numerically simulated using three-dimensional finite-difference time-domain (3D FDTD) method. We will also discuss about the measured characteristics of the designed polarizer which is to be fabricated by using electron-beam
A compact picosecond pulsed laser source using a fully integrated CMOS driver circuit

Yuting He, Yuhua Li, Orly Yadid-Pecht, Univ. of Calgary (Canada)

Picosecond lasers have applications in areas such as telecommunication, fluorescence lifetime measurements and supercontinuum generation. Direct modulation of a laser diode with ultrashort current pulses offers a compact and low-cost approach to generate picosecond laser pulses. A fully integrated complementary metal-oxide-semiconductor (CMOS) driver circuit is designed and applied to operate a 4GHz distributed feedback laser diode. The CMOS driver circuit combines sub-circuits including a voltage-controlled ring oscillator, a voltage-controlled delay line, an exclusive-or (XOR) circuit and a current source circuit. Ultrashort current pulses are generated by the XOR circuit when the delayed square wave is XORed with the original square wave from the on-chip oscillator. Circuit post-layout simulation shows that the output current pulses injected into an equivalent circuit load of the laser diode have a pulse full width at half maximum (FWHM) of 200ps, peak current of 80mA and a repetition rate of 5.8GHz. This driver circuit is designed in a 0.13um CMOS process and taped out on a 0.3mm2 chip area. This CMOS chip is packaged and interconnected with the laser diode on a printed circuit board. Optical output waveform from the laser diode is captured by a 5GHz bandwidth photodiode and an 8GHz bandwidth oscilloscope. Measured results show that this laser source can output light pulses with a pulse FWHM of 150ps, pulse peak power of 6.7mW (55mA laser peak current) and repetition rate of 5.3MHz. This work achieves a compact picosecond pulsed laser source by using a CMOS integrated circuit and a direct modulation laser diode.

Actively stabilized silicon microring resonator switch arrays for optical interconnects (Invited Paper)

Li Yu, Andrew Poon, Hong Kong Univ. of Science and Technology (Hong Kong, China)

We report our progress towards actively stabilized silicon microring switch arrays for optical interconnects using our recently proposed slope-detection method. The stabilization scheme utilizes an in-resonator all-silicon photomonitor that detects the detuning of the microring resonance wavelength from a carrier wavelength at 1310 / 1550 nm. The photomonitor utilizes linear sub-bandgap surface-state absorption (SSA) on the unpassivated air-silicon waveguide interfaces, or alternatively, defect-state absorption in an ion-implanted silicon waveguide. The photocurrent generated is extracted from the monitor using a p-i-n diode. We form a feedback-control circuit using a microprocessor to realign in real-time the detuned resonance wavelength based on the photocurrent using an electrooptic or thermo-optic tuner integrated in the microring. Our experiments demonstrate a SSA-based photomonitor with a cavity-enhanced responsivity of ~ 3 mA/W at 1550 nm and ~ 10 mA/W at 1310 nm upon a bias voltage of -1 V. We observe a 1 - 2 dB transmission intensity modulation upon a chip temperature modulation of 14°C (from 18°C - 32°C) for an actively stabilized microring that is aligned with the carrier wavelength at 1550 nm at room temperature (25°C). This suggests an >5dB improvement compared to an unstabilized microring transmission. We obtain open eye-diagrams for stabilized microrings upon 30Gb/s data transmission. We are currently characterizing actively stabilized silicon microring linear (e.g., 1 ? 4) and two-dimensional (e.g., 2 ? 2, 4 ? 4) switch arrays. We will discuss the feasibility of extending this stabilization scheme to large-scale N x N switch arrays.

On-chip optical matrix processor for parallel computing (Invited Paper)

Lin Yang, Jianfeng Ding, Lei Zhang, Ruiqiang Ji, Institute of Semiconductors (China)

Matrix-vector multiplication is a fundamental operation in modern digital signal processing fields. Inspired by the intrinsic spatial parallelism of optics, much effort has been made to develop optical apparatuses that can perform such a parallelizable operation. The Stanford multiplier is one of the most notable demonstrations, which is composed of light source array, optical lens, spatial light modulator (SLM) matrix and photodetector array. Almost all implementations are large in volume and high in power consumption. Moreover, many removable elements adopted make them extremely sensitive to the environmental vibration. To overcome these limitations, we propose an on-chip optical matrix-vector multiplier (MVM), which is composed of laser-modulator array, multiplexer, splitter, microring modulator matrix and photodetector array. The fan-out and fan-in with optical lenses in the traditional optical MVMs are replaced by the power splitting and wavelength multiplexing with waveguide devices in the proposed optical MVM, which greatly reduces the complexity and size of the system. The discrete components in the traditional optical MVMs are replaced by the integrated ones in the proposed optical MVM, which improves the stability and power efficiency of the system. 1.67109 multiplications and accumulations per second is implemented by a demo system with a 474 microring modulator matrix.

Ultrafast optical signal processing on silicon-based platforms (Invited Paper)

Dawn Tan, Singapore Univ. of Technology & Design (Singapore)

The development of silicon-based photonic components and systems has advanced tremendously over the last decade, largely for applications in optical interconnects. The role of silicon-based platforms for both linear and nonlinear optics remains highly pertinent because of their ability to be integrated with CMOS-based electronics. In this paper, we present recent research progress pertaining to ultrafast optical signal processing on silicon-based platforms. Advances in photonic devices for different multiplexing systems on a chip will be discussed. On – chip multiplexing strategies for mode – division multiplexing and wavelength division multiplexing for meeting 200GHz dense wavelength division multiplexing standards across the C – and L – bands will be discussed. In addition, the development of a silicon-based nonlinear optics platform with high nonlinear figures of merit will be presented. Nonlinear optical devices fabricated from the developed platform possess nonlinear parameters 500 times larger than that in silicon nitride waveguides, while possessing negligible nonlinear losses at 1.55µm. Ultra – broadband, low power nonlinear wavelength generation using these devices, as well as their potential for realizing advanced light sources for optical interconnect – based applications will be presented.

Recent advances in strained silicon photonics (Invited Paper)

Pedro Damas, Xavier Le Roux, Mathias Berciano, Delphine Marris-Morini, Eric Cassan, Laurent Vivien, Institut d’Electronique Fondamentale (France)

Silicon photonics is being considered as the future photonic platform, mainly for the reduction of photonic system costs and the increase of the number of functionalities on the same integrated chip by combining photonics and
electronics. However, silicon is a centrosymmetric crystal, which inhibits Pockels effect; a second order nonlinear effect which allows for light modulation at speeds that are not limited by carriers and driven at very low power consumption. Nevertheless, this limitation can be overcome by straining the crystal lattice and breaking the crystal symmetry of silicon. This crystal modification is achieved by depositing a SiN high-stress overlay. Over the last few years, several researches have been performed exploring Pockels effect in strained silicon. In this work, we present recent developments on the subject taking into account parasitic effects including plasma dispersion effect and fixed charge effect under an electric field. We experimentally demonstrate Pockels effect in silicon waveguides strained by a SiN overlay deposited by PECVD as a function of the wavelength and the waveguide width. Recent results on high-speed measurements have been performed to well dissociate Pockels effect and plasma dispersion effect.

9751-46, Session 7
Whispering gallery microresonators at exceptional points (Invited Paper)
Sahin Kaya Ozdemir, Lan Yang, Washington Univ. in St. Louis (United States)

Whispering-Gallery-Mode (WGM) microresonators have become versatile platforms for exploring basic science and for fabricating functional devices due to their high-quality factors and highly-confined optical mode volumes. They have been used for sensing, cavity-QED, optomechanics, optical filtering and low threshold lasers. In this talk, we will report and discuss yet another important use of single and coupled WGM microresonators: controlling optical processes and the flow of light in on-chip systems. In particular, we will present techniques and methods on how to bring a system of waveguide coupled WGM resonators to the vicinity of exceptional points (EPs) that are non-Hermitian degeneracies at which complex eigenvalues and the corresponding eigenstates of a physical system coalesce. The presence of an EP affects the system significantly, leading to nontrivial physics with interesting counterintuitive features. We will report on our experimental studies where we have showed how to reverse the effect of loss in optical systems and how the propagation properties of light in WGM microresonators can be controlled in the vicinity of EPs. We will end the talk discussing some of the opportunities and challenges in the WGM research.

9751-28, Session 8
Design and optimization of photolithography friendly photonic components
James Pond, Xu Wang, Jonas Flückiger, Adam Reid, Jens Niegemann, Amy Liu, Numerical Solutions, Inc. (Canada); Lukas Chrostowski, University of British Columbia (Canada)

Silicon photonics is a scalable, cost-effective technology for the production of photonic integrated circuits (PICs). The emergence of silicon photonics as a dominant technology for PICs is largely because it leverages decades of investment in design and fabrication technologies for electronic integrated circuits. However, the photolithography requirements for photonic and electronic components are importantly different. In photonics, geometries are generally curved, sidewall roughness is critically important, and, while the feature sizes are generally much larger than in electronics, photonic device performance can be extraordinarily sensitive to the precise final geometry. For example, even nanometer scale variations in the gap between waveguides can have a dramatic impact on the splitting ratio of waveguide couplers or the quality factors of ring resonators. The use of optical proximity correction (OPC) can greatly reduce these problems but does not eliminate them altogether. The designer is therefore faced with the problem of potentially optimizing a component using highly accurate numerical simulations that cannot be manufactured to the desired geometrical accuracy leading to a discrepancy between targeted and actual performance. To solve this problem, we present a method for designing and optimizing photonic components that are photolithography friendly so that the simulated geometry can be readily manufactured. As an example, we consider the case of waveguide Bragg gratings which are particularly challenging to manufacture by photolithography.

9751-29, Session 8
Verilog-A passive and active components modeling for silicon photonic circuits process design kit (PDK) assembly
Bayram Karakus, Fabien Gays, André Myko, Thomas Anfray, Christophe Kopp, CEA-LETI (France)

With the increasing demand on data speed and bandwidth, Silicon Photonics is considered as an inescapable and advantageous technology due to its perfect integration with CMOS design process. Photonic Integrated Circuits (PICs) allow to generate, module, process and detect light. We propose to use the Verilog-A language for modeling silicon photonic integrated circuits. Behavioral Verilog-A models are implemented in SPICE electrical simulator (ELDO) for completing electrical modeling and in standard Electronic Design Automation (EDA) tools already used for SOI-CMOS circuit design. All our Verilog-A behavioral models take into account the optical polarization, the carrier injection, the bidirectional propagation constraints and interactions, the temperature dependence, the spectral dependence and for active components the impact of the electric interconnections (Back End), the Box and the substrate (Front End). Different models of photonic devices (transmitter and receiver parts) have been developed for passive components, such as straight waveguides (RIB and STRIP), directional couplers(DC), gratings couplers (GC), bend guides, and for active components such as laser, Mach-Zehnder interferometer modulators with heater (MZIMH), ring modulators with heater (RM) and germanium-on-silicon lateral pin photodiode (PINPD). Finally, these models are being incorporated in a Process Design Kit (PDK) which is a specific photonics library designed to work with the EDA tools in order to assist the design flow of silicon photonic integrated circuits.

9751-30, Session 8
An integrated Mach-Zehnder modulator bias controller based on eye-amplitude monitoring
Min-Hyeong Kim, Hyun-Yong Jung, Yonsei Univ. (Korea, Republic of); Lars Zimmermann, IHP GmbH (Germany); Woo-Young Choi, Yonsei Univ. (Korea, Republic of)

A novel integrated Mach-Zehnder modulator (MZM) bias controller based on eye-amplitude monitoring is demonstrated in IHP’s 0.25-μm BiCMOS technology. The bias controller monitors the MZM output light, automatically moves the MZM bias voltage to the optimal value that produces the largest eye amplitude, and maintains it there even if the MZM transfer characteristics change due to thermal drift. The controller is based on the feedback loop consisting of Si photodetector, trans-impedance amplifier, rectifier, square amplifier, track-and-hold circuit, comparator, polarity changer, and charge-pump, all of which are monolithically integrated. The area of the controller is 0.083-mm² and it consumes 92.5-mW. Our bias controller shows successful operation for a commercially-available 850-nm LiNbO3 MZM modulated with 3-Gbps PRBS data by maintaining a very clean eye for at least 30 minutes. Without the controller, the eye for the same MZM modulation becomes completely closed due to thermal drift. The data rate is limited by the Si PD integrated in the controller not by the controller architecture. Since our controller is based on the Si BiCMOS technology which can also provide integrated Si photonics devices on the same Si, it has
9751-31, Session 8

**Tunable arrayed waveguide grating driven by surface acoustic waves**

Antonio Crespo-Poveda, Univ. de València (Spain); Alberto Hernández-Minguez, Paul-Drude-Institut für Festkörperelektronik (Germany); Bernardo Gargallo, Univ. Politècnica de València (Spain); Klaus Biermann, Abbés Tahraoui, Paulo V. Santos, Paul-Drude-Institut für Festkörperelektronik (Germany); Pascual Muñoz, Univ. Politècnica de València (Spain); Andrés Cantarero, Mauricio M. de Lima Jr., Univ. de València (Spain)

Wavelength multiplexers are essential components in wavelength-division multiplexing (WDM) technology, which is widely used in nowadays fiber optic communications. However, most of the signal processing and routing is still performed electronically at the network nodes. In this way, a higher efficiency could be accomplished by replacing the electronic components, making use of the faster response time inherent to optical phenomena to control and process the signals. A promising proposal to realize compact and fast active devices consists of using a surface acoustic wave (SAW) to modulate multiple optical waveguides (WG) through the acousto-optical effect [1].

In this contribution, compact tunable wavelength-division multiplexers driven by SAWs in the low GHz range are demonstrated. In our approach, a standing SAW modulates the refractive index of the arrayed WGs, and each wavelength component periodically switches paths between the preset output channel and the adjacent channels, at a fixed applied acoustic power. Two different layouts are measured, in which multi-mode interference (MMI) couplers or free propagating regions (FPRs) are separately employed as couplers. The fabricated multiplexers operate on five equally distributed wavelength channels, with a spectral separation of 2 nm. The operational period of the device is of approximately 2 ns, with a SAW-light interaction length of 120 microns. The devices have been monolithically processed on (Al,Ga)As, and this technology can be implemented in virtually any material platform.


9751-32, Session 9

**Gas sensors using single layer patterned interference optical filters**

Thomas D. Rahmlow Jr., Robert L. Johnson, Kieran Gallagher, Omega Optical, Inc. (United States)

Optical interference filters consist of multiple groups of high and low refractive index materials. By precisely controlling the thickness of each layer, reflected light from each interface can constructively or destructively interfere to produce unique spectral performance as a function of wavelength. This manufacturing innovation turns this standard design on its side. All layers of a particular material are deposited, or printed, at the same time. Layer thickness is determined by patterning the filters using photolithography techniques. Multiple filters can be printed at the same time as well as reference channels replacing a complex filter wheel with a single, light weight, all optical ‘chip’.

Since the filter is built on its side, the low index layers are air or can be vacuum. This unique design capability creates some very exciting possibilities - the air/vacuum layers are nearly dispersion free. The vacuum layers offer no absorption over the full spectral range. Air filter designs can be exploited for detection of minute levels of contaminants, aerosols, and gas based hazards. Example designs include a methane filter and a combined carbon dioxide and monoxide sensor using open air optical filters that are tuned to the absorption bands of these gases. The open air filter is an enabling technology for a new class of ultra-light, highly sensitive sensors which can be produced at low cost and high volume.

9751-33, Session 8

**Integrated microsystems for optical sensing and imaging applications (Invited Paper)**

Roman Kleindienst, Stefan Sinzinger, Technische Univ. Ilmenau (Germany)

Compact optical systems generally form the backbone of integrated optoelectronic microsystems. Miniaturization as well as integration requirements result in system configurations with folded optical axis such as in planar integrated free-space optics. For optical devices in such systems geometries, the surface profiles of the corresponding optical elements deviate from classical spherical or aspherical shapes. Optimized plane-symmetric or freeform optical elements are required instead. We discuss design, fabrication and characterization of freeform optical elements for the integration of optical microsystems. The systems performance is demonstrated for imaging as well as sensor applications.

9751-34, Session 9

**Vertical split-ring resonators apply on sensing and metasurface**

Wei-Lun Hsu, Pin Chieh Wu, Jia Wern Chen, Ting-Yu Chen, National Taiwan Univ. (Taiwan); Bo Han Cheng, Academia Sinica (Taiwan); Wei Ting Chen, National Taiwan Univ. (Taiwan); Greg Sun, Univ. of Massachusetts Boston (United States); Ding Ping Tsai, Research Ctr. for Applied Sciences - Academia Sinica (Taiwan)

Split-ring resonators (SRRs), are the artificial structures in sub-wavelength scale, which attract wide attentions because of its resonance of electric and magnetic dipolar response. Recently, we developed a technique with high precision alignment that enables us to fabricate the vertical split-ring resonator (VSRR), which exhibits the ability of phase and reflection modulation by controlling the geometric size along z (vertical) direction. In comparison with planar SRR, the VSRR structure couples directly with not only the electric field but also the magnetic field under normal illumination. The fundamental plasmonic properties and potential applications of VSRR are investigated and proposed in this work.

The split-ring resonators structure stands up vertically on the substrate which increase the sensing volume. The resonance dip of measured spectrum is shifted as the refractive index of the environment is changed. The sensitivity of VSRR is about ?/?n ~ 603 nm/RIU. Based on the generalized Snell's law, a VSRR based metasurface enables the beam steering functionality with high extinction ratio for normal incident light. Comparing with the planar rod based metasurface, the VSRR based metasurface could save 48% fabrication area on footprint, enabling the metasurface with high density. The VSRR paves a new way to develop the novel plasmonic devices. In the future, high density and sensitivity VSRRs could be applied on opto-electronic devices.
Low-cost fabrication of optical waveguides, interconnects, and sensing structures on all-polymer-based thin foils

Maher Rezem, Christian Kelb, Axel Günther, Maik Rahlves, Eduard Reithmeier, Bernhard Roth, Leibniz Univ. Hannover (Germany)

Micro-optical sensors based on optical waveguides are widely used to measure temperature, force and strain but also to detect biological and chemical substances such as explosives or toxins. While optical micro-sensors based on silicon technology require complex and expensive process technologies, a new generation of sensors based completely on polymers offers advantages especially in terms of low-cost and fast production techniques. We have developed a process to integrate micro-optical components such as embedded waveguides and optical interconnects into polymer foils with a thickness well below one millimeter. To enable high throughput production, we employ hot embossing, which is capable of reel-to-reel fabrication with waveguide cross-sections of down to one micron and a surface roughness in the optical range. The waveguides are characterized with respect to refractive index profiles, attenuation, coupling efficiency and data-rate. Furthermore, we demonstrate coupling structures and fabrication processes especially suited to integrate various light sources such as vertical-cavity surface-emitting lasers (VCSEL) and organic light emitting diodes (OLED) into the thin polymer foil structures. Using these structures we have realized a prototype of an all-polymer and waveguide based deformation sensor based on intensity modulation entirely fabricated utilizing our process. In addition, we integrated light sources and detectors into the sensor and demonstrate its applicability for optical deformation measurement. In future applications, we aim at a low-cost and highthroughput reel-to-reel production processes enabling the fabrication of large distributed sensor arrays or disposable single-use sensing structures, which will open optical sensing to a large variety of applications ranging from medical diagnosis and process monitoring to automotive technology.

Frequency range selection method of trans-impedance amplifier for high-sensitivity lock-in amplifier used in the optical sensors

Chang-In Park, Su-Jin Jeon, Mi Jung, Young-Wan Choi, Chung-Ang Univ. (Korea, Republic of)

Lock-in amplifier (LIA) has been proposed as a detection technique for optical sensors because it can measure low signal in high noise level. LIA uses synchronous method, so the input signal frequency is locked to a reference frequency that is used to carry out the measurements. Generally, input signal frequency of LIA used in optical sensors is determined by modulation frequency of optical signal. It is important to understand the noise characteristics of the trans-impedance amplifier (TIA) to determine the modulation frequency. The TIA has a frequency range in which noise is minimized by the capacitance of photo diode (PD) and the passive component of TIA feedback network. When the modulation frequency is determined in this range, it is possible to design a robust system to noise. In this paper, we propose a method for the determination of optical signal modulation frequency selection by using the noise characteristics of TIA. Frequency response of TIA in this selection method is measured by using spectrum analyzer and minimum noise region is confirmed. The LIA and TIA circuit have been designed as a hybrid circuit. The optical sensor is modeled by the laser diode (LD) and photo diode (PD) and the modulation frequency was used as the input to the signal generator. The experiments were performed to compare the signal to noise ratio (SNR) of the minimum noise region and the others. The results clearly show that the SNR is enhanced in the minimum noise region of TIA.

4D Light-field Sensing System for People Counting

Guangqi Hou, Institute of Automation (China); Chi Zhang, Institute of Automation (China) and Univ. of Chinese Academy of Sciences (China); Yunlong Wang, Institute of Automation, University Of Science And Technology Of China (China); Zhenan Sun, Institute of Automation (China)

Counting the number of people is still one important task in social security applications and many methods based on video surveillance have been proposed in recent years. In this paper, we design a novel optical sensing system to acquire the depth map of scene directly from one light-field camera. The light-field sensing system can count the people crossing the passageway and record the direction and intensity of rays at a snapshot without any assistant light device. Depth maps are extracted from raw light-ray sensing data. Our smart sensing system is passive imaging and can appear the depth difference of head and shoulders of each person naturally, and then a human model is built. Through detecting the model in light-field image, the number of passing people can be counted rapidly.

The depth acquisition methods, such as Time-Of-Flight and Structured Light, need NIR laser or other invisible additive light source, and the light source may be harmful to eyes, so our motivation is to design a new passive sensing system without any additional light source which can appear the difference between head and shoulder.

The proposed system can capture the passengers from two passageways. After decoding processing, depth maps are extracted from 4D light-field data through structure tensor method. In the depth maps, there is the depth disparity from head to foot and the one between head and shoulder is very robust. Though the results, we can verify the feasibility of the sensing system, and the experiments containing more people will be executed for enhancing our system.

Super-resolution PMD camera for applied metrology

Henrik Lietz, Jörg Eberhardt, Hochschule Ravensburg-Weingarten (Germany)

In the field of two-dimensional image acquisition, super-resolution (SR) approaches are still an interesting topic. Multi frame SR shows a high potential to increase not only the pixel resolution but also the resolving power of an optical system significantly. This is reached by superimposing several low-resolution (LR) sub-pixel shifted images to one SR image. On the other hand, the 3D- PMD (Photonic Mixing Device) camera is a promising technology that acquires a range image of three-dimensional objects quickly using modulated light. However, it supports only a relatively low spatial resolution so far. The challenge here is to transfer traditional SR to PMD cameras. This work describes the challenges in implementing a SR PMD camera, similarities and differences of well-known SR-algorithms and analyses the resulting data for its application in measurement tasks. Due to functionally related characteristics of the PMD camera, the SR-approach cannot be easily transferred from the two-dimensional image acquisition to the three-dimensional imaging. For example, PMD cameras require multiple images that contain different phase information to be able to output one distance image. In addition, these cameras often use variable exposure times to achieve high dynamics during image generation. Both have a direct effect on the amplitude and range images of an image sequence and thus to the following SR overlay. To conclude, differences between metrological and photographic applications are described and an application-specific evaluation is proposed.
9751-39, Session 10

**Analysis of position error by time constant in read-out resistive network for gamma-ray imaging detection system**

Su-Jin Jeon, Chang-In Park, Byung-Hee Son, Mi Jung, Teak-Jin Jang, Chun-Sik Lee, Young-Wan Choi, Chung-Ang Univ. (Korea, Republic of)

Position-sensitive photomultiplier tubes (PSPMTs) in array are used as gamma ray position detector. Each PMT converts the light of wide spectrum range (100 nm - 2500 nm) to electrical signal with amplification. Because detection system size is determined by the number of output channel in the PSPMTs, resistive network has been used for reducing number of output channel. The output signal in PSPMTs is current pulse generated in each PMT which contains information like energy and position. The current pulses are distributed to the four output current pulses according to a ratio by resistive network. The detected positions are estimated by the peak value of distributed current pulses. However, due to parasitic capacitance of PSPMTs connected to resistor in the resistive network, the time constants is considered. When the duration of current pulse is not long enough, peak value of distributed pulses is reduced and detected position error is increased. In this paper, we analyzed the detected position error in the resistive network and variation of time constant according to input position of the PSPMTs.

9751-40, Session 10

**Modeling and calibration of pulse-modulation based ToF imaging systems**

Andreas Süss, Fraunhofer-Institut für Mikroelektronische Schaltungen und Systeme (Germany) and IMEC (Belgium); Gabor Varga, Fraunhofer-Institut für Mikroelektronische Schaltungen und Systeme (Germany) and RWTH Aachen Univ. (Germany); Michael Marx, Peter Fürst, Stefan Gläsener, Fraunhofer-Institut für Mikroelektronische Schaltungen und Systeme (Germany); Wolfram Tiedke, TriDiCam GmbH (Germany); Melanie Jung, Andreas Spickermann, Bedrich J. Hosticka, Fraunhofer-Institut für Mikroelektronische Schaltungen und Systeme (Germany)

Conversely to the continuous wave time-of-flight (CW-ToF) imaging scheme, pulsed modulation ToF (PM-ToF) imaging is a promising depth measurement technique for operation at high ambient illumination. It is known that non-linearity and finite charge-transfer speed impact trueness and precision of ToF systems. As pulses are no eigenfunctions to the shutter system, this issue is especially pronounced in pulsed modulation. Despite these effects, it is possible to find analytical expressions founded on physical observations that map scenery parameters such as depth information, reflectance and ambient light level to sensor output. In the application, the inverse of this map has to be evaluated. In case of CW-ToF, this inverse function can be easily found if the system can be modeled as an LTI system. For PM-ToF, an inverse function cannot be yielded in a direct manner, as models proposed in the literature were transcendental. Recently, an alternative approach that indirectly approximates the inverse function was presented. This method was founded on 1D doping concentration profiles, which, however, are typically not made available to end users. Also, limitations of the 1D approximation as well as device fluctuations are yet to be explored. This work presents a calibration methodology that copes with detector insufficiencies such as finite charge transfer speed and parasitic light sensitivity. Contrarily to the state of the art, no prior knowledge on processing details of the underlying devices is required. The work covers measurement setup, a benchmark of various calibration schemes and deals with issues such as overfitting or defect pixels.

9751-41, Session 10

**Benchmarking time-of-flight based depth measurement techniques**

Andreas Süss, Véronique Rochus, Maarten Rosmeulen, Xavier Rottenberg, IMEC (Belgium)

In the last decade significant progress has been made on optical non-contact time-of-flight (ToF) based ranging techniques. Direct implementations based on time-correlated single photon counting (TCSPC) as well as multiple indirect realizations based on e.g. single-photon synchronous detection (SPSD), continuous-wave modulation (CW) or pulse modulation (PM) have been presented. All those modulation/demodulation techniques can be employed in scanning (scanning LIDAR) as well as non-scanning (Flash-LIDAR) schemes. Many parameters impact key performance metrics such as depth measurement precision or angular resolution. Unfortunately, publications or datasheets rarely quote all relevant parameters. Thus, benchmarking between different approaches based on published metrics is cumbersome. The authors believe that such a benchmark would have to be founded on modeling in order to ensure fair comparison. This work presents an overview over the most common ToF based depth measurement approaches, how these can be modeled and how they compare.

9751-42, Session 10

**A hybrid 3D LIDAR imager based on pixel-by-pixel scanning and DS-OCDMA**

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

We proposed a new hybrid 3D LiDAR, pixel-by-pixel scanning LiDAR imager, is a hybrid of scanning 3D LiDAR and flash 3D LiDAR. Unlike traditional LiDAR scanners, this measures a scene with 1200*600@60FPS and emits the pulsed laser periodically and measures the travelling time of the pulse without latency. The emitted pulse of each pixel is modulated by DS-OCDMA techniques. The modulated function uses the unique device identification number, the pixel position in the line, and checksum. It eliminates the possibility of mutual interference from other LiDARs that it identifies whether the received laser pulse is transmitted laser pulses from itself by using the device ID. The pixel ID makes that it emits the laser pulse continuously without waiting time to receiving the return light to the detector. After the completion of receiving process, this hybrid 3D LiDAR generates the point cloud data of the travel time, amplitude, width, and speed of the pixels as the measured results. We verified the proposed design concept using the simulation with PhySimWiFi for ns-3. From the simulation results, we concluded that our proposal is amply sufficient to a better alternative of scanning 3D LiDARs and flash 3D LiDARs. Our hybrid 3D LiDAR is mainly applicable to map building for the autonomous vehicle and mobile robot. It can analyze and collect data from a real-world object or environment to construct digital 3D models, like a 3D camera. It is also applicable for surveillance such as speed limit enforcement and security CCTV.
9752-1, Session 1

**Silicon-based phase shifters for high figure of merit in optical modulation (Invited Paper)**

Kensuke Ogawa, Kazuhiro Goi, Norihiro Ishikura, Hiroki Ishihara, Shinichi Sakamoto, Fujikura Ltd. (Japan); Tsung-Yang Liow, Xiaoguang Tu, Guo-Qiang Lo, Dim-Lee Kwong, Institute of Microelectronics (Singapore); Soon Thor Lim, Institute of High-Performance Computing (Singapore); Min Jie Sun, Optic2Connect (Singapore); Ching Eng Png, Institute of High-Performance Computing (Singapore)

High-speed optical modulation beyond 100 Gb/s for optical-fiber communications in advanced modulation formats such as dual-polarization quadrature phase-shift keying (DP-QPSK) has been achieved by using lateral PN-junction carrier-depletion silicon Mach-Zehnder (MZ) modulators. A silicon MZ modulator monolithically integrated with optical circuits for polarization-division multiplexing (PDM) has been fabricated on a silicon-on-insulator wafer in a chip footprint as small as 5 x 6.5 mm². Optical-fiber transmission up to 1000 km in 128-Gb/s DP-QPSK format has been demonstrated by using the monolithic silicon MZ modulator copackaged with electrical modulator drivers in a ceramic-based metal package in a small form factor of 15x35-mm² footprint and 4.5-mm height. Peak-to-peak RF voltage of ~6.5 V in 50-ohm impedance-matching processes. In theoretical analysis, optical phase modulation beyond 100-Gbaud symbol rate is feasible in carrier-depletion mode under reverse bias. The reverse-biased lateral PN-junction carrier-depletion phase shifters are reviewed and their performances are evaluated in terms of DC figure of merit.

9752-2, Session 1

**Hybrid silicon-vanadium dioxide electro-optic modulators**

Kevin J. Miller, Petr Markov, Robert E. Marvel, Richard F. Haglund, Sharon M. Weiss, Vanderbilt Univ. (United States)

Small-footprint, low-power devices that can modulate optical signals at THz speeds are crucial for next-generation on-chip photonics. We describe hybrid silicon–vanadium dioxide (Si-VO2) electro-optic modulators as a candidate platform for achieving this performance benchmark. Vanadium dioxide is a strongly correlated material exhibiting a semiconductor-to-metal transition (SMT) accompanied by large changes in electrical and optical properties. While VO2 can be switched optically on a sub-picosecond time scale, the ultimate electrical switching speed remains to be determined. Here we report a record switch-on time for the high-speed electrical SMT, with instrumentation-limited switching times less than 2ns and switch-off times as fast as 3ns. In a Si-VO2 linear absorption modulator geometry, we demonstrate 5 dB modulation in response to a 100ns electrical pulse and 1 dB modulation for a 10ns electrical pulse. The switching performance is complicated because the VO2 phase-transition dynamics unfold on two different time scales. First, strong nanoscale electric fields inject electrons into semiconducting VO2 via the Poole-Frenkel mechanism, leading to a rapid SMT along the current path that forms in VO2 between electrical contacts. Subsequently, a slower Joule heating process expands the metallic filament in VO2. Hence, in the linear absorption modulator configuration, faster switching is accompanied by lower extinction ratios. However, by utilizing a hybrid plasmonic mode or photonic resonator configuration, we show that the modulation depth can be improved dramatically, and also discuss how modulation speed may be improved at the same time.

9752-3, Session 1

**Analysis of Depletion Silicon Phase Shifter Based on Computer Simulation**

Ching Eng Png, A*STAR Institute of High Performance Computing (Singapore) and Optic2Connect Pte Ltd (Singapore); Min Jie Sun, Optic2Connect Pte Ltd. (Singapore); Soon Thor Lim, A*STAR Institute of High Performance Computing (Singapore); Kensuke Ogawa, Fujikura Ltd. (Japan)

In this work we report the efficiency and loss performance of a depletion type silicon phase shifter, with a silicon overlay of 220nm, rib width of 500nm, and etch depth of 125nm. With reference doping concentration of P=5?10^17 cm^-3 and N=5?10^17 cm^-3, a 4mm phase shifter has a Vpi of 3.6V and an active loss of 5.2dB. The performance of the phase shifter can be further improved by understanding the dopant variances using our simulation visualization where the electrical profile and the optical profile can be solved in the same domain and presented a clear understanding of the mode field overlap with the depletion area. We analysed the phase shifter performance of 9 doping variances that covers 2?10^17 cm^-3 to 8?10^17 cm^-3 for both p and n dopants. For a 4mm phase shifter operates at <6V and <5dB loss, recommended doping concentrations should typically range from 2?10^17 cm^-3 to 5?10^17 cm^-3. We also studied junction placement variances and our study shows that an increase in n dopant region with equal p and n doping (5?10^17 cm^-3) will cause phase and loss performance degradation. Our results also suggested that with reduced p dopant concentration (2?10^17 cm^-3), both loss and phase performance will improve by 32% and 20% respectively when p region > n region. The doping configuration studies provide a comprehensive analysis for dopant optimizations based on a depletion silicon phase shifter, which will aid in identifying suitable dopant configurations in a fabrication environment.

9752-4, Session 1

**Stacked double-layer nanomembrane Fano Modulators**

Yi-Chen Shuai, National Institute of Standards and Technology (United States); De Yin Zhao, The Univ. of Texas at Arlington (United States); Corey Stambaugh, National Institute of Science and Technology (United States); John R. Lawall, National Institute of Standards and Technology (United States); Weidong Zhou, The Univ. of Texas at Arlington (United States)

We report a novel bi-layer photonic crystal slab (PCS) electro-optic intensity modulator designed for free-space normally incident light and lending itself to multiplexing. The modulator exploits a Fano resonance in a coupled double-layer silicon nanomembrane (SNM) capacitor-like structure. Electrically-induced changes in carrier accumulation shift the wavelength of the Fano resonance, altering the device reflectivity and transmission. A 6 × 6 array...
9752-5, Session 2

Erbium Compound Nanowires as High Gain Amplifiers and Lasers for Potential Silicon Photonics Applications (Invited Paper)

Cun-Zheng Ning, Arizona State Univ. (United States) and Tsinghua Univ. (China); Leijun Yin, Zhicheng Liu, Arizona State Univ. (United States); Hao Sun, Yongzhuo Li, Jianxing Zhang, Tsinghua Univ. (China)

Erbium-based materials and waveguides are important for amplifiers and light sources for silicon photonics. But the low optical gain in doped materials has hindered their applications in integrated photonics. Here we present a different class of erbium compound materials in nanowire form where erbium concentration can be orders of magnitude higher than in doped materials. The high erbium concentration coupled with single crystal quality results in optical gain exceeding 30 db/cm. In this talk, material growth and optical characterization will be described. We will also present more recent efforts in laser design and fabrication based on such erbium compound nanowires.

9752-6, Session 2

Large bandwidth and high power Germanium photodetector (Invited Paper)

Yu Yu, Wuhan National Lab. for Optoelectronics (China) and Huazhong Univ. of Science and Technology (China); Guanyu Chen, Xinliang Zhang, Wuhan National Lab. for Optoelectronics (China) and Huazhong Univ. of Science and Technology (China)

Germanium photodetector (PD) is the key component of the silicon photonics and it has experienced great development during the past decade. The 3dB bandwidth and power handling capability are the two main issues limiting further applications, both in tele-communication and data-communication. In most cases, the bandwidth is hard to exceed 40 GHz due to the large parasitic parameter, and the power handling capability is usually restrict by the limited saturation optical power under single part illumination condition.

In this talk, we report CMOS compatible germanium PD with both large bandwidth and high power handling capability. The ultrahigh speed operation is realized based on the principle of gain peaking, and several gain peaked structures are proposed and demonstrated to achieve the desired high bandwidth. The high power operation is realized by adopting novel dual-illuminated structures. Compared with the single part illumination condition, the measured maximum DC photocurrent and peak RF power are increased obviously. The comprehensive optimization of both optical and electrical parameters for simultaneous large bandwidth and high power applications is also discussed.

9752-7, Session 2

Silicon dual-ring resonator-based push-pull modulators

Xiaoming Sun, Technische Univ. Berlin (Germany); Linjie Zhou, Shanghai Jiao Tong Univ. (China); Matthias Jäger, Technische Univ. Berlin (Germany); Despoina Petousi, IHP GmbH (Germany); Lars Zimmermann, Klaus Petermann, Technische Univ. Berlin (Germany)

Electro-optical silicon modulators are a key element in photonic integrated circuits (PICs) for optical telecommunications and interconnects. Comparing to the Mach-Zehnder interferometer (MZI), the microring resonator is a good candidate for ultra-compact modulators. However, it is challenging to obtain chirp-free modulation in a conventional ring modulator with the refractive index modulation directly imposed on the ring waveguide. In this paper, we propose and analyze two types of silicon dual-microring resonator-based push-pull modulators to achieve chirp-free modulation with a high modulation depth.

In one configuration where the two rings are connected in series with one ring on through transmission and the other on drop transmission, the output power contrast of the “on” and “off” states is enhanced due to the interaction of resonances from the two ring, leading to a high modulation depth. The optical bandwidth for a given modulation depth is wider than that of a single ring modulator. The frequency chirp of the modulated signal can be fully eliminated by operating both rings in the critical coupling regime. In the parallel configuration where the two rings are coupled with two parallel bus waveguides, the electromagnetically induced transparency (EIT)-like is generated with its EIT peak power dependent on the relative resonance wavelengths of the two rings. By push-pull tuning of the two rings, the EIT peak is modulated, leading to an intensity modulation with a low drive voltage. The frequency chirp of the modulated signals is eliminated as the two rings always shift in the opposite wavelength directions. The chirp-free modulation is an essential requirement for long-haul optical transmission. Our two dual-ring modulator configurations provide a solution for ring modulators to be used in optical telecommunications.

9752-8, Session 2

SWIR InGaAs/GaAsSb type-II quantum well photodetectors and spectrometers integrated on SOI

Ruijun Wang, Muhammad Muneeb, Univ. Gent (Belgium); Stephan Sprengel, Gerhard Boehm, Technische Univ. München (Germany); Roel G. Baets, Univ. Gent (Belgium); Markus-Christian Amann, Technische Univ. München (Germany); Gunther Roelkens, Univ. Gent (Belgium)

The short-wave infrared wavelength range (2-3 μm) is attractive for applications in gas sensing and next generation communication systems. Photodetectors and wavelength (de)multiplexers are key components that have to be developed for these systems. In this contribution, we report the integration of InGaAs/GaAsSb type-II quantum well photodetectors and spectrometers on the silicon photonics platform. In this photodetector epitaxial layer stack, the absorbing active region consists of 6 periods of W-shaped quantum wells, which can also be used to realize lasers. The efficient coupling between silicon waveguides and quantum well photodetectors is realized by tapered III-V waveguides. The photodetectors have a very low dark current of 12 nA under -0.5V at room temperature. The devices show a responsivity of 1.2 A/W at 2.32 μm, and higher than 0.5A/W over the 2.2-2.4 μm wavelength range. On the silicon-on-insulator platform we also demonstrate high performance short-wave infrared spectrometers. 7-channel spectrometers in the 2.3-2.4 μm range with a resolution of 5nm and 1.4nm are demonstrated, showing a cross-talk below -24dB and an insertion loss of lower than 3 dB.
CMOS-compatible polarization rotator design based on asymmetrical periodic loaded waveguide structure

Yao Sun, Winnie N. Ye, Carleton Univ. (Canada)

Silicon-on-insulator (SOI) technology is a promising platform for low-cost and large volume production of commerical applications due to its manufactural compatibility with the complementary metal-oxide semiconductor (CMOS) process. However, SOI based photonic integrated circuits (PICs) are notoriously known for their high polarization sensitivity. Consequently, polarization management components are necessary.

In this paper, we propose and numerically demonstrate a polarization rotator design based on asymmetrical periodic loaded structures on a 220 nm SOI platform. Polarization rotator designs based on such structure was first demonstrated by Shani et al. in 1991. However, designs based on such structure have only been demonstrated on III-V materials (GaAs, InP etc.) which makes the design CMOS incompatible. In our design, we address the CMOS compatibility issue by using only SOI waveguides. Our design is formed by periodically altered longitudinally perturbations along a channel waveguide, where the periodic perturbations on either side are mismatched laterally. The proposed device has a compact device size of 20.88 μm. The device is predicted to achieve >90% conversion efficiency over a wavelength range of 30 nm, with peak conversion efficiencies of 99.79% (for TE to TM) and 99.95% (for TM to TE) at around 1550 nm. The periodic structure enables flexible waveguide parameter selections. The proposed design is not only fully CMOS compatible and can be fabricated by simple two step lithography process. The device has a SiO2 top cladding, which makes it ready for monolithic integration onto SOI based PICs.

Tunable direct bandgap GeSn lasers for monolithic integration on Si platform (Invited Paper)

Dan Mihai Buca, Stephan Wirths, Forschungszentrum Jülich GmbH (Germany); Richard Geiger, Paul Scherrer Institut (Switzerland); Christian Schulte-Braucks, Nils von den Driesch, Daniela Stange, Forschungszentrum Jülich GmbH (Germany); Thomas Zabel, Paul Scherrer Institut (Switzerland); Bahareh Marzban, RWTH Aachen Univ. (Germany); Zoran Ikonic, Univ. of Leeds (United Kingdom); Jean-Michel Hartmann, CEA-LETI (France); Siegfried Mantl, Forschungszentrum Jülich GmbH (Germany); Jeremy Witzens, RWTH Aachen Univ. (Germany); Hans C. Sigg, Paul Scherrer Institut (Switzerland); Detlev Grützmacher, Forschungszentrum Jülich GmbH (Germany)

No Abstract Available

Direct bandgap GeSn light-emitting diodes for short-wave infrared applications grown on Si

Nils von den Driesch, Daniela Stange, Stephan Wirths, Denis Rainko, Gregor Musoller, Forschungszentrum Jülich GmbH (Germany); Zoran Ikonic, Univ. of Leeds (United Kingdom); Jean-Michel Hartmann, CEA-LETI (France) and Univ. of Grenoble Alpes (France); Detlev Grützmacher, Siegfried Mantl, Dan M. Buca, Forschungszentrum Jülich GmbH (Germany)

Energy-efficient computing, a driving force for future device applications, would strongly benefit from monolithic integration of photonics with Si-CMOS technology. The experimental proof of fundamental direct bandgap, group IV GeSn alloys [1] has constituted an important step towards realisation of the last remaining puzzle piece for electronic-photonic integrated circuits, the efficient group IV laser source. In this contribution, we present electroluminescence studies of reduced-pressure CVD grown, direct-gap GeSn LEDs with Sn contents up to 11 at.%.

Structural and compositional investigations were performed using XRD, as well as SIMS and TEM to confirm high crystalline quality, abrupt interfaces and incorporated strain of the grown structures. Besides homojunction GeSn LEDs, we will also discuss different heterojunction LEDs, such as GeSn/Ge multi quantum wells (MQWs). Those devices consist of seven GeSn wells with a thickness of 21 nm (Ge barrier 14 nm) and 8 at.% Sn concentration, resulting in a residual compressive strain of ~0.71% of the whole structure.

Electrical characterization of the devices revealed distinct forward- and reverse bias regimes enabling both, detection and light-emitting applications.

The emission characteristics of the samples are evaluated from room temperature down to 40 K. At cryogenic temperatures, narrow light emission of the MQW samples at an energy of 0.62 eV (2.1 μm) and a FWHM of only ~30 meV are observed, proving their potential for short-wave IR light emitters.

The findings will be supported by band structure calculations, also providing insight on limitations of the GeSn/Ge MQW approach and benefits from introduction of ternary alloys. [1] S. Wirths & R. Geiger et al., Nature Photon. 9, 88-92 (2015)
compatible material thanks to the recent advances in nanoelectronics based on CNTs. Here, we report on the study of the light emission coupling from CNTs into optical resonators implemented on the silicon-on-insulator (SOI) platform. A theoretical and experimental analysis of the light interaction of CNTs with micro-ring resonators based on slot waveguides and slot photonic crystal heterostructure cavities were carried out.

9752-13, Session 3
Black silicon-based infrared radiation source
Momen Anwar, Si-Ware Systems (Egypt) and Ain-Shams Univ. (Egypt); Yasser M. Sabry, Ain-Shams Univ. (Egypt) and Si-Ware Systems (Egypt); Philippe Basset, Frédéric Marty, Univ. Paris-EST (France); Tarik Bourouina, Univ. Paris-EST (France) and Si-Ware Systems (France); Diaa A. Khalil, Ain-Shams Univ. (Egypt) and Si-Ware Systems (Egypt)

Micromachined infrared sources are enabling component for interferometric and spectroscopic sensors. Their compact size and low cost transform bulky instruments to the sensor scale, which is needed for a wide range of applications in the conventional and unconventional environments. The silicon micromachined sources should be engineered to have good emissivity across a large wavelength range because the intrinsic emissivity of silicon is low. This optimization was reported in literature by either the deposition of black metal at the surface of an emitter or the use of deep phonic crystal cavities, which complicates the fabrication technology and results in sharp dip lines in the spectral emissivity, respectively. In this work we report a micromachined infrared radiation source based on the black silicon structure for the first time in the literature, up to the authors' knowledge. The structure has needle-shaped surface texture where with stochastic variation of the needle location, diameter and height leading to a wide spectral absorptivity and emissivity. The silicon chip is fabricated using SOI wafer, while the thermal mass is optimized by etching the handle layer silicon underneath the black silicon. The black silicon structure itself is realized by a maskless cryogenic deep reactive ion etching of silicon for improving the absorptivity and, thus, the emissivity of the structure. A resistive heating element is located in the center of the device used to heat the black silicon by applying an electrical voltage. The temperature of the device is characterized versus the applied voltage and the radiated spectrum is captured in the 1300 nm to 2500 nm spectral range; limited by the spectrum analysis instrument. The reported source opens the doors for completely integrated MEMS spectral sensors onchip.

9752-14, Session 3
Ultra-high amplified strains in 200-mm optical germanium-on-insulator (GeOI) substrates: towards CMOS-compatible Ge lasers
Vincent Reboud, Alban Gassenq, Guilherme Osvaldo Dias, CEA-LETI (France); Kevin Guilloy, Jose Maria Escalante Fernandez, Samuel Tardif, Nicolas Pauc, CEA-INAC (France); Jean-Michel Hartmann, Julie Widiez, Emmanuel Gomez, CEA-LETI (France); Edith Bellet-Amalric, Université Grenoble Alpes, CEA INAC (France); Daivid Fowler, Denis Rouchon, Ivan Duchemin, CEA-LETI (France); Yann-Michel Niquet, Francois Rieudour, CEA-INAC (France); Jérôme Faist, ETH Zürich (Switzerland); Richard Geiger, Thomas Zabel, Paul Scherrer Institut (Switzerland); Esteban Marin, Institute for Quantum Electronic, ETH Zurich (Switzerland); Hans C. Sigg, Paul Scherrer Institut (Switzerland); Alexei Chelnokov, CEA-LETI (France); Vincent Calvo, CEA-INAC (France)

One of the main challenges for silicon photonics is to obtain efficient CMOS compatible laser sources for all-photonics platform. The photo generation efficiency in Germanium (Ge) improves dramatically when Ge transforms to a direct bandgap material under very high mechanical stress [1]. Last year, we demonstrated first 200 mm optical GeOI substrates fabricated from epitaxial Ge layers on Si as donors using Smart Cut™ technology [2]. They were composed of a thick germanium layer on 1 µm thick buried oxide (BOX). The strongly improved crystalline quality of the Ge allows to avoid mechanical breaking under strong tensile strains. Here we report our latest results on further strain amplification in GeOI membranes. By amplifying the residual tensile strain in GeOI substrates with micro-bridges and micro-crosses, we achieved in 350 nm thick Germanium layers uni-axial strain up to 4.8% and bi-axial tensile strain up to 1.9 %, respectively. The 1.9% record strain is considered in literature to be above the threshold from which Ge starts to present direct band gap. Optical properties is compared with predictions from tight binding modeling and we show first DBR based laser cavities fabricated on the suspended micro-bridges. The electrical injection into such systems will be discussed.

Our results open the way of new devices based on strained germanium and mid-infrared lasers fully compatible with CMOS technology.

Photonics meets a modern transistor: building high-performance electronic-photonic systems with integrated silicon-photonics (Invited Paper)

Vladimir M. Stojanovic, Univ. of California, Berkeley (United States)

Today's chips suffer from a large mismatch between internal computational capability and inability of the input/output interface links to deliver the required data from the outside environment, both in terms of energy-cost and bandwidth-density. Silicon-photonic technology is well positioned to overcome these two fundamental difficulties of electrical links, but proper integration strategies need to be applied to preserve its advantages.

In this talk we'll present the latest results on the integration of silicon-photonic interconnects in both the 45nm SOI logic process [1-3] (the process in which many advanced processors like Power 7, Cell, and Espresso are built) and a bulk CMOS memory periphery process [4-5]. We also illustrate some critical aspects of this technology that need to be addressed from integration, circuits and systems side. These results present a culmination of a 10-year multi-university program between Massachusetts Institute of Technology, University of California, Berkeley and University of Colorado, Boulder, aiming to integrate photonics monolithically into processes with advanced transistors.

Moreover, just like integrating the inductor into CMOS chips at the end of 1990s revolutionized the radio design and enabled mobile revolution, the integration of silicon-photonic active and passive devices with modern CMOS transistors is greatly positioned to revolutionize a number of systems beyond computers and data-centers - sensor platforms (ultrasound, bio-screening), imaging (portable LIDAR systems), as well as the wireless communications infrastructure with photonic-assisted phase-arrays, low-phase noise signal sources and large bandwidth, high-resolution ADCs, to name a few.

Simplified architecture for photonic analog-to-digital conversion, utilizing an array of optical modulators

Hayk Gevorgyan, Anatoly M. Khilo, Masdar Institute of Science & Technology (United Arab Emirates)

In this work, a novel optically sampled and electronically quantized analog-to-digital converter (ADC) system is introduced. High sampling rate and relaxed analog bandwidth requirements for photodetectors and electronic quantizers are attained by using multi-channel architecture. In contrast to previously studied multi-channel photonic ADCs, the proposed ADC uses a dedicated electro-optic modulator for each of the channels, each modulating an optical pulse train delayed by proper amount with differential delay lines. The idea of using multiple modulators greatly simplifies the architecture, potentially leading to significant improvement in performance in comparison to previous photonic ADCs. Specifically, because the individual channels are processed independently, wavelength demultiplexers are not required, which leads to significantly simplified wavelength alignment and virtually eliminated channel crosstalk. Moreover, more complete utilization of the laser spectrum leads to significant improvement of the energy efficiency. Due to importance of having a compact, on-chip photonic ADC, implementation of the proposed ADC in silicon platform is analyzed. It is shown that the proposed ADC is fully compatible with silicon photonics technology. The individual modulators can be implemented as Si microring resonator modulators, which are significantly more compact and efficient than a Mach-Zehnder modulator required in previous photonic ADCs. The impact of microring modulator parameters and modulator nonlinearity on ADC performance are analyzed.

CMOS-compatible transmitters and short-reach data link power efficiency (Invited Paper)

Douglas M. Gill, Chi Xiong, Jonathan E. Proesel, Jessie C. Rosenberg, Jason S. Orcutt, Marwan H. Khater, John J. Ellis-Monaghan, Andreas D. Stricker, Edward Kiewra, Yves C. Martin, Wilfried Haensch, William M. J. Green, IBM Thomas J. Watson Research Ctr. (United States)

This talk will discuss CMOS compatible transmitters and the impact they have on short reach transmission link power efficiency. CMOS-compatible traveling-wave Mach-Zehnder modulators (MZMs) have an optimal design point, which is dictated by the MZM phase shifter efficiency-loss figure of merit (FOM) and the attainable peak-to-peak MZM drive voltage. If operational bandwidth concerns are neglected, the optimum link efficiency performance of the transmitter (TX) can be expressed by a simple analytic expression we define as a relative transmitter penalty (RTP), which is calculated from the phase shifter efficiency-loss FOM and attainable TX Vpp drive voltage. The RTP succinctly conveys TX impact on link budget by quantifying the combined penalty from MZM optical loss and limited TX extinction ratio. I will highlight the interplay between RTP and source laser wall-plug efficiency toward overall link power efficiency, in order to convey trade-offs between various technology solutions and link efficiency. Differences between the expected power efficiency of CMOS drive circuits for lumped element versus travel wave modulator designs will be touched upon, as well as trade-offs between expected ring modulator drive efficiency and power consumption for stabilizing modulator performance against temperature fluctuations.

Silicon large-scale optical switches using MZIs and dual-ring assisted MZIs (Invited Paper)

Linjie Zhou, Shanghai Jiao Tong Univ. (China)

Optical signal switching and routing are essential functions for optical telecommunications and interconnects. The conventional optical-electronic-optical (OEO) conversion schemes can on long satisfy the requirements for compact size, high speed, and low power consumption in next generation telecomm and datacom networks. The realization of optical switching in the optical domain can greatly reduce the system volume, complexity, and power consumption. We present our recent progress on silicon optical switches using a Mach-Zhender interferometer (MZI) or a dual-ring assisted MZI (DR-MZI) as the basic switching element. The 474 and 16716 optical switch fabrics are constructed based on a Benes network architecture, which requires the least number of switching elements for non-blocking switching. The 16716 MZI switch chip occupies an area of 775.6 mm². The measured on-chip insertion loss is <5 dB and the crosstalk is <-20 dB. Although the MZI switch is broadband (10’s nm), the switching power consumption is relatively high (~20 mW). To reduce the switching power, the MZI switch is revised to incorporate a microring resonator in each arm to utilize the resonance slow light effect. The 16716 DR-MZI switch chip has an on-chip insertion loss of ~5 dB. The minimum EO switching power is only 1.4 mW. The switch optical bandwidth is ~35 GHz and the worst crosstalk is ~18 dB.

New approaches for energy saving in silicon photonics (Invited Paper)

Zhiping Zhou, Qingzhong Deng, Tiantian Li, Xinhai Li, Peking Univ. (China)
Low energy operation is a must for using silicon photonic system to replace the conventional electrical interconnection systems. Three energy-saving approaches in silicon photonics are highlighted in this paper: low driving voltage for Mach-Zehnder modulator (MZM), negative chirp compensation for MZM-based long-haul transmission, and athermal filter for wavelength division multiplexing (WDM). These methods serve to reduce energy consumption of modulation and WDM, and are thus valuable to the development of future communication systems.

9752-21, Session 5

Nucleic acids optical biosensors based on SiPM technology

Maria Francesca Santangelo, Consiglio Nazionale delle Ricerche (Italy) and Univ. degli Studi di Palermo (Italy); Emanuele Luigi Sciuto, Univ. degli Studi di Catania (Italy); Alessandro C. Busacca, Univ. degli Studi di Palermo (Italy); Salvatore Petralia, Maria Elobia Castagna, Sabrina Conoci, STMicroelectronics (Italy); Sebania Libertino, Consiglio Nazionale delle Ricerche (Italy)

Among the different fields of biosensor applications, the biomedical sector attracts special attention due to the countless needs to monitor disease-related parameters and to monitor parameters associated with the maintenance of health. Optical transduction is the most used detection mechanism to quantify small amounts of DNA target through hybridization reactions or amplified by Polymerase Chain Reaction (PCR). In this work, we used a Si-based detector, having low noise and high sensitivity. It is a Silicon Photomultiplier (SiPM), a device formed by the series between Single Photon Avalanche Diode (SPAD) operating in Geiger mode and quenching resistor, in parallel connections. A SiPM formed by 25 pixels, each one optically and electrically isolated from the others thanks to the presence of trenches, was electro-optically characterized and used to measure the fluorescence emitted by CYS and FAM solutions. The device dimensions ensure the best signal-to-noise ratio. To test the SiPM experimental detection limit we measured the fluorescence emitted by 12µL of solutions of CYS and FAM at concentrations ranging from 100 fm to 100 nM. The fluorescence current measured increases proportionally to the concentration of the fluorophore in the sample for CYS the signal is linear in the range 100fm-100nM, over six order of magnitudes, while for FAM it is linear in the range 500fm-25nM. These results underline the SiPM extreme sensitivity, its ability to detect even very weak fluorescence signals, and opens new possibilities to all those applications in which to operate with very small amounts of analyte is a requirement.

9752-22, Session 5

Monolithically-integrated Young interferometers for label-free and multiplexed detection of biomolecules

E. Savra, Antonia Malainou, Alexandros Salapatas, National Ctr. for Scientific Research Demokritos (Greece); Athanasios Botias, ThetaMetrisis S.A. (Greece); Panagiota Petrou, National Ctr. for Scientific Research Demokritos (Greece); Ioannis Raptis, ThetaMetrisis S.A. (Greece); Eleni Makarona, Sotirios E. Kakabakos, Konstantinos Misiakos, National Ctr. for Scientific Research Demokritos (Greece)

Young interferometers are amongst the most sensitive transducers for label-free monitoring of bioassays. However, the inability to monolithically integrate on the same chip light sources along with the interferometric sensing elements has so far hindered their wider application. Very recently, interferometric silicon chips with monolithically-integrated light-emitting devices have been presented. The LEDs, coupled to co-integrated monomodal waveguides shaped as Young interferometers through mainstream silicon technology, are silicon avalanche diodes emitting white light when biased beyond their breakdown voltage. The cleaved edges of the sensing and the reference arms emit against an imaging screen that captures in one dimension the interferometric fringes. As opposed to the standard purely monochromatic Young interferometer, the light sources are broadband. A band-pass interference filter allows a 25 nm band (825-850 nm) to pass through and create the well known sinusoidal signal on a CCD array. Though counter-intuitive, the use of relatively broad band light in Young interferometry is possible due to the fact that the various photons arrive at the edges of the sensing and reference arms with the same phase shift. Thanks to appropriate photonic engineering, chips with arrays of ten transducers have been employed for the label-free determination of pesticides in drinking water samples following a competitive immunoassay based on transducer bio-functionalization with pesticide-protein conjugates. Currently, detection limits in the nM range have been achieved for several analytes. The sensor is further evaluated for multi-analyte detection through the bio-functionalization of individual transducers on the same chips with different biomolecules.

9752-23, Session 5

Synchrotron-based Laue micro-diffraction and Raman spectroscopy investigation of highly-strained GeOI micro-bridges for photonics applications

Alban Gassenq, Samuel Tardif, Ivan Duchemin, Kevin Guillou, CEA-LETI (France); Guilherme Osvaldo Dias, Denis Rouchon, Jean-Michel Hartmann, Julie Widiez, CEA-LETI (France); Jose Maria Escalante Fernandez, CEA-LETI (France); Dauid Fowler, CEA-LETI (France); Yann-Michel Niquet, CEA-INA (France); Jerôme Faist, ETH Zürich (Switzerland); Richard Geiger, Thomas Zabel, Hans C. Sigg, Paul Scherrer Institut (Switzerland); Nicolas Pauc, Francois Rieutord, Alexei Chelnokov, CEA-INA (France); Vincent Reboud, CEA-LETI (France); Vincent Calvo, CEA-INA (France)

Introducing a large tensile strain of several percents in a Ge layer is considered promising in order to improve its optical properties and possibly turn germanium into an efficient light emitter which is CMOS compatible. Theoretical strain values required to have a direct bandgap are rather high: between 4 and 5% for uniaxial stress and 2% for biaxial stress. Several approaches are currently explored in order to reach such strain levels [1,2,3]. Conveniently, the obtained strains are measured using Raman spectroscopy, with coefficients linearly linking the wavenumber shift to strain, being dependent on the nature of the strain and its orientation. However, Raman conversion rules were empirically defined for low strain values (for example <1% for uniaxial [4] and <2.6% for biaxial loading [5]). Since very large strains can be now induced in Ge micro-bridges [1,6], Raman coefficients need to be revisited. In this work, Laue micro-diffraction experiments were performed at the ESRF synchrotron in the beamline BM32 on strained Ge membranes fabricated in high crystalline quality 200 mm Germanium-On-Insulator (GeOI) wafers. We established new conversion rules up to 4.8% strain, allowing a re-evaluation of previous literature papers. Furthermore, the high potential of Laue diffraction methods for direct strain characterization in Ge devices for photonics and microelectronics applications.

9752-24, Session 6

High-speed resonant detection via defect states in silicon disk resonators (Invited Paper)
Andrew P. Knights, Jason J Ackert, McMaster Univ. (Canada)

The paper will explain in detail how deep-level mediated detection in silicon waveguides can provide excellent performance at 2000nm and beyond; a wavelength region where Ge is insensitive. We suggest that in the foreseeable future these types of detectors will provide the only viable solution in receiver circuits in the mid-IR regime.

9752-25, Session 6

Dispersion engineering of silicon-on-sapphire (SoS) waveguides for mid-infrared applications
Raghi S. El Shamy, Hany Mossad, Mohamed A. Swillam, The American Univ. in Cairo (Egypt)

In this work we present novel and detailed dispersion analysis of (SOS) strip waveguide in the mid-IR region. The effect of the various design parameters on each mode has been illustrated and carefully studied. The analysis has been extended to cover fundamental and higher order TE and TM modes over the entire range of operation of this waveguides. The finite element method (FEM) and finite difference method have been both utilized to double verify the analysis.

This dispersion analysis has been also utilized to propose novel functional devices in the MIR such as mode converter, switches, modulators and TE/TM-pass and TM-pass polarizer design based on the birefringence between the TE and TM mode.

9752-26, Session 6

Keeping 2D materials visible even buried in SOI wafers
Ergun Simsek, Bablu Mukherjee, The George Washington Univ. (United States)

Five years ago, experiments (Blake et al., Appl. Phys. Lett. 91, 063124, 2007) had proven that the theoretically calculated oxide thickness values (~95 nm and ~285 nm) are the most suitable for graphene’s visual detection. Since then these numbers have become the industry standards for graphene research. Similar studies conducted for monolayers of transition metal dichalcogenides (TMDs) have shown that these thickness values are also good for TMDs’ visibility.

On the other hand, monolayer TMDs are highly vulnerable and their optoelectronic properties might be damaged easily with environmental factors such as dirt, heat, humidity and gaseous environment containing O2-, ion and H2O molecules etc. One possible solution is covering them with a thin oxide or nitride layer. However, such additional layer might decrease their visibility dramatically.

In this work, we numerically calculate the visibility of graphene and four commonly used TMDs (namely MoS2, MoSe2, WS2, WSe2) placed between two oxide layers. We find that the capping layer should not be thicker than 60 nm. Furthermore we derive analytical equations where the thickness of the capping layer can be calculated as a function of underlying oxide layer thickness (or vice versa) for the highest possible visibility under white, green, and red light. The current industry standards (~95 nm and ~285 nm for the underlying oxide thickness) might be still used for red light illumination, but thinner oxides should be used for white and green light illumination. The details of our findings and their experimental validation will be discussed at the conference.

9752-27, Session 6

Mid-infrared silicon-on-sapphire waveguide-coupled photonic crystal microcavities
Yi Zou, The Univ. of Texas at Austin (United States); Swapnajit Chakravarty, Omega Optics, Inc. (United States); Ray T. Chen, The Univ. of Texas at Austin (United States)

Photonic crystals (PCs) have generated significant interest in the scientific community due to their ability to guide and trap light in length scales of the wavelength of light. Recently, integrated mid-infrared photonics has gained considerable attention due to the immense potential for new applications in optical interconnects and sensing. The silicon on sapphire (SoS) material platform is ideal for mid-IR integrated photonics. Sapphire has a transparent window up to 5.5 μm. Additionally, sapphire cladding provides a high refractive index contrast with the core silicon. PC structures of any given dimension can be fabricated in SoS without the possibility of bending and buckling in free-standing silicon membranes from SOI. In this paper, we experimentally demonstrate a PC microcavity side coupled to a W1.05 PC waveguide fabricated in silicon-on-sapphire working in mid-IR regime at 3.43 μm. Using a fixed wavelength laser source, propagation characteristics of PC waveguides without microcavity are characterized as a function of lattice constant to determine the light line position, stop gap and guided mode transmission behavior. The L21 PC microcavity is chosen with resonance normalized frequency below the sapphire light line. The resonance of the L21 PC microcavity is coupled to the W1.05 PCW in the guided mode transmission region and measured by thermal tuning of the cavity resonance across the fixed source wavelength. Resonance quality factor ~3500 is measured from the temperature dependency curve.

9752-28, Session 6

Nanoscale confinement of silicon slot waveguides in the MIR
Rania Gamal, Yehia Ismaiel, Mohamed A. Swillam, The American Univ. in Cairo (Egypt)

A novel analysis for a doped silicon slot waveguide is proposed. This analysis illustrate the different working region of this waveguide configuration in the NIR and MIR. The effect of the doping on achieving high field confinement in the MIR is also studied. These waveguides support a plasmonic-like mode with nanoscale confinement in the MIR. It also demonstrates a negative group velocity range of operation that can be suitable for slow light applications. The plasmonic range and negative dispersion range is well studied and can be easily tuned. These different operating ranges can be easily optical or electrical controlled for dynamic applications. The potential for biological and environmental sensing for the aforementioned structures is investigated as well.

9752-29, Session 7

Subwavelength grating waveguide-integrated athermal Mach-Zehnder interferometer with enhanced fabrication error tolerance and wide stable spectral range
Peng Xing, Jaime Viegas, Masdar Institute of Science & Technology (United Arab Emirates)
The thermal sensitivity of the photonic devices has been a major concern in integrated circuits which consist both of photonic and electronic components. Passive athermal design highly reduces the temperature sensitivity of the photonic devices within a large temperature range and wide spectral band covering the C+L bands used in the fiber communication. Current passive athermal designs reported in the literature have a strong dependency on fabrication variability, in particular to variations of waveguide linewidth. We propose an athermal Mach-Zehnder interferometer (MZI) which has a subwavelength grating waveguide implemented in one of the arms to increase its fabrication error tolerance. The design is demonstrated with a CMOS compatible fabrication run on a silicon on insulator wafer, with minimum feature size of 100 nm. In this work we will discuss the design principles of the subwavelength grating, loss mechanism, fabrication procedure and experimental results obtained. The fabricated devices have a temperature sensitivity of less than 10 ppm/K over a spectral range from 1.5µm to 1.64µm. Also, the fabricated devices have a stable performance within the aforementioned specifications even with fabrication linewidth variations from -20 nm to 40 nm.

9752-30, Session 7

Design and characterization of low-loss 2D grating couplers for silicon photonics integrated circuits

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We present the characterization of Silicon-on-insulator (SOI) photonic-crystal based 2D grating-couplers (2D-GC) fabricated by CEA-Leti in the frame of the FP7 Fabulous project, which is dedicated to the realization of devices and systems for low-cost and high-performance passive-optical-networks. The analyzed samples included different test structures, including 2D-GC connected to another 2D-GC by different waveguides in a Mach-Zehnder like configuration, and 2D-GC connected to two separate 2D-GCs, so as to allow a complete assessment of different parameters. Measurements were carried out using a tunable laser source operating in the extended telecom bandwidth and a polarization controlling system at the input of device-under-test. The measured data yielded an overall fiber-to-fiber loss of 7.5 dB for the structure composed by an input 2D-GC connected to two identical 2D-GCs at the output (one for each polarization). This value was obtained at the peak wavelength of the grating and the 3-dB bandwidth of the 2D-GC was assessed to be 43nm. Assuming that the waveguide losses are negligible, so as to make a worst-case analysis, the coupling efficiency of the single 2D-GC results to be equal to -3.75 dB, constituting, to the best of our knowledge, the lowest value ever reported for a fully CMOS compatible 2D-GC. For the same device the minimum polarization-extension ratio, measured on the whole device bandwidth, was found to be 25.4 dB. It is worth noting that both the obtained values are in good agreement with those expected by the numerical simulations performed using full 3D analysis by Lumerical FDTD-solutions.

9752-31, Session 7

CMOS-compatible spot-size converter for optical fiber to sub-um silicon waveguide coupling with low-loss low-wavelength dependence and high tolerance to misalignment

Marie-Josee Picard, Christine Latrasse, Carl Larouche, TeraXion Inc. (Canada); Yves Painchaud, TeraXion Inc. (Canada); Michel Poulin, Francois Pelletier, Martin Guy, TeraXion Inc. (Canada)

One of the biggest challenges of silicon photonics is the efficient coupling of light between the sub-micron SiP waveguides and a standard optical fiber (SMF-28). We recently proposed a novel approach based on a spot-size converter (SSC) that fulfills this need. The SSC integrates a tapered silicon waveguide and a superimposed structure made of a plurality of rods of high index material, disposed in an array-like configuration and embedded in a cladding of lower index material. The superimposed structure is designed to provide an efficient adiabatic transfer, through evanescent coupling, to a 220 nm thick Si waveguide tapered down to narrow tip on one side, and a large mode overlap to the optical fiber on the other side. An initial demonstration was made using a SSC fabricated with some post-processing steps and an optical fiber having a mode-field diameter of 6.6 µm. Extremely small coupling loss of 0.5 dB for TE-polarized light at 1550 nm with minimum wavelength dependence was obtained. In this paper, new results will be presented for CMOS-compatible SSCs designed for operation at 1310 and 1550 nm for both TE and TE/TM polarizations, and for coupling to a SMF-28 fiber.

9752-33, Session 7

A low-cost technique for adding microlasers to a silicon photonic platform

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In this paper we report the physical micromanipulation of standard InP telecommunications laser die in a liquid medium by means of optoelectronic tweezers. Optoelectronic tweezers is a technique based on light-induced dielectrophoresis (the movement of polarisable particles due to electrical gradients). It allows the patterning of electric fields near a photoconductive surface through the projection of light patterns onto the device. The light patterns can then be used to dynamically create dielectrophoretic traps to manipulate objects at the micrometer scale. Optoelectronic tweezers have been shown to use much less power than optical tweezers, they do not require a coherent light source to function and the creation of multiple traps is straightforward. These properties make the technique a very good candidate for massively parallel micromanipulation of optoelectronic components for assembly on a photonic platform.

Using Stokes’ Law, we estimate dielectrophoretic forces on the laser die in the order of nN, corresponding to measured velocities in excess of 1 mm s^-1 for these devices 250 µm in size. The use of Stokes’ Law is justified by a Reynolds number in the order of 0.1. Those velocities guarantee that, with a standard package size of 1 cm2, the devices can be positioned within seconds. We measure a positional accuracy better than 2 µm and 2 degrees for translation and orientation of the microlasers, respectively.
9752-36, Session 7

Ultrafast all-optical arithmetic logic based on hydrogenated amorphous silicon microring resonators

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Research in nonlinear silicon photonics can add great benefit to computational integrated circuits, where the potential of processing optical signals at several hundreds of Gbit/s goes beyond that of the current and future limitations of fully electronic integrated circuits—while still taking advantage of the cost savings and CMOS compatibility of silicon. In this work, we demonstrate the theoretical working principle of a silicon-based all-optical half adder using AND-XOR Boolean logic, and a 2-bit full adder alternative demonstrating the application of this technique to higher-level mathematics. The nonlinear Kerr effect is used to (red)shift the transmission spectrum of an add-drop microring resonator to effectively switch the propagation of the inputted light between its two output ports. The Kerr effect is chosen as the most promising nonlinear effect for ultrafast all-optical switching, as the refractive index (resonant wavelength) of the applied material (microring resonator) is instantaneously increased with increases to light intensity. Hydrogenated amorphous silicon (a-Si:H) is used, rather than crystalline silicon (c-Si), due to its higher nonlinear Kerr coefficient and lower two-photon absorption—an effect that increases loss and imposes a slow and opposite shift in refractive index. The proposed technique uses identical inputs that function as both the switching mechanism(s) and the propagating data to allow for cascading stages of logic. The technique also allows for low-complexity designs that occupy a low spatial footprint, as the half adder and 2-bit adder use only one and three microring resonators, respectively.

9752-34, Session 8

Diamond quantum nanophotonics (Invited Paper)

Marko Loncar, Harvard School of Engineering and Applied Sciences (United States)

No Abstract Available

9752-35, Session 8

Flat-top MZI filters: a novel robust design based on MMI splitters

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Multimode Interferometers (MMIs) are an attractive alternative to directional couplers, ensuring more relaxed tolerances to fabrication errors and broader operation bandwidth. The drawback is that only a limited discrete set of splitting ratios is achievable with MMIs of constant cross section. This issue clearly limits their use in flat-top interferometric filters, which design requires, in general, free choice of the splitting ratios. Here we show for the first time that it is possible to design 4-stage flat-top interferometers using only standard MMIs with 50:50 and 85:15 splitting ratios. The design approach is based on the representation of the system on the Bloch sphere. Flat-top interferers with different free spectral ranges have been designed and fabricated on the silicon photonics platform of VTT, based on 3 µm thick rib and strip waveguides. Two different layouts have been explored: one where all components are collinear and a more compact one which elements have been folded in a spiral shape. All interferers have been designed for TE polarization, and they work in a wavelength range comparable with the 100 nm bandwidth of the MMI splitters. Even though fabrication imperfections and non-ideal behaviour of both waveguide bends and MMIs led to reduced extinction compared to simulations, most devices show in-band extinction exceeding 15 dB. The in-band losses of the most central channels did not exceed 1.5 dB compared to the reference straight waveguide. The designed interferers can be employed in cascaded configurations to achieve broadband and fabrication tolerant flat-top wavelength (de)multiplexer.

9752-32, Session 8

Ultra-low-power silicon photonics wavelength converter for phase-encoded telecommunication signals

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The development of compact, low power, silicon photonics CMOS compatible components for all-optical signal processing represents a key step towards the development of a fully functional platform for the next generation all optical communication networks. Wavelength conversion functionality at key nodes would be highly desirable to achieve transparent interoperability and wavelength routing allowing efficient management of network resources operated with high speed, phase encoded signals. All optical wavelength conversion functionality already has been demonstrated in Si-based devices, mainly utilizing the strong Kerr effect that Silicon exhibits at Telecom wavelengths. Unfortunately Two Photon Absorption (TPA) and Free Carrier (FC) effects strongly limits their performance, even at moderate power level, making them not suitable for low power, efficient on chip wavelength conversion purposes. Amorphous silicon has recently emerged as viable alternative to crystalline silicon, showing both an enhanced Kerr and reduced TPA coefficients, at Telecom wavelength, with respect to the c- silicon counterpart. Here we propose an ultra low power, passive, CMOS compatible, 1-mm long amorphous silicon waveguide based wavelength converter operated at a maximum pump power level of only 70 mW. We demonstrate TPA-free successful Four Wave Mixing (FWM)-based wavelength conversion of Binary Phase Shift Keyed (BPSK) and Quadrature Phase Shift Keyed (QPSK) signals at 20 Gbit/s bitrate with <1 dB power penalty at BER = 10^-5. Moreover, by considering the measured nonlinear parameter of our waveguides, we estimated that the 0-dB FWM efficiency level could be obtained by using a L_eff=10-mm waveguide (pump power of 120 mW) which is still well below the TPA threshold.

9752-37, Session 8

Ultra-low-loss fully-etched grating couplers for perfectly-vertical grating compatible with DUV lithography tools

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Hybrid integration of VCSELs onto silicon-on-insulator (SOI) substrates has emerged as an attractive approach for cost-effective and energy-efficient directly modulated laser sources for silicon-based PICs by leveraging flip-chip (FC) bonding techniques and silicon grating couplers (GCs). In this context, silicon GCs, should comply with the process requirements imposed by the complimentary-metal-oxide-semiconductor manufacturing tools addressing in parallel the challenges originating from the perfectly vertical incidence. Firstly, fully etched GCs compatible with deep-ultraviolet
lithography tools offering high coupling efficiencies are imperatively needed to maintain realistic fabrication cost. Secondly, GC’s tolerance to VCSEL bonding misalignment errors up to ± 2 microns is a prerequisite for practical deployment. Finally, a major challenge originating from the perfectly vertical coupling scheme is the minimization of the direct back-reflection to the VCSEL’s outgoing facet which may destabilize its operation. Motivated from the above challenges, we used numerical simulation tools to design an ultra-low loss, bidirectional VCSEL-to-SOI optical coupling scheme for either TE or TM polarization, based on low-cost fully etched GCs with a Si-layer of 340 nm without employing bottom reflectors or optimizing the buried-oxide layer. Comprehensive 2D Finite-Difference-Time-Domain simulations have been performed considering the back-end-of-line stack associated with the 3D integration technology exploiting all the inter-metal-dielectric (IMD) layers. Simulation results predicted for the first time in fully etched structures a coupling efficiency of as low as -1.3 dB at 1540 nm and -1.6 dB at 1560 nm with a minimum direct back-reflection of -15.3 dB and -11.7 dB for TE and TM polarization, respectively.

9752-38, Session 9

Subwavelength suspended structures in silicon (Invited Paper)

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Nowadays, silicon-on-insulator is a leading technological platform in the near-infrared telecommunication wavelengths range (NIR: around 1.55µm). Unfortunately, the use of this platform in the mid-infrared band (MIR: 2µm to 25µm) is not straightforward, since the bottom silicon dioxide layer introduces significant losses for wavelengths beyond 4µm. At wavelengths up to 4µm propagation losses can be partially reduced using a thicker silicon guiding layer than in near-infrared. However, in order to exploit the full transparency window of silicon, the silicon dioxide around the guiding zones should be removed, leaving a suspended silicon waveguide in which the lossy SiO2 substrate is replaced by air. The first implementation of a suspended structure in the MIR was based on rib waveguides with fully etched holes which allow for the HF removal of the SiO2. This approach requires two etch steps, one for the rib waveguide and the other for the holes in the Si slab. We have recently proposed a new suspended waveguide that only requires one etch step, making use of a subwavelength grating (SWG) periodic arrangement of fully etched holes, placed at both sides of the waveguide core. The SWG works as a lateral cladding with a low equivalent refractive index that mechanically supports the waveguide core and allows for SiO2 removal. Experimental results confirm the feasibility of this technique, with propagation losses of 1.2dB/cm at a wavelength of 3.8µm. In this work we will review recent advances in the design and fabrication of SWG suspended waveguides and devices operating in the MIR.

9752-40, Session 9

Microheater-integrated silicon coupled photonic crystal microcavities for low-power thermo-optic switching over a wide spectrum

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As important building blocks in silicon photonics, integrated thermo-optic (TO) switches with compact size, wide optical bandwidth, low loss, low switching power, and ease of design and fabrication, are highly desired. In this paper, we design, fabricate and characterize a compact and high-performance TO switch based on two coupled LO type photonic-crystal (PC) microcavities integrated with a micro-heater on a SOI substrate. Different separations of PC cavities inserted with nanoholes are investigated by simulations, and an optimized 3.78µm-long coupled PC microcavities are used to provide 6nm-wide resonance dip in the transmission spectrum. Measurement results on the fabricated device verifies this 6nm-wide resonance dip and shows an optical extinction ratio of ~20dB. This relatively wide resonance enables broader operational bandwidth than widely-used ring resonators and have potential for applications in coarse wavelength-division-multiplexing. The microheater is designed aside the PC microcavities, and its heat transfer characteristics is numerically simulated. The resonance shifts of the device under different DC driving power are measured, with a tuning efficiency of 0.63nm/mW demonstrated. The constant switching power for switching over the 6nm-wide operational spectrum is measured to be 18.2mW. On-off switching is performed, and a rise time of 14.8µs and a fall time of 18.5µs are measured. The measured on-chip optical loss is about 1dB. While TO tuning is used here to demonstrate the functional switching on the silicon coupled PC microcavities, higher switching speed could be achieved by free carrier modulation in our future work, enabling more potential applications including high-speed optical interconnects.

9752-41, Session 9

Chiral spiral waveguides based on MMI crossings: theory and experiments

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We introduce a novel type of chiral spiral waveguide where the usual waveguide crossings are replaced by 100:0 Multimode Interferometers (MMIs), i.e. 2x2 splitters that couple all the input light in the cross output port. Despite the topological equivalence with the standard configuration, we show how resorting to long MMIs has non-trivial advantages in terms of footprint and propagation length. An accurate analytic model is also introduced to show the impact of nonidealities on the spiral performances, including propagation loss and cross-talk. We have designed and fabricated three chiral spirals on our platform, based on 3 µm thick silicon strip waveguides with 0.13 dB/cm propagation loss, and 1.58 mm long MMIs. The fabricated spirals have 7, 13 and 49 loops respectively, corresponding to the effective lengths 6.6 cm, 12.5 cm and 47.9 cm. The proposed model is successfully applied to the experimental results, highlighting MMI extinction ratio of about 16.5 dB and MMI loss of about 0.08 dB, that are much worse compared to the simulated 50 dB extinction and 0.01 dB loss. This imposes an upper limit to the number of rounds, because light takes shortcuts through the MMs. Furthermore, the novel chiral spiral waveguides outperform what is achievable in mainstream silicon photonics platforms based on submicron waveguides in terms of length and propagation losses, and they are promising candidates for the realization of integrated gyroscopes. They can be significantly further improved by replacing the MMIs with adiabatic 100:0 splitters, ensuring lower cross-talk and broader bandwidth.
Nonlinear distortions in silicon microring resonator filters and their impact on integrated photonic ADCs
Kenaish Al Qubaisi, Anatoly M. Khilo, Masdar Institute of Science & Technology (United Arab Emirates)

A dynamic model based on temporal coupled-mode theory for modeling integrated optical resonator response in presence of silicon nonlinearities is presented. The vectorial nature of the optical modes of strongly confining silicon waveguides is taken into account by using the previously reported effective areas for two-photon absorption (TPA), as well as effective areas corresponding to free-carrier absorption and free-carrier dispersion effects derived in this work. The model is applied to study dynamics of microring resonator filters excited by short optical pulses. The nonlinearities in resonator response lead to nonlinear distortions in modulated pulse trains, potentially limiting the dynamic range of analog photonic systems such as photonic analog-to-digital converters. Nonlinear distortions introduced by microring resonators are studied as a function input optical pulse train parameters for different values of resonator finesse, pulse train modulation index, average pulse energy, and ratio of the input pulse bandwidth to the filter bandwidth. As expected, high-finesse filters introduce higher nonlinearities because of internal power enhancement. The leading source of nonlinearity for short optical pulses was found to be the quadratic nonlinearity due to TPA. The impact of resonator nonlinearities on the nonlinearity of the whole analog photonic system can be reduced with differential detection, which (under ideal conditions) totally eliminates all even nonlinearities, such as the TPA-induced nonlinearity. The impact of free-carrier dispersion can be reduced by optimizing the filter passband with respect to the bandwidth of the pulses. This work highlights fundamental performance limits of analog photonic systems built using silicon photonics technology.

Novel spot size converter for coupling standard single mode fibers to SOI waveguides
Marco Michele Sisto, Bruno Fissette, Jacques-Edmond E. Paultre, Alex Paquet, Yan Desroches, INO (Canada)

We have designed and numerically simulated a novel spot size converter for coupling standard single mode fibers with 10.47mm mode field diameter to 500nm x 220nm SOI waveguides. Simulations based on the eigenmode expansion method show a coupling loss of 0.4dB at 1550nm for the TE mode at perfect alignment. The alignment tolerance on the plane normal to the fiber axis is evaluated at ±2.2µm for ≤1dB excess loss, which is comparable to the alignment tolerance between two butt-coupled standard single mode fibers.

The converter is based on a cross-like arrangement of SiOxNy waveguides immersed in a 12µm-thick SiO2 cladding region grown on top of the SOI chip. The waveguides are designed to collectively support a single degenerate mode for TE and TM polarizations. This guided mode features a large overlap to the LP01 mode of standard telecom fibres. Along the spot size converter length (450µm), the mode is first gradually confined in a single SiOxNy waveguide by tapering its width. Then, the mode is adiabatically coupled to a SOI waveguide underneath the structure through a SOI inverted taper. The shapes of SiOxNy and SOI tapers are optimized to minimize coupling loss and structure length, and to ensure adiabatic mode evolution along the structure, thus improving the design robustness to fabrication process errors. A tolerance analysis based on standard microfabrication capabilities suggests that coupling loss penalty from fabrication errors can be maintained below 0.3dB. The proposed spot size converter is fully compliant to industry standard microfabrication processes available at INO.

Generation of tunable, high repetition rate frequency combs with equalized spectra using carrier injection based silicon modulators
Nagajaran K.P., Shankar Kumar Selvaraja, V. R. Supradeepa, Indian Institute of Science (India)

High repetition-rate frequency combs with tunable repetition rate and carrier frequency are extensively used in areas like Optical communications, Microwave Photonics and Metrology. A common technique for their generation is strong phase modulation of a CW-laser. This is commonly implemented using Lithium-Niobate based modulators. With phase modulation alone, the combs have poor spectral flatness and significant number of missing lines. To overcome this, a complex cascade of multiple intensity and phase modulators are used. A comb generator on Silicon based on these principles is desirable to enable on-chip integration with other functionalities while reducing power consumption and footprint. In this work, we analyse frequency comb generation in carrier injection based silicon modulators. We observe an interesting effect in these comb generators. Enhanced absorption accompanying carrier injection, an undesirable effect in data modulators, shapes the amplitude here to enable high quality combs from a single modulator. Thus, along with reduced power consumption to generate a specific number of lines, the complexity has also been significantly reduced.

We use a drift-diffusion solver (Silvaco), FDTD solver (Luminous) and Soref-Bennett relations to calculate the variations in refractive indices and absorption of an optimized Silicon P-I-N modulator driven by an unbiased high frequency (10GHz) voltage signal. Our simulations demonstrate that with a device length of 1cm, a driving voltage of 2V and minor shaping with a passive ring-resonator filter, we obtain 37 lines with a flatness better than 5-dB across the band and power consumption an order of magnitude smaller than Lithium-Niobate modulator based generators.

Improving the opto-microwave performance of SiGe/Si phototransistor through edge-illuminated structure
Zerihun G. Tegenge, ESIEE Paris (France); Carlos Viana, Univ. Paris-Est Marne-la-Vallée (France) and ESIEE Paris (France); Jean-Luc Polleux, ESIEE Paris (France) and Univ. Paris-Est (France); Marjorie Grzeskowiak, Elodie Richalot, Univ. Paris-Est (France) and ESIEE Paris (France)

This paper demonstrates the opto-microwave (OM) experimental study of edge and top illuminated SiGe phototransistors (HPT) implemented using the existing industrial SiGe2RF Telefunken GmbH BiCMOS technology. Its technology and structure are described. Two different optical window size HPTs with top illumination (5x5μm2, 10x10μm2) and an edge illuminated HPT having 5μm x5μm size are presented and compared. A two-step post fabrication process was used to create an optical access on the edge for edge illuminated HPT through a simple polishing and dicing techniques. We perform Opto-microwave Scanning Near-field Optical Microscopy (OM- SNOM) analysis on edge and top illuminated HPTs in order to observe the fastest and the highest sensitive region of the HPTs. This analysis also allows understanding the parasitic effect from the substrate. Thus, this paper will draw a conclusion on the design aspect of SiGe/Si HPT. A low frequency OM responsivity of 0.45A/W and cutoff frequency (f-3dB) of 890MHz was measured for edge illuminated HPT. Compared to the top illuminated HPT of the same size, the edge illuminated HPT improves the f-3dB by a factor of more than two and also it improves the low frequency responsivity by a factor of more than four. These results demonstrate that a simple etched HPT is still enough to achieve performance improvements compared to the
top illuminated HPT without requiring a complex coupling structure. Indeed, it also proves the potential of edge coupled SiGe-HPT in the ultra-low-cost silicon based optoelectronics circuits with a new approach on the optical packaging and system integration.

9752-45, Poster Session

Device characterization of the VCSEL-on-silicon as an on chip light source

Myung-Joon Kwack, Ki-Seok Jang, Jiho Joo, Hyundai Park, Jin Hyuk Oh, Jaeygu Park, Sanggi Kim, Gyungock Kim, Electronics and Telecommunications Research Institute (Korea, Republic of)

Advancement of silicon photonics technology can offer a new dimension in data communications with un-precedent bandwidth. Increasing the integration level in the silicon photonics is required to develop compact high-performance chip-level optical interconnects for future systems. Especially, monolithic integration of light source on a silicon wafer is important for future silicon photon integrated circuits, since realizing a compact on-chip light source on a silicon wafer is a serious issue which impedes practical implementation of the silicon photon interconnects. At present, due to the lack of a practical light source based on Group IV elements, flip chip-bonded or packaged lasers based on III-V semiconductor are usually being used as external light sources, to feed silicon modulators on SOI wafers to complete a photonic transmitter, except the reported silicon hybrid lasers monolithic-integrated on SOI wafers. To overcome above problem, we have proposed a compact on-chip light source, the directly monolithic-integrated VCSEL on a bulk silicon wafer (VCSEL-on-Si), based on the transplanted epitaxial film by substrate lift-off process and following device-fabrication on the bulk Si wafer. This can offer practical low-power-consumption light sources integrated on a silicon wafer, which can provide a complete chip-level I/O set when combined with monolithic-integrated vertical-illumination Ge-on-Si photodetectors on the same silicon wafer. In this work, we report the characterization of direct-modulation VCSELS-on-Si for 7-850 nm with CW optical output power > 2 mW and the threshold current < ~3 mA, over 10 Gb/s operations. We also discuss about the thermal characteristics of the VCSELS-on-Si.

9752-46, Poster Session

Resonance-spacing tuning over whole free spectral range in a single microring resonator

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Tuning of resonance spacing is a highly desirable functionality for many applications in optical filtering and microwave photonics. However, the conventional microring resonators such as microring and microdisk usually have resonances separated by a fixed spacing (i.e. the free spectral range). And when tuning the resonance wavelength with refractive-index tuning methods, the resonances are shifted for the same amount, leading to an unchanged resonance spacing. Here, to achieve the tuning of resonance spacing, a single microring resonator structure formed by incorporating a reflectivity-tunable loop mirror is theoretically and experimentally demonstrated on silicon-on-insulator platform. Based on the optical mode-splitting in the resonator, spacing between two adjacent resonances can be tuned from zero to one whole free spectral range (FSR) by controlling the strength of coupling between the two counter-propagating degenerate modes in the microring resonator. To exactly control the coupling strength, a reflectivity-tunable loop mirror is introduced into the microring resonator. This tunable reflective element is obtained by using a Mach-Zehnder interferometer (MZI) as the coupler of the loop mirror and the reflectivity is tuned by changing the differential phase shift between the two MZI arms. In experiment, by integrating metallic microheaters on the MZI arms, the tuning of resonance spacing over the whole FSR (117 nm) is achieved within 9.82 mW heating power dissipation. Compared to the previous report based on coupled microrings, our single ring resonator structure shows a larger tuning range with a lower power dissipation and does not require an additional trimming or tuning for the alignment of resonance frequencies between the microrings.

9752-47, Poster Session

Inverse design of non-periodic components for silicon photonics

Imanol Andonegui, Ibon Alonso, Angel J. Garcia-Adeva, Univ. del País Vasco (Spain)

We report a critical assessment of the utility of non-uniform gratings for enhancing light coupling to photonic integrated circuits (PICs). Grating couplers, performing as a very attractive vertical coupling scheme for the silicon waveguide, have been widely demonstrated. The design procedure for these components is strictly limited to the prediction of the Bragg condition constrained by the selection of the adequate period length for a certain target wavelength. However, the coupling efficiency of grating couplers could be enhanced when more parameters are taken into account, but then the design procedure turns to be much more complex as such structures cannot be designed using current analytic methods, or by tuning a small number of parameters by hand. Noticeably, an Inverse Design (ID) method provides a promising way for doing it. Moreover, this technique opens the way for developing non-uniform gratings, for which no period is considered and each groove becomes an independent diffraction element. These gratings not only match the coupling efficiency of conventional periodic corrugated waveguides but they allow to devise more sophisticated components such as wavelength splitters or polarization splitters, just to cite some.

9752-48, Poster Session

Si photonics expands to mid-wave and long-wave infrared: fundamentals and applications

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Nowadays, Si has been explored as an alternative light emitter. Although several proposals on how to increase internal quantum efficiency in this indirect bandgap material were successful, the luminescence mode is not without pitfalls (low emission power, temperature quenching, need for additional technological steps). Moreover, regardless of the numerous attempts made to obtain efficient above bandgap luminescence from Si and beyond, Si and SiGe materials in Si-based optoelectronic devices, it seems intuitive that emission wavelengths further than 1 mkm are not likely to perform. To bridge the nonradiative channels impact at light power output, we come out with exploring below bandgap thermal emission (TE) instead of conventional below bandgap luminescence. In this case, output photons come as the result of intraband thermal agitation of injected electrons and holes in a bulk material and become the source of broad-band (3-12 mkm) TE before they recombine. This approach provides for application of indirect bandgap semiconductors in photonics and helps to remarkably increase operating temperature. It is a functional principle of several new unconventional photonics devices (like light down converters, IR LEDs, IR dynamic scene simulators, and radiative coolers) operating at T > 300 K. But the most significant factor is that all these advantages are already realized in the host material which has been and will remain the primary platform for microelectronics in the future.
MEMS-based IR-sources

Sebastian J. Weise, Bastian Steinbach, Steffen Biermann, Micro-Hybrid Electronic GmbH (Germany)

Our well-established series JSIR350 achieves best performance characteristics with the combination of an IR chip made in USA and Micro-Hybrid’s unique packaging. The series JSIR350 sources are MEMS based infrared emitters. The MEMS chips used in Micro-Hybrid’s infrared emitters consist of nanoamorphous carbon (NAC). The substrate is made of a Si-chip with a back-etched membrane. The thin film processing is conducted by Magnetron Sputtering. The last layer of the IR-chip is a protective layer which consists of silicon nitride and protects the active element against environmental influences. These IR sources are characterized by a high radiation output caused by membrane temperature up to 850°C. Thus, they are excellent for NDIR gas analysis and are ideally suited for using with Micro-Hybrid’s pyroelectric or thermopile detectors. We developed a process to hermetically seal our IR emitter. The patent pending method HermeSeal can be applied to our MEMS based IR sources. This new technology enables us to seal the housings of infrared radiation sources and detectors with soldered infrared filters or windows and thus cause the parts to be impenetrable to gases. The components do not show any permeation of water vapor or (environmental) gases in contrast to bonded elements. The hermetic cap allows new applications in harsh environments – such as high temperature, high partial gas pressure and high humidity. Applying the newly developed technology allows for long term stable infrared components for gas sensors, gas monitoring and gas analysis as well as flame detection.
GI-core polymer waveguide based on polynorbornene for optical interconnection (Invited Paper)

Katsuma Kitazoe, Ryota Kinoshita, Akihiro Horimoto, SUMITOMO BAKELITE Co., Ltd. (Japan)

To meet the increasing demand for board level high speed data transmission in the area of high performance computing, much attention has been paid to employ high performance polymer optical waveguide. So far, optical interconnects have been considered to have advantages over electronic solutions in various aspects, such as lower power consumption, larger information carrying capacity and immunity to crosstalk. It is one of the advantages that waveguides are possible to be curved and crossed light paths in the same circuit plane. GI-core polymer waveguides are capable of confining the signal light around the core center more tightly, by which the GI-core waveguides exhibit low propagation loss, low crosstalk, and low modal dispersion. Therefore, GI-core reduces the loss in meshed waveguide compared to SI-core meshed waveguides. The material of our GI-core polymer waveguide is Polynorbornene. The varnish for both core and cladding is prepared and coated onto a substrate then the coated layers are exposed to a UV light through a photomask and heated at a certain temperature. After heating, index profile changes and GI Waveguide is formed. This is our original photo-addressing method We confirm that extremely low crossings loss is observed in both 90-degree (0.46 dB/500 crosses) and 45-degree (1.32 dB/500 crosses). Also, we succeed high-speed data transmission. We expect that this ultra low crossing loss GI-core waveguide will be one of the promising components giving a strong impact on high performance computing systems in near future.

High-precision 3D printing: fabrication of micro-optics and integrated optical packages

Ruth Houbertz, Moritz Esslinger, Multiphoton Optics GmbH (Germany); Sönke Steenhusen, Fraunhofer-Institut für Silicatforschung (Germany); Gianni Preve, Consorzio Nazionale Interuniversitario per le Telecomunicazioni (Italy)

Supercomputing is reaching out to ExaFLOP processing efficiencies, creating fundamental challenges for the way that computing systems are designed and built. The governing topic is the reduction of power used for operating the computer system, and eliminating the excess heat generated from the system. Current thinking sees optical interconnects on most interconnect levels to be a feasible solution to many of the challenges, although there are still limitations to the technical solutions, in particular with regard to manufacturability in high volume.

We present new concepts for micro-optical devices that allow for higher integration and degrees of automation by additive manufacturing. Our two-photon-absorption (TPA) machine achieves surfaces of optical quality and enables rapid prototyping and rapid manufacture of micro-optical components such as lenses, waveguides, and integrated optical components. The fabrication process is compatible with ORMOCER® materials of excellent transmission in the data and telecom regime, but not limited to this class of materials. We introduce a new type of grating coupler, which allows to significantly decrease the overall package size in vertical direction by enabling flat mounted glass fibers. Apart from the higher degree of miniaturization, we discuss a concept to relax the fiber positioning tolerances compared to present grating couplers, which often still require passive and active alignment. The focus of our discussion is on production speed, reliability, automation and reduction of total process steps for fabrication of electro-optical boards.

High-bandwidth and low-loss multimode polymer waveguides and waveguide components for high-speed board-level optical interconnects (Invited Paper)

Nikos Bamiedakis, Jian Chen, Richard V. Penty, Ian H. White, Univ. of Cambridge (United Kingdom)

Multimode polymer waveguides are being increasingly considered for use in short-reach board-level optical interconnects as they exhibit favourable optical properties and allow direct integration onto standard PCBs with conventional methods of the electronics industry. Siloxane-based multimode waveguides have been demonstrated with excellent optical transmission performance, while a wide range of passive waveguide components that offer routing flexibility and enable the implementation of complex on-board interconnection architectures has been reported. In recent work, we have demonstrated that these polymer waveguides can exhibit very high bandwidth-length products in excess of 30 GHz·m despite their highly-multimoded nature, while it has been shown that even larger values of > 60 GHz·m can be achieved by adjusting their refractive index profile. Furthermore, the combination of refractive index engineering and launch conditioning schemes can ensure high bandwidth (> 100 GHz·m) and high coupling efficiency (< 1 dB) with standard multimode fibre inputs with relatively large alignment tolerances (~1820 µm). In the work presented here, we investigate the effects of refractive index engineering on the performance of passive waveguide components (crossings, bends) and provide suitable design rules for their on-board use. It is shown that, depending on the interconnection layout and link requirements, appropriate choice of refractive index profile can provide enhanced component performance, ensuring low loss interconnection and adequate link bandwidth. The results highlight the strong potential of this versatile optical technology for the formation of high-performance board-level optical interconnects with high routing flexibility.

Low-Loss Graded Index Multimode Polymer Crossed Waveguides Fabricated Using the Imprint Method

Yutaro Oizumi, Takaaki Ishigure, Keio Univ. (Japan)

In this paper, we fabricate low-loss graded-index (GI) multimode polymer crossed optical waveguides with various crossing angles using a very simple technique, the imprint method. Currently, board-level optical interconnection technologies have been required for enabling exaflops-scale high-performance computers. Hence, optical printed circuit boards (OPCBs) integrating multimode polymer optical waveguides are drawing much attention. In particular, intensive efforts have been made for developing low-loss crossed waveguides for realizing optical shuffling on OPCBs. So, we have demonstrated that GI cores allow to decrease the light leakage at the intersections in crossed waveguides, resulting in lower crossing loss compared to the step-index (SI)-core counterpart. Actually, GI-core perpendicularly crossed polymer waveguides were successfully fabricated using the photo-addressing method or an imprint method: lower crossing loss was experimentally verified over SI-core crossed waveguides. Although the imprint method is a simple fabrication technique, the propagation losses of the fabricated
waveguides have not been low enough because of the surface roughness on the core-cladding boundary. Therefore, in this paper, we improve the surface roughness using the imprint method for reducing the propagation loss of the waveguides and obtain low-loss GI cross-guides: a crossing loss of 0.01 dB/crossing for perpendicularly GI-core waveguides is observed, which is one-order of magnitude lower than the crossing loss (~0.1 dB/crossing) for Si-core. Moreover, for the optical shuffling, we fabricate GI-core waveguides with various crossing angles and confirm that even if the crossing angle is varied, the light leakage at the intersections is much lower in the GI-core than in Si-core.

9753-5, Session 1

Comparison of self-written waveguide techniques and bulk index matching for low-loss polymer waveguide interconnects

Derek Burrell, Christopher T. Middlebrook, Michigan Technological Univ. (United States)

Polymer waveguides (PWGs) are used within photonic interconnects as inexpensive and versatile alternatives to traditional optical fibers. The PWGs are typically aligned to silica fibers for coupling. An epoxide elastomer is then applied and cured at the interface for index matching and rigid attachment. Self-written waveguides (SWWs) are proposed as an alternative to further reduce connection insertion loss (IL) and alleviate marginal misalignment issues. Elastomer material is deposited after the initial alignment, and SWWs are formed by injecting ultraviolet (UV) light into the fiber or waveguide. The coupled UV light cures channels between the two differing structures. A suitable cladding layer can be applied after development. Such factors as longitudinal gap distance, UV cure time, input power level, polymer material selection and choice of solvent affect the resulting SWWs. Experimental data are compared between purely index-matched samples and those with SWWs at the fiber-PWG interface. It is shown that <1 dB IL per connection can be achieved by either method and results indicate potential advantages to self-writing over index matching alone. Successfully fabricated SWWs will enable the fiber and PWG to act as one continuous low-loss rigid interconnect.

9753-6, Session 2

A chip scale optical Tx/Rx based on silicon photonics from views of multi-mode transmission (Invited Paper)

Ichiro Ogura, Photonics Electronics Technology Research Association (Japan)

We describe Si-photonics-based chip-scale optical Tx/Rx technologies for optical interconnection focusing on high density packaging and low cost assembly with multimode optics. A new high density chip-scale packaging concept “optical I/O core” has been proposed which consists of Si-photonics platform, hybrid integrated CMOS driver/receiver IC, and cover glass with electrical/optical I/Os.

The optical I/O core has been demonstrated with form factor of 5 mm x 5 mm that operates up to 28 Gbps/ch with 4 ch transceiver or 12 ch Tx/Rx configurations. The power consumption of hybrid integrated ICs is 5 mW/Gbps.

The use of multimode optics is the key to reduce the assembly costs employing passive alignment techniques. To do this we have developed built-in optical guide named “optical pin” as optical I/Os which consists of UV curable resin fabricated on the silicon-photonics platform using a photolithographic technique. With optical pins and through-glass via in the cover glass, the optical and electrical I/Os are located on the top glass surface of optical I/O core. The optical interface is compliant with encircled-flux for coupling to GI-50 MMF and we demonstrated 25-Gbps/ch error-free operation over 300-m with 1310-nm optimized MMF.

Having common features of electrical and optical I/Os, the optical I/O core can be used as a building block of pluggable transceivers, embedded optics and LSI integrated optical interposers for variety of applications ranging from chip to chip communications to interconnects in datacenters and HPCs.

9753-7, Session 2

Silicon photonics for 100 Gbit/s intra-data center optical interconnects (Invited Paper)

Stefan Meister, Technische Univ. Berlin (Germany) and Sicoya GmbH (Germany); Moritz Grehn, Sicoya GmbH (Germany); Hanjo Rhee, Technische Univ. Berlin (Germany) and Sicoya GmbH (Germany); Marco Vitali, Sicoya GmbH (Germany); Christoph Theiss, Technische Univ. Berlin (Germany) and Sicoya GmbH (Germany); Sebastian Kupijai, Awa Al-Saadi, Danilo Bronzi, Marvin Henniges, David Selicke, Muhammad Atif, Technische Univ. Berlin (Germany); Erik Schwartz, Technische Univ Berlin (Germany); Stefan Lischke, David Stolarek, Andreas Mai, Mehmet Kaynak, Harald H. Richter, Lars Zimmermann, IHP GmbH (Germany); Sven Otte, Sicoya GmbH (Germany)

Future data centers will be dimensioned to handle immense data traffic, mainly driven by 5thGen mobile networks. Optical interconnects for these mega data centers need to satisfy three main technical challenges - energy efficiency, data rate and reach, simultaneously at a fierce cost target of 1$/Gbit/s. Highest integration levels and smallest footprints are the only feasible ways to accomplish this cost requirement. Higher integration not only encompasses the chip itself but also further integration of manufacturing procedures. Consequently, every aspect of a transceiver design must be reconsidered.

The highest impact on the integration level can be expected from the use of a full CMOS backend for complex wiring in combination with monolithic cointegration of electronics and photonics on one single chip. As a result, higher signal integrity and lower parasitics can be achieved which strongly benefits the driver power consumption and receiver sensitivity. Furthermore, the chip size, as well as assembly cost can be greatly reduced. In addition, wafer scale testing and low cost scalable packaging techniques are essential. Cointegration only becomes commercially viable through small footprints of the photonic building-blocks in relation to the electronic blocks. The respective photonic platform needs to provide nano-waveguides with ultra-small cross-sections for small bending radii, enabling the design of small and complex photonic integrated circuits. The chip size is typically dominated by the widely used Mach-Zehnder modulators with footprints in the square millimeter range. However, economic application of cointegration designs relies on the availability of modulators with small footprint and low loss.

9753-8, Session 2

Silicon germanium on graded buffer as a new platform for optical interconnects on silicon

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In the recent years, silicon germanium quantum well devices have been used for the demonstration of high speed, low power consumption and compact optical modulators and photodetectors, for inter- and intra-chip optical communications. The main challenge for their integration with a silicon-based photonic platform relies on the lattice constant difference between silicon and germanium. Recently, it was shown that a Ge-rich SiGe virtual substrate on graded buffer, used to grow high quality Ge/SiGe quantum wells active regions can also be used as a low loss waveguide despite low light confinement. An optical link including an electro-absorption modulator, a photodetector and a passive SiGe waveguide was demonstrated [1]. However in this work, only straight waveguides were used. We will show here that such Ge-rich SiGe waveguide on graded buffer can also be used for any advanced passive structures. By tuning light confinement, sharp bends with radius as low as 12 µm were successfully obtained, while a Mach Zehnder interferometer including Multimode Interference (MMI) beam splitter shows an extinction ratio of more than 10 dB. These results pave the way for the demonstration of wavelength division multiplexing devices and their integration with active devices to go towards SiGe based photonic integrated transceiver on silicon.


9753-9, Session 2

Low latency, area, and energy efficient Hybrid Photonic Plasmonic on-chip Interconnects (HyPPI)

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Moore’s Law for traditional electric integrated circuits is facing more and more challenges in both physics and economic aspects. Among those challenges is the fact that the bandwidth per compute on the chip is dropping while the energy needed for data movement keeps on rising. Here, we benchmark various interconnect technologies including electrical, photonic, and plasmonic options. We contrast them with hybridizations where we consider plasmonics for active manipulation devices, and photonics for passive propagation integrated circuit elements, and further propose another novel hybrid link that utilizes an on chip laser for intrinsic modulation thus bypassing electro-optic modulation. Our analysis proves that such hybridization is able to overcome the shortcomings of both pure photonic and plasmonic links. Further, it shows superiority in a variety of performance parameters such as point-to-point latency, energy efficiency, bandwidth, ability to support wavelength division multiplexing, crosstalk coupling length, and bit flow density which is a new metric that we defined to reveal the trade-off between footprint and performance. Our proposed hybrid links show significantly superior performance.

9753-10, Session 2

An efficient total-internal-reflection optical switch based on reverse breakdown of pn junction and thermo-optic effect in silicon

Jong-hun Kim, Hyo-Hoon Park, KAIST (Korea, Republic of)

The optical path-switching device is considered as a key component for applications to chip-level optical interconnection and WDM communication. We propose a new structure of silicon total-internal-reflection (TIR) optical switch, which is insensitive to wavelength and temperature. The switch device is consist of asymmetrically y-branched multimode waveguides and a reflector which is formed with a pn diode and placed at the branched node. At the rest of the reflector, the incident light is reflected suffering the refractive index difference due to the plasma dispersion effect of the pre-doped carriers. The switching to the transmission state is attained by the thermo-optic effect smearing the index difference under a reverse breakdown of the pn junction. The device was fabricated using a standard CMOS-compatible process. In the switching region, the rib waveguides are formed with a width of 5 µm using a SOI wafer. As the total internal reflector, a pn diode with a simple pn junctions for efficient current injection is formed with an inclined angle corresponding to a half of the branch angle. From this reflector, we confirmed the switching operation with a shallow TIR region of 1-um-width. At 6°-branch-angle, an extinction ratio of 12 dB and an insertion loss of -4.2 dB are achieved with a thermal heating power of 15.1 mW. These performances are the best data for the Si TIR switches in our knowledge.

9753-11, Session 3

Technical and economic challenges and opportunities for optical interconnect technologies (Invited Paper)

Daniel Mahgerefteh, Craig Thompson, Finisar Corp. (United States)

The massive parallelism of data center and supercomputer architectures makes optical interconnects a significant portion of their cost. The technical requirements vastly vary between short reach < 30 m high bandwidth-density board mountable optics to 0-10 km high aggregate rate pluggable transceivers each at rates > 100 Gb/s. However low cost with low targets approaching $1/Gb/s is a common, challenging demand for all applications. Si photonics has attracted much attention recently especially since a number of commercial CMOS foundries including IBM and ST Microelectronics are adding Si photonics into their manufacturing lines. It is presumed that the wafer level processes, test, and packaging developed for CMOS can lead to low cost for optics. Competing technologies in the market are multi-mode VCSEL and InP DMLs. Here we show that the dominant technology has to offer the lowest cost for the single channel transceiver application, which represents 90% of the data center market and which historically dominates sales. We show that Si photonics is currently significantly more expensive than MM VCSEL for single channel, but that it can make a successful entry into the 4 channel SM market with significant growth, capturing 20% of the data center market. We compare speed of operation, transmission reach, power consumption, and cost structure of Si photonics, MM VCSEL and InP DML and limiting factors and prospects for each. In addition we show that MM VCSEL has fundamentally lower power consumption than Si Photonics and is a good candidate for super-computing applications.

9753-12, Session 3

Integrating III-V, Si, and polymer waveguides for optical interconnects: RAPIDO (Invited Paper)

Timo Aalto, Mikko Harjanne, VTT Technical Research Ctr. of Finland Ltd. (Finland); Bert-Jan Offrein, Charles Caër, IBM Research - Zürich (Switzerland); Christian Neumeyer, Vertilas GmbH (Germany); Antonio Malacarne, Consorzio Nazionale Interuniversitario per le Telecomunicazioni (Italy) and Scuola Superiore Sant’Anna (Italy); Mircea Guina, Tampere Univ. of Technology (Finland); Frank Hudson Peters, Tyndall National Institute (Ireland); Petri Melanen, Modulight, Inc. (Finland)

Optical interconnect technologies are being developed using a variety of materials, fabrication methods, integration concepts and signal formats. In
this paper we present a hybrid integration approach that is developed in the EU-funded RAPIDO project to produce an ideal combination of technologies for the next generation of optical interconnects with scalability to Pb/s systems.

As light sources we use long-wavelength (1.3 µm) VCSELs that are directly modulated up to 50 Gb/s, or acting as CW lasers. In the latter case electro-absorption modulators (EAMs) are used to reach up to 80 Gb/s bandwidth. While extending from point-to-point links into optical intra-system networks we use semiconductor optical amplifiers (SOAs) for packet switching, as well as to extend the reach of the optical interconnects to tens of kilometers. Both SOAs and EAMs are based on dilute nitride materials that enable low-cost fabrication on large GaAs wafers and uncooled operation in the challenging environment of supercomputers and data centers.

For wavelength multiplexing and for the integration of passive and active functions we use the combination of silicon photonics and polymer photonics. With micron-scale dimensions in both silicon and polymer waveguides we can reach single-moded, low-loss and polarization independent operation. Low coupling losses between all photonic parts are obtained over an ultra-wide bandwidth using adiabatic spot-size converters and no grating couplers. With the combination of silicon and polymer waveguides we also aim to demonstrate athermal multiplexers and very power-efficient transceivers for optical interconnects. These will also apply advanced modulation formats, such as PAM-4.

9753-13, Session 3
Extended temperature performance of 120 Gb/s midboard optical engine
Josh Cornellius, Samtec Optical Group (United States); Aaron Baumer, SAMTEC USA (United States); Eric Zbinden, David Langsam, Marc Verdiell, William J Kozlofsky, John F Hazell, Samtec Optical Group (United States); Catherine M Eichhorn, Samtec Optical Group (United States) and Samtec (United States); Sharon M Lutz, Thomas J Mitcheltree, US Conec (United States)

Industrial and military requirements for optics dictate the ability to operate reliably over a myriad of extreme environmental conditions such as extended temperature, increased shock and vibration, high particulate environments, etc. While it is paramount that the transceiver be able to maintain performance over these extreme conditions, considerations for the optical interconnects in the signal path are often overlooked. In general, optical performance tends to degrade as the operating temperature drifts from nominal conditions. Likewise, optical connector performance degrades at higher shock and vibration levels. As a result, optical products are generally limited to operating at case temperatures between 0 °C – 70 °C and struggle at high shock and vibration levels. In this paper we demonstrate the performance of the Samtec 12 channel FireFly at 10Gbps, -40 °C and 85 °C case temperature coupled with the expanded beam MXC connector from US Conec. Optical eye diagrams and receiver sensitivity for a link that includes 100m of OM3 fiber, reliability results for transmitters operating at extended temperature, and shock and vibration data are presented.

9753-14, Session 3
A novel method for optical engine testing
Bo Lin, Jeffrey DeMeritt, Randall Harrison, Craig Strause, Nicholas Hein, Corning Incorporated (United States)

Prior to assembling optical cables, it is of critical importance to be sure that optical engines are indeed function well for both low and high speed operations. Low speed operation includes engine handshake set up and “static” functionality tests while high speed operation is for data communication where PRBS, eye and power consumption need to meet performance spec.

An engine test system needs to have the ability to fully communicate with the engine under test (EUT). One can achieve such requirements by putting together discrete components and equipment such as high frequency photo diodes, driving circuits and a general purpose high frequency analyzer. Unfortunately, such a setup is expensive and inconvenient to use.

To overcome these problems, we utilize a working optical cable. Specifically, we cut the cable into two halves. Each half of the cable already has all the required communication elements – the ability to receive and deliver high frequency optical signals. By coupling the high frequency optical signals to and from the half cable to EUT, we can find out if the EUT meets all functionality requirements. Furthermore, the ability for coupling half of an optical cable into an optical engine already exists in the optical cable assembly set up. Dedicated cable test instruments which are much cheaper than general purpose high frequency analyzers are also widely available.

This combined usage of half an optical cable together with existing electronic cable testing equipment greatly simplifies optical engine test. Such a setup has been successfully used at Corning.
9753-15, Session 4

**Multilayer optical interconnects using ultrafast laser direct written 3D waveguides and ion exchange surface waveguides (Invited Paper)**

Kevin Chen, Yawen Huang, Sheng Huang, Rongtao Cao, Univ. of Pittsburgh (United States); Ming-Jun Li, Corning Incorporated (United States)

Glass materials have been considered as excellent substrate materials for electrical and optical packaging at board levels. Comparing with silicon wafer, glass-based packages offer 5 to 10 times cost saving due to material and size scaling. The integration of glass panels with PCB base materials have become feasible recently due to advent of commercial thin glass substrates such as Corning Willow glass.

In this paper, we explore a combined approach to realize multi-layer optical interconnection in thin glass substrates with various thickness from 25-µm to 100-µm. Waveguide fabricated by ion exchange process akin to Corning Gorilla glass fabrication process were used to produce surface waveguide on both sides of glass substrates to interface with optoelectronic components. Using ultrafast laser direct writing scheme, electronic vias, 3D waveguides, and waveguide devices can be fabricated simultaneously through the glass substrates and inside glass substrates to realize optical functions such as optical vias, wavelength filtering, evanesence coupling, and wavelength division multiplexing. This paper discusses a number of fabrication and device issues to show the feasibility of thin glass panels for multi-layer optical interconnect.

9753-16, Session 4

**Planar polymer and glass graded index waveguides for data center applications**

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Embedded optical waveguide technology for printed circuit boards has advanced considerably over the past decade both in terms of materials and achievable waveguide structures. Two distinct classes of planar graded index multimode waveguide have recently emerged based on polymer and glass materials.

We report on the suitability of graded index polymer waveguides, fabricated using the Mosquito method, and graded index glass waveguides, fabricated using ion diffusion on thin glass foils, for deployment within future data centre environments as part of an optically disaggregated architecture.

To this end, we first characterise the wavelength dependent performance of different waveguide types to assess their suitability with respect to two dominant emerging multimode transceiver classes based on directly modulated 850 nm VCSELs and 1310 silicon photonics devices.

Furthermore we connect the different waveguide types into an optically disaggregated data storage system and characterise their performance with respect to different common high speed data protocols used at the intra and inter rack level including 10 Gb Ethernet and Serial Attached SCSI.

9753-17, Session 4

**Electro-optical circuit board with single-mode glass waveguide optical interconnects**

Lars Brusberg, Dominik Pernthaler, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); Daniel Weber, Technische Univ. Berlin (Germany); Bogdan Sirbu, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); Christian Herbst, Technische Univ. Berlin (Germany); Christopher Frey, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); Marco Queisser, Markus Wöhrmann, Dionyssios Manessis, Beatrice Schild, Technische Univ. Berlin (Germany); Hermann Oppermann, Yann Eichhammer, Henning Schröder, Andreas Hakansson, Tolga Tekin, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany)

A glass optical waveguide process has been developed for fabrication of electro-optical circuit boards (EOCB). Very thin glass panels with planar integrated single-mode waveguides can be embedded as a core layer in printed circuit boards for high-speed board-level chip-to-chip and board-to-board optical interconnects over an optical backplane. Such single-mode EOCBs will be needed in upcoming high performance computers and data storage network environments in case single-mode operating silicon photonic ICs generate high-bandwidth signals [1]. The paper will describe the project results of the ongoing PhoxTroT project, in which a development of glass based single-mode on-board and board-to-board interconnection platform is successfully in progress. The optical design comprises a 500 µm thin glass panel (Schott D263Teco) with purely optical layers for single-mode glass waveguides. The board size is accommodated to the mask size limitations of the fabrication (200 mm wafer level process, being later transferred also to larger panel size). Our concept consists of directly assembling of silicon photonic ICs above cut-out areas in glass-based waveguide panels. A coupling element will be assembled on bottom side of the glass-based waveguide panel for 3D coupling between board-level glass waveguides and chip-level silicon waveguides. The laminate has a defined window for direct glass access for assembling of the photonic integrated circuit chip and optical coupling element. The paper describes the design, fabrication and characterization of glass-based electro-optical circuit board with format of 228 x 305 mm².

References


9753-18, Session 4

**Assembly and performance of silicone polymer waveguides (Invited Paper)**

Brandon W. Swatowski, Dow Corning Corp. (United States); Calob K. Lostutter, Molex, Incorporated (United States); W. K. Weidner, Dow Corning Corp. (United States); Malcolm H. Hodge, Molex, Incorporated (United States); Thomas R. Marrapode, Molex Fiber Optics (United States)

We report on the functionality and key performance properties of 50µmx50µm flexible graded index silicone polymer waveguides. The materials show low optical propagation losses of < 0.04 dB/cm @ 850 nm over 1 m lengths as well as stability to 2000 hours 85°C/85% relative humidity and 5 cycles of 260 °C solder wave reflow testing. Methods to fabricate large area (12”x18”) panels are demonstrated that are appropriate for scaled manufacturing of a polymer based optical printed
wiring boards. Total optical loss of demonstration boards are optimized, which includes propagation, coupling, bends, and feature losses such as crossings. The polymer waveguide boards are terminated with a passive direct fiber attach method, which is compatible with MPO formats. Passive direct fiber connectorization between fiber and waveguide show minimal extrinsic losses to that of an active connectorization method. Fully MPO connectorized waveguide panels are realized and their optical performance properties assessed.

9753-19, Session 4

Low-loss optical coupling between waveguide and optical modules via 45-degree mirrors realized with graded-index core structure

Yoshie Morimoto, Takaaki Ishigure, Keio Univ. (Japan)

In this paper, we present a structural design for multimode waveguide realizing low-loss coupling with optical modules (e.g. VCSEL source and PD) via a 45-degree mirror using a ray-trace simulator. Following the simulated design, we experimentally fabricate a low-loss graded-index (GI) circular-core polymer optical waveguide using the Mosquito method, then a 45-degree mirror is formed on its one end, and experimentally demonstrate the low insertion loss of the waveguide.

Recently, on-board optical interconnects using multimode polymer waveguides have been drawing much attention. We have demonstrated the superior optical properties of GI circular-core polymer optical waveguides applicable to optical printed circuit boards (O-PCBs) over conventional step-index (SI) square-core waveguides. Generally, on O-PCBs, light sources and photodiodes (PDs) are supposed to be connected with the waveguides via 45-degree mirrors, so the optical loss caused at the mirrors is a concern.

In this paper, we focus on an optical link composed of two polymer waveguides connected with a multimode fiber, a VCSEL and a PD: one end of both waveguides has a 45-degree mirror for coupling with a VCSEL and a PD. We calculate the link loss dependence on the waveguide structure and confirm that GI core waveguides exhibit low insertion loss due to the tight optical confinement in the core, even if a 45-degree mirror is formed. We fabricate GI circular-core waveguides using the Mosquito method, and successfully form a 45-degree mirror. The GI circular-core waveguide link exhibits remarkable low insertion loss, realized with the high coupling efficiency with other modules.

9753-20, Session 5

Light emitters and modulators on SOI for optical interconnects (Invited Paper)

Yikai Su, Ciyuan Qiu, Yong Zhang, Ruili Liu, Shanghai Jiao Tong Univ. (China)

We discuss light emitters and modulators in silicon photonic interconnects. In particular, we experimentally demonstrate resonant luminescence from Ge quantum dots embedded in a photonic crystal ring resonator (PCRR) at room temperature. Six sharp resonant peaks are observed, which correspond to the resonant modes supported by the PCRR. We further study a silicon-graphene ring modulator, a silicon spatial light modulator, and a high speed silicon-graphene nanobeam modulator. These devices show great potential in future high density and high capacity interconnection systems.

9753-21, Session 5

Design of ultra-compact plasmonic-organic waveguide modulator

Qian Gao, Alan X. Wang, Oregon State Univ. (United States)

The ever-increasing demands to store, communicate, and compute information create an unceasing driving force for transformative photonic technologies. Chip-scale photonic integrated circuits (PICs) established a roadmap for scaling down photonic components to meet the challenges of energy reduction and bandwidth enhancement. However, it also creates an even urgent need for innovative devices and better materials. Hybrid plasmonic-organic devices will combine the large nonlinear optical effects of E-O polymers with the ultra-strong optical field confinement and localization of SPPs. In this paper, we design a new hybrid plasmonic-organic waveguide E-O modulator through band shifting of a 5-75nm long plasmonic grating waveguide (PGW) infiltrated with E-O polymers, which can dynamically control the optical transmission from low loss transparent mode into high absorption mode by resonance-enhanced plasmonic absorption. With advanced optical coupling structures using dipole nanoantennas and group index tapers, we expect to achieve ~3dB optical loss for the “ON” state, and ~5dB extinction ratio to the “OFF” state. In the meanwhile, we will discuss how to resolve engineering challenges to integrate E-O polymers into PGW modulators, particularly on how to efficiently pole the E-O polymer in narrow (~100nm) metal slits. Our theoretical analysis shows that such hybrid plasmonic-organic modulators have the potential to achieve 100GHz bandwidth and 1fJ/bit energy efficiency.

9753-22, Session 5

Low-loss hybrid ultra-thin silicon and polymer waveguide and modulator application

Shiyouhi Yokoyama, Feng Qiu, Andrew M. Spring, Kyushu Univ. (Japan)

Optical polymers are the promising material of choice for the waveguide application due to their optical transparency, adjustable refractive index, low dielectric loss, and compatibility with many materials and substrates. This widespread compatibility enables the construction of the unique hybrid polymer device to the silicon waveguide. One of the successful demonstrations in recent progress is the silicon hybrid modulator using the electro-optic (EO) polymer. The hybrid silicon and polymer modulators have already demonstrated a very low half-wave voltage and multi-GHz bandwidth response. While, the fabrication of the hybrid waveguide is quite elaborate, involving the high-resolution lithography, controlled etching, and ion implantation process.

In order to simplify the hybrid silicon and EO polymer modulator, and reduce its propagation loss, we apply ultra-thin silicon to polymer waveguide application. The waveguide consists of silicon core with a thickness of 30 nm and a width of 2 micro-m, and the cladding is the polymer. In such a thin silicon core, the side-wall scattering can be significantly reduced, thus the measured propagation loss of the waveguide is 1.5 dB/cm. The optical mode calculation reveals that 55% of the optical field extends into the polymer cladding. A Mach-Zehnder modulator is performed by using the hybrid ultra-thin silicon and EO polymer waveguide. We measured the half-wave voltage of the modulator to be 4.6 V at 1550 nm. We also investigate a mode converter which can couple the light from the hybrid polymer waveguide to the silicon strip waveguide. The coupling loss between two devices is estimated to be 0.5 dB.
High quality factor trapezoid subwavelength grating waveguide micro-ring resonator
Zheng Wang, The Univ. of Texas at Austin (United States); Xiaochuan Xu, Omega Optics, Inc. (United States); D. L. Fan, Yaguo Wang, Ray T. Chen, The Univ. of Texas at Austin (United States)

In the recent decade, silicon photonics has been attracting intensive research interest for optical communications owing to its advantageous compact dimensions and high-volume manufacturability. Particularly, silicon photonics micro-ring resonator on silicon-on-insulator (SOI) platform have been considered as a basic building block for a vast range of applications such as switches, modulators, and sensors. A majority of these applications involve opto-matter interaction, which can be substantially enhanced by the high quality factor ring resonators. However, the conventional integrated silicon photonics micro-ring resonators suffer from the intrinsic dilemma in achieving both high light confinement and strong opto-matter interaction with environment. Specifically, a high confinement of light that ensures the desired low loss propagation also suggests limited opto-matter interaction which jeopardizes its performance. Several waveguiding structures have been proposed, e.g. slot waveguide ring resonators, but the quality factor significantly deteriorates due to the high propagation loss. Recently, subwavelength grating (SWG) waveguides have been demonstrated as a promising solution for the aforementioned dilemmatic difficulties, where the ratios of silicon and cladding material of SWG waveguides can be readily engineered in low dimensions for achieving designed macroscopic performances. However, the quality factor of SWG ring resonators is unsatisfying because of the large bending loss of the SWG. In this manuscript, we investigate the bending loss mechanism and propose a trapezoid SWG based ring resonator with a high quality factor. The proposed ring resonators can greatly improve the performance of the traditional ring resonators.

Miniature mid-infrared thermo-optic switch with photonic crystal waveguide-based silicon-on-sapphire Mach-Zehnder interferometers
Yi Zou, The Univ. of Texas at Austin (United States); Swapnajit Chakravarty, Omega Optics, Inc. (United States); Chi-Jui Chung, Ray T. Chen, The Univ. of Texas at Austin (United States)

Silicon is the dominant choice of semiconductor for microelectronics. Si nanophotonics is anticipated to play a critical role in the future ultra-compact system integration due to the maturity of sub-micron silicon complementary metal oxide semiconductor (CMOS) technology. In recent years, significant potential of silicon photonics in the mid-infrared wavelengths has been realized for optical sensing and interconnect applications. Photonic crystals (PCs) are well known for their slow light effect, hence provide a promising platform for developing novel mid-infrared optoelectronic devices with significantly reduced device size and power consumption. In this paper, the active control of photonic crystal waveguides (PCWs) incorporated in Mach-Zehnder interferometer in silicon-on-sapphire has been investigated. We designed and fabricated a PCW based silicon thermo-optic (TO) switch operating at 3.43 μm. A novel device structure was proposed to enhance the heat exchange efficiency between the source and the active PCW region, which resulted in a faster switching time compared with the conventional structure. The required π phase shift between the two arms of the MZI has been successfully achieved within an 80 μm interaction distance. The maximum modulation depth of 74% was demonstrated for switching power of 170 mW. The small footprint and low power consumption provide a milestone towards mid-infrared integration.

Multimode and single-mode fibers for data center and high-performance computing applications (Invited Paper)
Scott Bickham, Corning Optical Communications (United States)

Data centers (DCs) and high performance computing (HPC) applications have traditionally used a combination of copper, multimode fiber and single-mode fiber interconnects with relative percentages that depend on factors such as the line rate, reach and connectivity costs. The percentage of single-mode fiber deployed in the DC has also grown slightly since 2014, coinciding with the emergence of mega data centers with extended distance needs beyond 100m. This trend will likely continue in the next few years as DCs expand their capacity from 100G to 400G, increase the physical size of their facilities and begin to utilize silicon-photonic transceiver technology. However there is still a need for the low-cost and high-density connectivity, and this is sustaining a deployment of multimode fiber for links ≤ 100m. In this paper, we discuss options for single-mode and multimode fibers in DCs and HPCs and introduce novel multimode fiber concepts which provide solutions for intra-and inter-rack connectivity and provide low coupling loss and long reach with silicon-photonic transceivers operating at 1310nm. We also discuss the trade-offs between single-mode fiber attributes such as bend-insensitivity, large mode field diameter and reduced coating diameter, all of which could help enable more robust connectivity in data centers.

Integration of 150-Gbps/fiber optical engines based on multicore fibers and 6-channel VCSELs and PDs
Mikko Karppinen, Antti Tanskanen, Veli Heikkinen, Petri Myöhänen, Noora Salminen, Jyrki Ollila, Olli Tapaninen, VTT Technical Research Ctr. of Finland Ltd. (Finland); Petter Westbergh, Johan Gustavsson, Anders Larsson, Chalmers Univ. of Technology (Sweden); Rashid Safaisini, Roger King, Philips GmbH U-L-M Photonics (Germany); Minsu Ko, Dietmar Kissinger, Ahmet Ça?rı Ulusoy, IHP GmbH (Germany); Thierry F. Taunay, Lalitkumar Bansal, OFS Fitel LLC (United States); Lars Grüner-Nielsen, OFS (Denmark); Efstratios Kehayas, James Edmunds, Leontios Stampoulidis, Gooch & Housego Systems Technology Group (United Kingdom)

850-nm VCSEL transceivers are a mature technology for low-power very-short-reach interconnects. Typically higher data rates and interconnection densities are implemented using fiber ribbon cables. An alternative solution is the novel multicore fibers, which enable a parallel optic data link in a single fiber. The multicore fibers are especially attractive for applications where ribbon cables and connectors are inconvenient, such as the space applications, where ribbon connectors are not matured yet and where hermetic packaging is often required. Robust hermetic feedthroughs are easier to implement with single fibers than with fiber ribbons. Huge throughput densities may be envisaged by fabricating ribbon cables of the multicore fibers.

We investigated the implementation of transmitter and receiver subassemblies based on multicore fibers coupled to 6-channel VCSEL and PD chips. The six multimode cores are arranged in 39 μm center-to-center throughputs may be envisaged by fabricating ribbon cables of the multicore fibers. The six multimode cores are arranged in 39 μm center-to-center distances to achieve a parallel optic data link in a single fiber. The multicore fibers are especially attractive for applications where ribbon cables and connectors are inconvenient, such as the space applications, where ribbon connectors are not matured yet and where hermetic packaging is often required. Robust hermetic feedthroughs are easier to implement with single fibers than with fiber ribbons. Huge throughput densities may be envisaged by fabricating ribbon cables of the multicore fibers. We investigated the implementation of transmitter and receiver subassemblies based on multicore fibers coupled to 6-channel VCSEL and PD chips. The six multimode cores are arranged in 39 μm center-to-center spacing into the fiber, and on the VCSEL and PD chips the active areas have circular array layout matching the fiber cores. Due to the small channel
Data-centric networks comprising of distributed data center and moderately high operational speed. This paper presents an overview of optical switching and routing must be employed with low cost data-center based topologies. Under extremely high capacity networking requirements.

9753-28, Session 6

Analysis of multi-mode to single-mode conversion at 635 nm and 1550 nm

Alethea Vanessa Zamora Gomez, A. Bogatzki, Norbert Arndt-Staufenbiel, Jens Hofmann, Henning Schröder, Fraunhofer-Institut für Zuverlässigkeit und Mikointegration (Germany)

We propose two low-cost and robust optical fiber systems based on the photonic lantern (PL) technology for operating at 635 nm and 1550 nm. The PL is an emerging technology that couples light from a multi-mode (MM) fiber to several single-mode (SM) fibers via a low-loss adiabatic transition. This bundle of SM fibers is observed as a MM fiber system whose spatial modes are the degenerate supermodes of the bundle. The adiabatic transition allows that those supermodes evolve into the modes of the MM fiber. Simulations of the MM fiber end structure and its taper transition have been performed via functional mode solver tools in order to understand the modal evolution in PLs. The modelled design consists of 7 SM fibers inserted into a low-index capillary. The material and geometry of the PLs are chosen such that the supermodes match to the spatial modes of the desired 0.22 NA step-index MM fiber in a moderate loss transmission. The dispersion of materials is also considered. These parameters are studied in two PL systems in order to reach a spectral transmission from 450nm to 1700nm. Additionally, an analysis of the losses as a function of the wavelength is presented. PLs are typically used in the fields of astrophotonics and space photonics. Recently, they are demonstrated as mode converters in telecommunications, especially focusing on spatial division multiplexing. In this study, we show the use of PLs as a promising interconnecting tool for the development of miniaturized spectrometers operating in a broad wavelength range.

9753-29, Session 7

Exabits/s integrated photonic interconnection technology for flexible data-centric optical networks (Invited Paper)

Le N. Binh, Thomas T. Wang, Huawei Technologies Duesseldorf GmbH (Germany); Gordon Liu Ning, Huawei Technologies Co., Ltd. (China)

Tremendous efforts have been recently developed for multi-Tbps over ultra-long distance and metro and access optical networks, especially when demands on data transmission and storage/ serving for 5G wireless. Optical transport network (OTN) has evolved from traditional IP/GMPLS DWDM to data-center based topologies. Under extremely high capacity networking environment, optical switching and routing must be employed with low cost and moderately high operational speed. This paper presents an overview of the followings:

• Data-centric networks comprising of distributed data center and data center concentric net topologies and demands on optical networking whose capacity reaching Exa-bps under flexible multi-wavelength channels of optical transport networks, thence general structures of active optical interconnecting technologies in both spatial and spectral domains with the aggregate bit rates ranging from 100G to 400G and to 10 or 32 Tbps.

• Integrated photonic components including multi-micro-ring modulators/ switches (RM/S) simultaneously performing as multiplexing and de-multiplexing functions, multi X-over switches incorporating RM/S as the basis elements for multi-Tbps and Exa-bps interconnection matrices. The proposed switching and transmission optical paths can handle variable baud rate of 100G to multi-Tbps. Design of integrated tunable bandwidth optical filters for incorporating with X-switches and cascaded all-pole-all-zero photonic bandwidth tunable filters are presented for forming Exa-bps optical interconnecting matrices. Unique designs employing discrete photonic ‘digital signal processing’ for ultra-compact flexible filters/ switches based on Si photonics for Exa-bps active interconnection are presented.

• Finally, experimental results on multi-channels transmissions and performances of optical switching matrices and effects on that of data channels are proposed and reported. Equivalent RM/S can be demonstrated with comb laser of 10 sub-carriers of 62.5 GHz spacing to a total of 2.4 Tbps using PAM4 56Gbaud.

9753-30, Session 7

High-performance flat data center network architecture based on scalable and flow-controlled optical switching system (Invited Paper)

Nicola Calabretta, Wang Miao, Harmen J. S. Dorren, Technische Univ. Eindhoven (Netherlands)

Traffic in data centers networks (DCNs) is steadily growing to support various applications and virtualization technologies. Multi-tenancy enabling efficient resource utilization is considered as a key requirement for the next generation DCs resulting from the growing demands for services and applications. Virtualization mechanisms and technologies can leverage statistical multiplexing and fast switch reconfiguration to further extend the DC efficiency and agility.

We present a novel high performance flat DCN employing bufferless and distributed fast (sub-microsecond) optical switches with wavelength, space, and time switching operation. The fast optical switches can enhance the performance of the DCNs by providing large-capacity switching capability and efficiently sharing the data plane resources by exploiting statistical multiplexing. Benefiting from the Software-Defined Networking (SDN) control of the optical switches, virtual DCNs can be flexibly created and reconfigured by the DCN provider.

Numerical and experimental investigations of the DCN based on the fast optical switches show the successful setup of virtual network slices for intra-data center interconnections. Experimental assessment of the DCN performance in terms of latency and packet loss show less than 10^{-5} packet loss and 640ns end-to-end latency with 0.4 load and 16-packet size buffer. Numerical investigation on the performance of the systems when the port number of the optical switch is scaled to 32×32 system indicate that more than 1000 ToRs each with Terabit/s interface can be interconnected providing a Petabit/s capacity. We will present results on 16×16 InP photonic wavelength and space switch and discuss the roadmap to the integration of larger port switches.

9753-32, Session 7

Optical circuit switches in computing systems: hype or reality? (Invited Paper)

Laurent Scharres, IBM Thomas J. Watson Research Ctr. (United States)
This paper analyzes the potential and outlines the challenges of optical circuit switching (OCS) as a power- and cost-efficient alternative to electrical-packet switches in computing systems. The importance of datacenter network equipment as signified by its >10 billion dollar market and double digit growth rates projected over the next several years, provides a huge opportunity for new switching technologies that can improve the efficiency of data movement and resource utilization. Optics in today's data centers and HPC has been mostly limited to high-bandwidth point-to-point interconnections. However, there are indications that systems may reap benefits by incorporating different OCS implementations. Specifically we focus on two areas:

- Initial inroads with millisecond-scale switching: OCS is rapidly gaining traction with mega-datacenter / cloud providers for network partitioning allowing higher utilization of costly server, memory, and storage equipment. Current OCS equipment is limited to coarse-grained reconfigurations due to the switching times exceeding milliseconds, which limits its applicability to relatively long-lived applications such as backups and VM-migration, and to workload placement at software-controlled time scales.

- Potential and challenges of micro- and nanosecond-scale OCS: More quickly reconfigurable optical switches provide potential for performance improvements over a larger class of workloads. Silicon photonic switch fabrics in particular can achieve μs- or ns-scale reconfigurability, low electrical power consumption, and high integration density. Microsecond-scale switches with tens of ports on a single chip are currently being developed; they have the potential to enable hybrid electrical-optical networks that could benefit scale-out programming frameworks such as MapReduce/Hadoop. To enable optical switching at the packet-scale and make it truly useful for both all-optical and hybrid switch networks, the underlying optical technology and control electronics have to switch within a few nanoseconds, and they need to be integrated in chip-scale packages to reduce the cost barrier for OCS entry and wider system use. In the DARPA POEM/TOPS program, we are developing technologies for and are exploring use scenarios of ns-scale OCS. Our performance comparisons to best-in-class electrically switched systems predict orders of magnitude better performance for graph-type data-intensive workloads in highly-interconnected rack-scale systems.

9753-34, Session 8

**Silicon optical routers for photonic networks-on-chip (Invited Paper)**
Lin Yang, Yuhao Xia, Yunchou Zhao, Qiaoshan Chen,
Institute of Semiconductors (China)

The performance of chip multiprocessor (CMP) is determined not only by the number of the processor cores integrated on a chip, but also by the communication efficiency among them. With CMP continuously requiring more communication bandwidths, metallic-based electrical networks-on-chip (NoC) gradually becomes the bottleneck for improving the performance of CMP due to its high power consumption, limited bandwidth and long latency. Photonic NoC is considered as a potential solution to overcome the limitations of its electrical counterpart. Optical router is an essential component for photonic NoC, which is responsible for switching data from one optical link to another one.

In this paper, we will review the status of the optical routers for photonic NoC and introduce our efforts on this topic. Firstly, we will introduce several demonstrated optical routers based on microring or Mach-Zehnder optical switches. Then, we will introduce a universal method for constructing an N-port non-blocking optical router for photonic NoC. The optical router constructed by this method has minimum optical switches, in which the number of the optical switches is reduced about 50% compared to the reported optical routers based on Mach-Zehnder optical switches, and therefore is more compact in footprint and more power-efficient. Finally, we will introduce the fabricated silicon electro-optic 4-port optical routers constructed by this method.

9753-35, Session 8

**SiN-assisted flip-chip adiabatic coupler between SiPh and Glass OPCBs**
Giannis N. Poulopoulos, Catherine Baskiotis, Dimitrios Kalavrouziotis, National Technical Univ. of Athens (Greece); Lars Brusberg, Henning Schröder, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); Dimitrios Apostolopoulos, Hercules Avramopoulos, National Technical Univ. of Athens (Greece)

As the need for higher bandwidth within the datacenter becomes increasingly intense, the research and industrial focus has moved towards the development of on-board optical links, since they are the key to establish new optically-enabled datacenter architecture paradigms. In this newly formed environment, graded index glass waveguides on glass PCBS have been presented as strong candidates for future single mode optical PCBS, since, among others, they present low propagation losses and low dispersion in the telecommunication window. To fully exploit their potential however, efficient light coupling solutions are required, especially with Silicon Photonics (SiPh) which are favored by the industry for commercial exploitation. A variety of out of plane coupling schemes have already been proposed, including integrated mirrors and gratings, suffering however from fabrication-assembly difficulties, bandwidth limitations and high coupling losses.
In this work, we demonstrate, for the first time to our knowledge, a SiN-assisted in-plane adiabatic coupler between SiPh and on-board Glass waveguides that can be realized employing standard flip-chip assembly equipment. Our numerical study is founded on an actual graded index Glass waveguide developed by Fraunhofer-I2M and relies on the supermode theory and the adiabatic theorem. The taper width profile is established by calculating the required width slope for uniform power loss along the taper while an EigenMode Expansion (EME) propagation solver is employed for estimating the optimal length. Vertical and lateral misalignment issues between the two coupled waveguides are investigated, resulting to a final design that exhibits <0.1 dB theoretical Si-to-Glass loss, over the entire C-band, and accounts for assembly and fabrication uncertainties.

9753-36, Session 8

**Bimorph actuators in thick silicon dioxide for photonic active alignment**

Kai Wu, Tjitte-Jelte Peters, Marcel Tichem, Technische Univ. Delft (Netherlands)

The PHASTFlex (Photonic Hybrid A$S$sembly Through Flexible Waveguides) project proposes an active micro-electro-mechanical systems (MEMS) alignment scheme for the next generation of multi-port hybrid photonic packages. In these packages, two photonic integrated circuits (PICs), a TriPlex interposer chip (a silicon dioxide/silicon nitride platform) and an InP chip, are assembled on a common carrier. After flip-chip bonding these two PICs on the carrier, flexible waveguide beams which are released by post-processing of the TriPlex chip, are positioned with respect to the waveguides on the InP PIC using on-chip MEMS functions. Electro-thermal actuators are used for waveguide beam positioning. These have to be created in the same waveguide layer, which is >76?m thick silicon dioxide. This paper focuses on designing and modelling bimorph actuators for waveguide beam out-of-plane positioning. The bimorphs consist of two layers: poly-Si (lightly doped) with 57?m thickness and 16?m thick silicon dioxide, and are heated up by a Cr heater. There are two sets of bimorphs which are adjacent to the waveguide beams. All the waveguide beams are connected by a crossbar at their free ends, so that they can be actuated simultaneously. By varying the length of heater and poly-Si electrical loops of the bimorphs, at a temperature of 600?K, the out-of-plane displacement of the waveguide beams can reach approximately 107?m. The models show that this type of bimorph is able to achieve sufficient out-of-plane motion for this photonic active alignment.

9753-37, Session 8

**Reduced nonlinearities in 100-nm high SOI waveguides**

Cosimo Lacava, Univ. degli Studi di Pavia (Italy) and Optoelectronics Research Ctr. (United Kingdom); Riccardo Marchetti, Valerio Vitali, Ilaria Cristiani, Guido Giuliani, Univ. degli Studi di Pavia (Italy); Maryse Fournier, Stéphane Bernabé, CEA-LETI (France); Paolo Minzioni, Univ. degli Studi di Pavia (Italy)

We experimentally investigated, using both continuous-wave and 10 Gbit/s modulated signals, the impact of optical nonlinear effects such as two-photon-absorption (TPA), free-carriers-absorption (FCA) and free-carrier-dispersion (FCD), in WDM integrated micro-filters exploiting different designs and exhibiting different waveguide cross-sections (from 500 ? 220 nm to 825 ? 100 nm). We will show that the use of 100-nm high waveguides allows reducing the impact of nonlinear losses, with respect to the standard waveguides, thus increasing by > 3 dB the maximum power that can be injected in the devices without causing significant nonlinearities. The experimental results showed that, at relatively high power level regime (> 3 dBm), FCD caused an undesired detuning of the filters resonance wavelength, and a distortion of the transmission spectrum of the filter. When a laser signal at the resonance wavelength is injected, even at moderate power (e.g. 0 - 3 dBm), TPA affects the overall device insertion losses. Interestingly, reduced-height waveguides (100 nm) show a higher threshold-power with respect to the standard waveguides (500 ? 220 nm). This behavior can be related to the reduced height of the waveguide: as recombination centers are mainly located on the waveguide surfaces, the use of a reduced-height structure allows for a faster free-carrier recombination. Measurements with OOK-modulated signals showed that TPA and FCA don’t affect the back-to-back BER of the signal, even when long pseudo-random-bit-sequences (PRBS) are used, as the FCD-induced filter-detuning increases filter losses but “prevents” excessive signal degradation. Further measurements including signal propagation are currently planned.

9753-38, Session 8

**Experimental study of silicon ring resonators and ultra-low losses waveguides for efficient silicon optical interposers**

Vincent Reboud, Benjamin Blampey, Paul Gindre, Olivier Dubray, Daivid Fowler, Olivier Lemonnier, Edouard Grelli, Maryse Fournier, Yvain Thonnart, Stéphane Bernabé, CEA-LETI (France)

The realization of on-chip interconnects to address many-core computer architectures requires the fabrication of multiplexers and demultiplexers with low crosstalk and loss. Microring resonators can in principle be easily scaled to satisfy these challenges of integrated silicon photonics.

We report here an in-depth characterization of the optical properties and performances of microrings, WDM links of four different wavelengths and we identify the best candidates to design an efficient optical interposer and Optical Network On Chip (ONoC). It allows us to select microring resonance linewidth to be at least 15 GHz in order to reach 10 Gb.s⁻¹ data transmission with negligible signal degradation. Designs can be easily modified to handle multiple wavelengths for ONoC applications.

In addition, future generations of optical multi-core processors will require the interconnection of several on-chip interfaces. It then becomes essential to obtain optical waveguides with ultra-low propagation losses to transport information over long distances (~10cm) on photonic chips. In order to make this feasible, ultra-low loss waveguides have been successfully fabricated reaching losses as low as 0.18 dB/cm. The implementation of these components significantly reduces the technical barriers to future ONoC systems using many-core architectures and optical interposers using Silicon Photonics.

9753-39, Session 9

**Si-based light-emitting devices based on Ge quantum dots in optical microcavities (Invited Paper)**

Jinsong Xia, Cheng Zeng, Yong Zhang, Huazhong Univ. of Science and Technology (China); Zuimin Jiang, Fudan Univ. (China)

Si-based light-emitting device is very important for on-chip optical interconnection on Si platform. In our research, we fabricate light-emitting devices through embedding Ge self-assembled quantum dots into optical microcavities. Ge self-assembled quantum dots emit light in telecommunication wavelengths in the range of 1.3 to 1.6 ?m, which is transparent for Si. Multiple layers of Ge self-assembled quantum dots are grown by molecular beam epitaxy (MBE). Then, they are embedded into...
In optical interconnection, it will be beneficial to use a single comb laser source to replace a laser array. In this context, high performance InAs quantum dot comb lasers have been grown on GaAs by MBE systems, transferred to Silicon substrates by Pd-mediated wafer bonding techniques and characterized for optical interconnection integrations. The special designed InAs quantum dot gain region and low temperature wafer bonding process developed at the University of Massachusetts Lowell enables the state-of-the-art InAs comb lasers on Si. A ridge waveguide InAs QD comb laser on Si with the 3 dB linewidth of 20 nm is obtained from the electroluminescence (EL) measurements, the comb spectrum exhibits uniform power >1mW for each channel with the variation less than 1dB. The silicon photonics waveguide and ring resonator passive components were fabricated on a SOI wafer by E-beam lithography. Finally, the emission from the comb laser array is coupled into the silicon photonic devices by aligning the two chips with high precision translation stages. After coupling the comb source into the silicon photonic transmitters, four individual laser emissions have been successfully filtered out. The details of the characterization of the comb laser and a four-channel silicon laser array will be presented.

9753-40, Session 9

**Low-power chip-level optical interconnects based on bulk-silicon single-chip photonic transceivers**

Gyungock Kim, Hyundai Park, Jiho Joo, Ki-Seok Jang, Myung-Joon Kwack, Sang Hoon Kim, In Gyoo Kim, Sun Ae Kim, Jin Hyuk Oh, Jaegyu Park, Sanggi Kim, Electronics and Telecommunications Research Institute (Korea, Republic of)

When photonic integrated circuits (PICs), defined for transmitting/receiving optical data, are successfully monolithically-integrated into major silicon electronic chips as chip-level optical I/Os, it will bring innovative changes in data computing and communications. Despite of recent remarkable progress of silicon photonic devices and various levels of photonic integration, efforts to implement silicon photonic devices as viable optical I/Os in electronic chips still face major obstacles, such as large device size, low operational efficiency, high power consumption, and substrate incompatibility issue with conventional electronic chips. Also, realizing a compact chip-level light source is a serious issue for practical implementation of a silicon photonic I/O scheme on an electronic chip. Due to these major problems, a new photonic I/O scheme which can overcome these obstacles and ease the transition to the electronic-photonic (EP) integration at silicon chip level, is of great interest. In this work, we present a new scheme for chip-level photonic I/Os, based on planar-integrated vertical photonic devices on bulk silicon, which increases the integration level of PICs to a complete photonic transceiver (TRx) including chip-level light source. We demonstrate a prototype of the single-chip photonic TRx based on a bulk silicon substrate, which realized 20 Gb/s low-power chip-level optical interconnects between fabricated chips for 7 - 850 nm. This proves that this scheme can offer compact low-cost chip-level I/O solutions and have a significant impact on practical electronic-photonic integration in high performance computers (HPC), cpu-memory interface, 3D-IC, and LAN, SAN, data center and network applications.

9753-42, Session 9

**Wavelength-controlled External-Cavity Laser with a Silicon Photonic Crystal Resonant Reflector**

Liam O’Faolain, Alexandros A. Liles, Univ. of St. Andrews (United Kingdom); Alfredo Gonzalez, Saydulla Persheyev, kapil Debnath, Univ of St Andrews (United Kingdom)

We present a new type of external-cavity laser design that employs as a resonant reflector a Silicon PhC cavity and a low-index polymer (SUB) bus waveguide. We employ a vertical coupling technique that allows for low insertion and transmission losses as well as the possibility of controlling the coupling between the bus waveguide and Silicon PhC. Thermal isolation between the components is also provided and the silicon area occupied is minimised; features vital for the realization of on-chip optical networks. By demonstrating a laser solution based on the vertical coupling architecture and in combination with the previously demonstrated modulators [1] and detectors [2], we pave the way for complete, compact Silicon Photonic WDM platform for chip-scale optical links.

Light is generated and amplified in a commercially available, Reflective Semiconductor Optical Amplifier with minimum fiber-to-fiber gain of 20 dB for wavelengths around 1550 nm and is then butt-coupled via a lensed fiber to a low refractive index bus waveguide on the SOI reflector chip. Optical feedback is provided by the PhC cavity, which on resonance couples light back to the waveguide and sets up the laser cavity. The lasing is defined by the resonance wavelength of the PhC cavity, the value of which can be very precisely controlled either lithographically or electro- optically, thus providing the precise wavelength control that is of utter importance for Wavelength Division Multiplexing.


9753-43, Session 9

**Low-loss curved subwavelength grating waveguide based on index engineering**

Zheng Wang, The Univ. of Texas at Austin (United States); Xiaochuan Xu, Omega Optics, Inc. (United States); D. L. Fan, Yaguo Wang, Ray T. Chen, The Univ. of Texas at Austin (United States)

Silicon photonics has been attracting tremendous interests in the past decade because of the potential to utilize the low cost, mass production
technologies in the semiconductor industry to manufacture photonic chips. However, the fact that silicon does not have either a direct band gap or the second-order nonlinearity makes generating and controlling photons on silicon chips a great challenge. Hybrid integration is considered as a potential solution to this issue. Plenty structures, such as slot waveguides and photonic crystal waveguides, have been studied to enhance the interaction between photons and the hybrid integrated materials. Recently, several groups have demonstrated that subwavelength grating (SWG) waveguide, comprised of periodic subwavelength silicon blocks and cladding materials, can be used as a fundamental building block for integrated optical devices. SWG waveguide owns a fascinating character which enables people to engineer the ratio of silicon and cladding material microscopically for desired optical properties macroscopically. While a vast range of SWG based photonic devices have been demonstrated with performance that cannot be achieved by traditional silicon waveguides, one important problem remaining unsolved is the large bend loss. Analytical analysis based on conformal transformation and equivalent index method indicates the bend loss comes from the mode mismatch between straight and curved SWG waveguide. In this paper, we propose and demonstrate that through optimizing the geometry of silicon blocks in SWG structures, the mode mismatching can be significantly ameliorated and the bend loss can be reduced by ~ 50%.

9753-27, Poster Session

**Full-mesh optical backplane with standard MM fiber ribbons**

Maddalena Ferrario, Domenico Coville, Pierpaolo Boffi, Mario Martinelli, Politecnico di Milano (Italy); Vito Basile, Irene Fassi, Istituto di Tecnologie Industriali e Automazione (Italy); Matteo Falcucci, Compel Electronics S.p.A. (Italy); Chiara Renghini, Paolo Scalmati, Somacis S.p.A. (Italy)

The rapid growth of ICT applications requires data centers to handle an ever increasing bandwidth capacity. Currently, interconnections at data center level are managed through electrical backplane with copper connections which have now reached their transmission capacity limits and alternative optical solutions have recently been explored. Optical waveguides embedded in standard FR4 boards and external circuit based on bare optical fibers routed on flexible sheets have been proposed which however don’t guarantee full-mesh, mechanically reliable and easy-maintenance interconnections.

In the present work a new optical interconnection layout is proposed where the overall backplane is divided into several independent optical sub-circuits handling with a broader spectrum, especially in the short and mid-infrared (MIR) range. This trend is due to potential applications in chemical sensing, spectroscopy and defense in the 2-10 µm range. The recent development of fibers covering the MIR range paves the way to wafer-level testing for mid-infrared photonic. We previously reported the development of a MIR photonic platform based on buried SiGe/Si waveguide with propagation losses between 1 and 2dB/cm. However the low index contrast of the platform makes the design of efficient grating couplers very challenging. In order to achieve a high fiber-to-chip efficiency, we propose a novel grating coupler structure, in which the grating is locally suspended in air. The grating has been designed with FDTD software. To achieve high efficiency, suspended structure thicknesses have been jointly optimized with the grating parameters, namely the fill-factor, the period and the grating etch depth. Using the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) optimization algorithm we obtained a configuration where the fiber-to-waveguide efficiency is above 57%. Moreover the optical transition between the suspended and the buried SiGe waveguide has been carefully designed by using an Eigenmode Expansion software. Transition efficiency as high as 86% is achieved.

9753-44, Poster Session

**Suspended mid-infrared fiber-to-chip grating couplers for SiGe waveguides**

Julien Favreau, Cédric Durantin, Jean-Marc Fédéli, Salim Boutami, CEA-LETI (France); Guang-Hua Duan, III-V Lab. (France)

Silicon photonics has taken great importance own to the applications in optical communications, ranging from short reach to long haul. Originally dedicated to telecom wavelengths, silicon photonics is heading toward circuits handling with a broader spectrum, especially in the short and mid-infrared (MIR) range. This trend is due to potential applications in chemical sensing, spectroscopy and defense in the 2-10 µm range. The recent development of fibers covering the MIR range paves the way to wafer-level testing for mid-infrared photonic. We previously reported the development of a MIR photonic platform based on buried SiGe/Si waveguide with propagation losses between 1 and 2dB/cm. However the low index contrast of the platform makes the design of efficient grating couplers very challenging. In order to achieve a high fiber-to-chip efficiency, we propose a novel grating coupler structure, in which the grating is locally suspended in air. The grating has been designed with FDTD software. To achieve high efficiency, suspended structure thicknesses have been jointly optimized with the grating parameters, namely the fill-factor, the period and the grating etch depth. Using the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) optimization algorithm we obtained a configuration where the fiber-to-waveguide efficiency is above 57%. Moreover the optical transition between the suspended and the buried SiGe waveguide has been carefully designed by using an Eigenmode Expansion software. Transition efficiency as high as 86% is achieved.

9753-45, Poster Session

**A new design for coupling light between silicon strip waveguide and plasmonic slot waveguide**

Bingqing Zhu, Hon Ki Tsang, The Chinese Univ. of Hong Kong (Hong Kong, China)

We propose and evaluate numerically and experimentally a new structure for coupling light from a silicon strip waveguide to a plasmonic slot waveguide (PSW). The conventional approach of a taper funnel for mode matching is insufficient to achieve high coupling efficiency. We propose the use of an additional silicon strip to slot mode converter to the conventional taper. This has a low insertion loss and achieves better mode matching. The experimental results show the proposed design can achieve a higher coupling efficiency than the conventional one in both cases of with or without cladding layers.

We fabricate several PSW on a 250nm thick silicon on insulator (SOI). The width of the slot is 220nm and we use gold as the metal for the plasmonic structure. The light is coupled in and out using subwavelength grating couplers. By comparing the transmission spectra of PSW of different lengths, we obtained the propagation loss of the PSW to be above 0.7dB/um. We propose the use of a further taper to achieve high coupling efficiency. We propose the use of an additional silicon strip to slot mode converter to the conventional taper. This has a low insertion loss and achieves better mode matching. The experimental results show the proposed design can achieve a higher coupling efficiency than the conventional one in both cases of with or without cladding layers.

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9753-46, Poster Session

**SWG-optimized MMI waveguides for dual and multi-beam splitting, beam position-shifting, and focusing purposes**

Zahra Abdolahi, Hao Jiang, Bozena Kaminska, Simon Fraser Univ. (Canada)

Optical links have potential to be used in many different fields for high-speed communications, considering their high bandwidths with high capacity for carrying information. Bent multimode waveguides are one of these optical interconnection architectures, which have a myriad of applications including their use as optical concentrators for harvesting light and waveguiding photovoltaics. In this work, a new design of bent multimode SU8 waveguide with plano-convex lenses is presented and fabricated on Si/SiO2. SiO2 is deposited on RCA-cleaned Si wafers using PECVD. The cross-section of the photodefined waveguide is 30μm×15μm and its radius of curvature is considered to be as large as 10 mm to minimize bending losses. The lens has a radius of curvature of 50μm. Prior to fabrication, the focal length of the lens was calculated using the thick lens formula (f=85 μm) and considered in the design. Also, Comsol multiphysics is exploited to predict the absorption and scattering optical loss in the designed waveguide. The fabricated waveguide is structurally characterized by optical microscope, SEM, and AFM. The results revealed that the waveguide has a smooth surface and uniform sidewalls. Furthermore, optical test is conducted using an IR laser with a wavelength of 780.8 nm. An optical efficiency of 12.4% was obtained. The results will be discussed further in the full paper.

9753-47, Poster Session

**High-performance Ge-on-Si avalanche photodetector**

Ki-Seok Jang, Sang Hoon Kim, In Gyoo Kim, Jin Hyuk Oh, Sun Ae Kim, Gyungook Kim, Electronics and Telecommunications Research Institute (Korea, Republic of)

For the next-generation high-speed data communication and interconnect systems, silicon photonics is regarded as a promising technology, providing cost-effective optical devices based on mature silicon CMOS fabrication technology. The development of high-sensitivity Ge-on-Si avalanche photodetectors (APDs), which are widely used in fiber-optic communications is of interest. In this paper, we present high-performance separate absorption-charge-multiplication (SACM) Ge-on-Si avalanche photodetectors operating up to 25 Gb/s. The vertical-illumination type Ge avalanche photodetectors were grown on a bulk-silicon wafer by reduced pressure chemical vapor deposition (RPCVD), and fabricated with CMOS-compatible process. The fabricated devices show a -3dB bandwidth (f-3dB) over 18 GHz at operational biases (gain> 10) in the wavelength range of 770-1550 nm. The on-wafer measured eye-diagram in the voltage region of gain > 10 shows good eye-openings up to 25 Gb/s. The measured maximum gain-bandwidth product is over 280 GHz. The high sensitivity better than -27.5 dBm at a BER < 10^-12, 770-1550 nm, and 10 Gb/s operation was measured for a 10 Gb/s Ge-on-Si APD photoreceiver module.

9753-48, Poster Session

**Composite axilens-axicon diffractive optical elements for generation of ring patterns with high focal depth**

Raghu Dharmavarapu, Anand Vijayakumar, Indian Institute of Technology Madras (India); Robert Brunner, Ernst-Abbe-Hochschule Jena (Germany); Shanti Bhattacharya, Indian Institute of Technology Madras (India)

A binary Fresnel Zone Axilens (FZA) is designed for infinite conjugate mode and the phase profile of a refractive axicon is combined with it to generate a composite Diffractive Optical Element (DOE). The FZA designed for two focal lengths generates a line focus along the propagation direction extending between the two focal planes. The ring pattern generated by the axicon is focused through the two focal planes of FZA whose radius depends on the propagation distance. Hence, the radius of the focused ring pattern can be tuned within the two focal planes. The integration of the two functions was carried out by shifting the location of zones of FZA with respect to the phase profile of the refractive axicon resulting in a binary composite DOE. The FZAs and axicons were designed for different focal depth values and base angles respectively, in order to achieve different ring tunability range within different focal depths. The elements were simulated using scalar diffraction formula and their focusing characteristics were analyzed. The DOEs were fabricated using electron beam direct writing and evaluated using a fiber coupled diode laser. The tunable ring patterns generated by the DOEs have prospective applications in microdrilling as well as microfabrication of circular diffractive and refractive optical elements.

9753-49, Poster Session

**Design and process consideration for minimizing optical loss in lens-based connector assemblies**

Xin Liu, Corning Optical Communications (United States)

The MXC connector, featuring the Prizm MT lensed ferrule technology, was specifically designed for Intel’s Silicon Photonics technology. It has a multi-fiber ferrule with integrated collimating lenses (up to 64 lenses) developed by USConec. It shares the same overall footprint as a traditional MT-type, multi-fiber rectangular ferrule. Corning has studied critical product design and process parameters that affect insertion loss performance. The development team demonstrates mated loss for MXC cable assemblies as low as 0.20dB for 8 fiber application at 1300nm wavelength, and 24 fiber applications can meet 0.70dB loss requirement.
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9754-2, Session 1

A high-precision six-degree-of-freedom relative position sensor
Claudia A. Sison, Gary B. Hughes, California Polytechnic State Univ., San Luis Obispo (United States); Philip M. Lubin, Peter Meinhold, Jonathan Y. Suen, Univ. of California, Santa Barbara (United States)

This paper describes an active triangulation laser measurement system for a specific application wherein the relative position of two fixed, rigid mechanical components is to be measured with high precision in six degrees of freedom (DOF). Potential applications include optical systems with feedback to control for mechanical vibration, such as devices with multiple focal planes. The method uses a planar array of laser emitters mounted on one component. The lasers are directed at a reflective surface on the second component. The reflective surface consists of a piecewise-planar pattern such as a pyramid, or more generally a curved reflective surface such as a hyperbolic paraboloid. The reflected spots are sensed at 2-dimensional photodiode arrays in the emitter plane. Changes in the relative position of the emitter plane and reflective surface will shift the location of the reflected spots within the photodiode arrays. Kinematic relative motion in any degree of freedom produces independent and predictable shifts in the reflected spot locations, permitting full six-DOF relative position determination between the two component surfaces. Response time of the sensor is limited by the read-out rate of the photodiode arrays. Algorithms are given for position determination with limits on uncertainty and sensitivity, based on laser and spot-sensor characteristics, and assuming regular surfaces. Additional uncertainty analysis is provided for surfaces containing irregularities, based on calibration data. A potential application is presented involving target vector determination using multiple focal planes that are mounted in a semi-rigid frame.

9754-3, Session 1

Low-cost facile interferometer for displacement mapping of harmonically-excited MEMS
Mateusz T. Madzik, Jaime Viegas, Masdar Institute of Science & Technology (United Arab Emirates)

In the context of MEMS/MOEMS design it is of great value to be able to image the displacement dynamics at a given excitation frequency, namely to map the modal displacements and correlate it to finite element models commonly used in order to validate such models. In this work, we present a simple, assembled from readily available components, low cost, imaging vibrometer based on a Twyman-Green interferometer with digital interferogram acquisition, allowing to map displacement contour levels of a harmonically excited piezoelectric membrane, on the principle of exposure integration. We experimentally demonstrate the capabilities of our setup on imaging the 4th mechanical mode of vibration of a 200 micrometer radius piezoelectric micromachined ultrasonic transducer membrane vibrating at 842 kHz, with an out-of-plane amplitude of 475 nm. Our results allow a direct visualization of the influence of etching trenches onto the vibrating membrane. FEM simulations are in excellent agreement with experiment and therefore validated by the experimentally obtained displacement maps.

9754-4, Session 1

Extraction of natural weight shift and foot rolling in gait based on hetero-core optical fiber load sensor
Yudai Otsuka, Yuya Koyama, Michiko Nishiyama, Kazuhiro Watanabe, Soka Univ. (Japan)

Gait in daily activity has been well-known to affect human health which may cause physical problems such as backache, bowleg, and asymmetric pelvis. Monitoring of natural weight shift and foot rolling on plantar pressure has been employed by researchers in order to analyze gait characteristics. Conventional gait monitoring systems have been developed for using shoes with piezoelectric sensors, which are useful because of unconstraint to human in walking, however these have some problems of temperature dependence and electric leakage. On the other hand, a hetero-core optical fiber sensor has many advantages of high sensitivity for macro-bending, lightweight, independence on temperature fluctuations, and no electric contact. This paper describes extraction of natural weight shift and foot rolling for gait evaluation by using a sensitive shoe, in the sense of which hetero-core optical load sensors are embedded for detecting plantar pressure. Plantar pressure of three subjects who wear the sensitive shoe in walking on the treadmill was monitored. As a result, the proposed sensitive shoe could discriminate three types of gaits based on weight shift and foot rolling in terms of centroid movement and centroid points on each time. Additionally, reliability of proposed sensor is confirmed by plantar pressure monitoring using electric load sensor as a reference. For these results, unconstraint gait monitoring system using hetero-core optical fiber load sensor which has same performance as electric load sensor is proposed.

9754-5, Session 1

Surface-enhanced spectroscopy: comparison of different methods (Invited Paper)
Jacob B. Khurgin, Johns Hopkins Univ. (United States)

In this talk I consider surface enhanced fluorescence and surface-enhanced Raman scattering as methods for detection of small amounts of substances including single molecule sensing. I will then explain phenomenon of quenching observed in fluorescence and resonance Raman but not in normal Raman spectroscopy and establish limits to surface enhancement. Finally, sensitivity of surface enhanced sensing and other methods, such as evanescent wave sensing will be compared and techniques for optimization will be outlines.

9754-6, Session 2

Spatially-resolved spectroscopy using swept-source optical interferometry
Ryoma Onita, Tatsutoshi Shioda, Saitama Univ. (Japan)

Swept source (ss) interferometry is one of the attractive method for fast capturing tomography. In previous, the ss-interferometry has been concentrated on a tomography and profilometry. In this study, we will present algorithms to obtain the spectral information from the tomography. Recently, optical interferometer has been used to get tomographic images, the advantage of the interferometer is providing high-resolution (from submicron to micron) and noninvasive measurement. Thus, it has been
applied to industrial and medical fields. On the other hand, the optical interferometer is well-known to be applied to the spectroscopy. By considering the similarity of the two optical setups, it has been reported to obtain spectrum from tomography by a time-domain low-coherence interferometry (TD-LCI). However it is difficult to shorten measurement time, because of a mechanical scanning of the reference optical path length.

Resolving the problem, we propose a spatially resolved spectroscopy using the ss-interferometry, in which a tunable-laser is used as a light source. In case of the multi-layered sample, an observed waveform involves superpositioned sinusoidal waves with different phases that corresponds to layers position. In order to distinguish the waves of different phases, we propose two different approaches. One is to use its Fourier-transformed(FT) signal, which shows the tomographic image. Observed peaks in the FT-signal are divided into isolated peaks and Fourier-transformed again. The other is the raw signal to be applied to a band-pass filter and to be Fourier-transformed. In our presentation, the experimentally observed spatially-resolved spectra with absorption coefficients and refractive indices will be shown and compared with two different ways with theories.

Mini and micro spectrometers pave the way to on-field advanced analytics

Clémantine Bouyé, Benoît d’Humières, Hugo Kolb, TEMATYS (France)

First introduced in the 1990’s, miniature optical spectrometers were compact, portable devices brought on the market by the desire to move from time-consuming lab-based analyses to on-field and in situ measurements. This goal of getting spectroscopy into the hands of non-specialists is driving current technical and application developments, the ultimate goal being, in a far future, the integration of a spectrometer into a smartphone or any other smart device (tablet, watch,...). In this article, we present the results of our study on the evolution of the compact and ultra-compact spectrometers market towards widespread industrial use and consumer applications.

Presently, the main market of miniature spectrometers remains academic labs. However, they have been adopted on some industrial applications such as optical source characterization (mainly laser and LEDs). In a near future, manufacturers of compact and ultra-compact spectrometers target the following industrial applications: agriculture crop monitoring, food process control or pharmaceuticals quality control. Next steps will be to get closer to the consumer market with point-of-care applications such as glucose detection for diabetics, for example.

To reach these objectives, technological breakthroughs will be necessary. Recent progresses have already allowed the release of micro-spectrometers. They take advantage of new micro-technologies such as MEMS (MicroElectroMechanical Systems), MOEMS (Micro-Opto-Electro-Mechanical Systems) or micro-mirrors arrays to reduce cost and size while allowing good performance and high volume manufacturability. Integrated photonics is being investigated for future developments.

It will also require new business models and new market approaches. Indeed, spreading spectroscopy to more industrial and consumer applications will require spectrometers manufacturers to get closer to the end-users and develop application-oriented products.

Design and optimization of indoor optical wireless positioning systems

Mark Bergen, The Univ. of British Columbia (Canada); Daniel Guerrero, Xian Jin, UBC Okanagan (Canada); Blago A. Hristovski, The Univ. of British Columbia (Canada); Hugo Chaves, Richard Klukas, Jonathan Holzman, UBC Okanagan (Canada)

Optical wireless technology is attracting considerable attention. Such technology is often implemented with fixed optical transmitters and mobile imaging receivers for application to high-speed Optical Wireless Communication (OWC) systems or high-precision Optical Wireless Location (OWL) systems. In this particular work, OWL systems are investigated for angle-of-arrival (AOA-based) based positioning. AOA-based positioning has the optical wireless receiver measure AOA vectors from surrounding optical beacons and then triangulate its position as the intersection of these AOA vectors. Such a process can enable effective positioning if two key technological challenges are met. First, the mobile optical wireless receiver must achieve a sufficiently high angular precision—by operating with a small AOA error over a broad angular field-of-view (FOV). In this work, an optical wireless receiver is implemented with a specially-engineered microlens having a small (i.e., 1°) AOA error over a broad (i.e., 120°) angular FOV. Second, the fixed optical wireless transmitters (i.e., optical beacons) must be distributed in a geometry that achieves a sufficiently low and uniform geometric dilution of precision (DOP) distribution. In this work, various forms of triangle, square, and hexagon optical beacon geometries are investigated to establish the desired low and uniform geometric DOP distribution. The developed optical wireless receiver and optical beacon geometries are implemented together, with frequency and wavelength multiplexing being used for signal discrimination, and it is found that especially small positioning errors can be achieved. These findings can lay the groundwork for high-precision indoor positioning in future OWL systems.
9754-10, Session 3

Smart slit assembly for high-resolution spectrometers in space

Benedikt J. Guldimann, Kyriaki Minoglou, European Space Research and Technology Ctr. (Netherlands)

This paper introduces a novel imaging spectrometer subsystem design, the Smart Slit Assembly (SSA) that improves space instrument performances and enables new features for future Earth Observation and Astronomy. Derived from CarbonSat requirements, a design of a SSA based on MEMS micro-shutters/mirrors and an associated space instrument concept is presented.

The SSA replaces the classical grating spectrometer slit aperture in the focal plane of the telescope with three core elements, namely an input multimode waveguide array followed by a spatial light modulator (SLM) and an output multimode waveguide array which ends at the slit aperture viewed by the spectrometer. The SLM’s in-and-outputs being coupled to waveguide arrays leads to an enhanced SLM with light de-coherence, polarization scrambling and scene/object homogenization capabilities. The additional advantage of this subsystem’s arrangement is that waveguide level homogeneous spatial light modulation can be achieved with spatially in-homogeneous coupling from in to output multimode waveguides, allowing new, simpler and less costly designs for the SLM part of the SSA.

The SSA is particularly useful for instance to (1) reduce straylight by scene/object selection or modulation (e.g. de-clouding, intensity equalization), (2) relax on the required dynamic range of the detectors, (3) increase spectral stability by waveguide level intensity homogenization/scrambling, (4) continuous in-flight monitoring of the co-registration between two or several spectrometer channels and (5) reduce polarisation sensitivity of the spectrometer(s). This extensive list of valuable functions shows that the SSA has the potential to change the way remote sensing instruments will be designed in future.

9754-11, Session 3

Linear rotary optical delay lines

Hang Qu, Hichem Guerboukha, Maksim Skorobogativi, Ecole Polytechnique de Montréal (Canada)

We present several classes of analytical and semi-analytical solutions for the design of high-speed rotary optical delay lines that use a combination of stationary and rotating curvilinear reflectors. Detailed analysis of four distinct classes of optical delay lines is presented. Particularly, we consider delay lines based on a single rotating reflector, a single rotating reflector and a single stationary reflector, two rotating reflectors, and two rotating reflectors and a single stationary reflector. We demonstrate that in each of these cases it is possible to design an infinite variety of the optical delay lines featuring linear dependence of the optical delay on the rotation angle. This is achieved via shape optimization of the rotating and stationary reflector surfaces. Moreover, in the case of two rotating reflectors, a convenient spatial separation of the incoming and outgoing beams is possible. For the sake of example, all the blades presented in this paper are chosen to fit into a circle of 10cm diameter and these delay lines feature in excess of 600ps of optical delay. Finally, two prototypes of rotary delay lines were fabricated using CNC machining, and their optical properties are characterized.

9754-12, Session 3

Coated fiber tips for optical instrumentation

John B. Barton, Sheetal Chanda, Sarah A. Locknar, Gary E. Carver, Omega Optical, Inc. (United States)

Compact optical systems can be fabricated by integrating coatings on fiber tips. Examples include fiber lasers, fiber interferometers, fiber Raman probes, fiber based spectrometers, and anti-reflected endoscopes. These interference filters are applied to exposed tips – either connectorized or cleaved. Coatings can also be immersed within glass by depositing on one tip and connecting to another uncoated tip. Angles of incidence at the coatings, related to various modes in a fiber, must be considered when designing applications. Our labs have shipped coated fiber tips for many of these applications. As an example, this paper addresses a fiber spectrometer for multispectral imaging - useful in biomedical scanning, flow cytometry, and remote sensing. Typically, strong signals and/or long integration times allow pixel arrays and gratings to provide quality images in many color bands. Our spectrometer uses serial arrays of reflecting fiber tips, delay lines between these elements, and a single element detector. This approach merges fast spectroscopy with standard spatial scanning to create datacubes of weak signals in real time. Each spectrum is acquired in a few microseconds. These attributes are critical during real-time applications such as in-vivo imaging. Techniques for fabricating these coated fiber tip arrays are described, including e-beam evaporation while monitoring reflectance from the tips during deposition. A bank of pulsed LEDs is used to compare the reflectance of freshly fabricated tips with a known reference tip. Good agreement is observed between measured and modeled performance. The spectral band count, spacing, and width are adaptable to a given application.

9754-13, Session 3

Fast and accurate read-out of interferometric optical fiber sensors

Dag R. Hjelme, Høgskolen i Sor-Trondelag (Norway); Ingebrigt Bartholsen, Norwegian Univ. of Science and Technology (Norway)

Optical fiber biosensors based on interferometric measurement of dimensional change in stimuli-responsive hydrogel immobilized on optical fiber end-face is an emerging sensor technology platform with many applications. Read-out of such sensors requires fast and accurate phase and frequency estimators to transform the interferometric signal to length and length changes. While frequency estimation techniques for single tone sinusoidal signals are widely available, the specifics of the optical fiber sensors and systems require new estimation methods to be implemented. We have earlier used full quadrature demodulation technique (QDT) and a simpler and faster frequency estimator based on the discrete Fourier transform. In this paper we present and evaluate an iterative (IQDT) algorithm that meets the requirement for accuracy and computation time. We evaluate the algorithm using a read-out instrument based on an 850 nm superluminescent light emitting diode (SLED) and a fiber coupled granting spectrometer interrogating micro Fabry-Perot (FP) sensors made of a semi-spherical stimuli-responsive hydrogel on a single mode fiber end face. The effective FP cavity length varied from 49 to 61 µm.

The results show that the IQDT algorithm can be implemented on a 32-bit microcontroller unit (MCU). With SLED bandwidth of 80 nm the IQDT frequency estimate calculates cavity length with a <0.2 % error( ±50 nm), while the IQDT phase estimate tracks changes in cavity length with a <0.013 % error( ±3 nm). The computation time for the IQDT algorithm is reduced by a factor 1000 compared to the full QDT for the same accuracy requirement.

9754-14, Session 4

Optical fiber oxygen sensor using layer-by-layer stacked porous composite membranes

Sayuri Ban, Ai Hosoki, Michiko Nishiyama, Atsushi Seki, Kazuhiro Watanabe, Soka Univ. (Japan)
Optical fiber oxygen sensors have attractive attentions such as no oxygen consume, thin size, light weight, flexibility, and immunity to electromagnetic interference. Ruthenium (Ru) complexes are known as luminescent materials whose luminescent light is quenched depending on oxygen concentrations when concentrations of Ru complexes are fixed. They emit phosphorescence with the wavelength of around 600 nm as exited light with the wavelength of 450 nm is irradiated into Ru complexes. As a result, phosphorescence is quenched depending on oxygen concentrations. Conventional optical fiber oxygen sensors have employed large core-diameter such as 1000 µm in order to obtain quenching abundantly, hence they have large transmission loss. Therefore, they have little practicability in the case of remote monitoring system, for example underwater explorations.

In this paper, we have successfully developed a novel optical fiber oxygen sensor with transmission Gl multi-mode fiber whose core diameter is 62.5 µm and cladding diameter is 125 µm. The sensing portion was fabricated on an end of the fiber with porous composite membranes which is made by glass beads and polyallylamine in layer-by-layer technique. The composite membranes immobilized Ru complexes. In experiments, in order to investigate characteristics of the number of layers for porous composite membranes, we tested several kinds of sensors having such as 5, 50 and 125 layers and confirmed phosphorescent intensity and change of phosphorescence against existence of oxygen. As a result, 5-layer and 50-layer sensors showed best sensitivity and reproducibility.

9754-15, Session 4

**Characterizing opto-electret based paper speakers by using a real-time projection Moiré metrology system**

Ya-Ling Chang, Kuan Yu Hsu, Chih-Kung Lee, National Taiwan Univ. (Taiwan)

Advancement of distributed piezo-electret sensors and actuators facilitates various smart systems development, which include paper speakers, opto-piezo/electret bio-chips, etc. The array-based loudspeaker system possess several advantages over conventional coil speakers, such as light-weightness, flexibility, low power consumption, directivity, etc. With the understanding that the performance of the large-area piezo-electret loudspeakers or even the microfluidic biochip transport behavior could be tailored by changing their dynamic behaviors, a full-field real-time high-resolution non-contact metrology system was developed. In this paper, influence of the resonance modes and the transient vibrations of an array-based loudspeaker system on the acoustic effect were measured by using a real-time electronic speckle pattern interferometer (ESPI) and microphones.

Trying to facilitate the dynamic measurement, Fourier spectrum of interference fringe obtained with pre-introduced spatial carrier frequency to distinguish the correct direction of object deformation was adopted. Retrieve the phase map from a single intensity map not only saves valuable computation time but also provides us with a platform for dynamic measurement as high-speed camera can be used to record the time-varying interference fringes first and then compute phase map after the deformation is introduced. To handle problems with domains mixed with vastly different signal-to-noise ratios interference fringes, windowed Fourier transform was also introduced. For phase unwrapping, least-squares method that leads to the use of Fourier transform to solve a Poisson’s equation with Neumann boundary conditions was implemented. The system performance of the newly developed real-time ESPPI and the piezo-electret paper speakers were cross-examined and verified by the experimental results obtained.

9754-16, Session 4

**Measurement of surface topographies in the nm-range for power chip technologies by a modified low-coherence interferometer**

Christopher Taudt, Tobias Baselt, Westsächsische Hochschule Zwickau (Germany) and TU Dresden (Germany) and Fraunhofer IWS Dresden (Germany); Bryan Nelsen, Westsächsische Hochschule Zwickau (Germany); Heiko Assmann, Infineon Dresden GmbH (Germany); Andreas Greiner, Infineon Technologies Dresden (Germany); Edmund Koch, TU Dresden (Germany); Peter Hartmann, Westsächsische Hochschule Zwickau (Germany) and Fraunhofer IWS Dresden (Germany)

Modern manufacturing technologies for power chip technologies, MEMS and thin-film processing set high demands regarding quality, precision and reliability. Especially the manufacturing of new, complex power semiconductor technologies requires production integrated, fast and precise measurement tools to ensure quality and function of these chips. Appropriate surface topography measurement technologies, especially for the control of critical dimensions, should therefore deliver nm-accuracy in the axial dimension while enabling a rather larger, µm-sized, measurement range along the sample’s surface.

This works introduces a modified low-coherence interferometry approach with tuneable resolution and measurement range. The key component of the interferometer is an element with known dispersion. This dispersive element delivers a controlled phase variation which can be detected in the spectral domain. A sample with a given height profile introduces a set of corresponding path-length-differences to the setup. Due to the known dispersion characteristics, it becomes possible to calculate the surface profile with nm-precision from the phase-varied spectral data. In the chosen setup, both axial resolution and measurement range are tuneable by the choice of the dispersive element. The basic working principle was demonstrated by a laboratory setup equipped with a broadband laser-driven plasma light source (200 - 1100 nm). Initial experiments were carried out on height steps of 100 nm. The analysed data showed that a resolution of 10 nm was possible. Furthermore, experiments to profile the surface of a wafer on the wafer’s edge were carried out. The data collected in this experiment was compared with measurements from a confocal laser scanning microscope. The main advantage of the proposed measurement approach is the possibility to collect data without the need for mechanical moving parts.

9754-17, Session 4

**Low-cost miniature spectrometer using mold plastic with air cavities**

Yu Wang, AMS-TAOS USA Inc. (United States)

A technology of low-cost miniature spectrometer using mold plastic with air cavities is reported. This technology uses one piece of plastic to replace whole system of traditional prism spectrometers. A typical traditional prism spectrometer usually has three major elements: a collimation lens, a prism and a focus lens. In our technology of “Low cost spectrometer using plastic and air cavities”, we use a single piece of plastic with three air cavities, where the first air cavity functions as a collimation lens to collimate the incident light from a thin slit, then the second air cavity functions as a dispersion prism to separate wavelengths from the incident light, and the third air cavity functions as a focus lens to focus separated wavelength to a linear detector. A prototype spectrometer has been built and tested.
9754-18, Session 4

Innovative fiber-laser-architecture-based compact wind lidar
Narasimha S. Prasad, NASA Langley Research Ctr. (United States); Steve Vetrovino, Allen Tracy, Rich Higgins, Russ Sibell, Sibelloptics, LLC (United States)

This paper describes an innovative, compact and eyesafe coherent lidar system developed for use in wind and wake vortex sensing applications. Based on an all-fiber and modular architecture, this advanced lidar system is configured to be compact and field ruggedized with reduced size, weight, and power consumption (SWaP). The all-fiber architecture is built upon fiber seed laser that is coupled to uniquely configured fiber amplifier modules and associated photonic elements including an integrated 3D scanner. The scanner provides user programmable continuous 360 degree azimuth and 180 degree elevation scan angles. As such, the system architecture eliminates free-space beam alignment issues and allows plug and play operation using graphical user interface software modules. Besides its all fiber architecture, the lidar system also provides pulselength agility to aid in improving range resolution. Operating at 1.54 microns and with a PRF of up to 20 KHz, the lidar is air cooled with overall dimensions of 30” x 46” x60” and is designed as a Class 1 system. The lidar is capable of measuring wind velocities greater than 120 +/- 0.2 m/s over ranges greater than 10 km and with a range resolution of less than 15 m. This compact and modular system is anticipated to provide mobility, reliability, and ease of field deployment for wind and wake vortex measurements. This lidar architecture is amenable for trace gas sensing and as such it is being evolved for airborne and space-based platforms.

In this paper, the key features of wind lidar instrumentation and its functionality will be discussed followed by results of recent wind measurements carried out near Boulder, Colorado.

9754-19, Session 4

A device based on the Shack-Hartmann wavefront sensor for testing wide aperture optics
Alexander N. Nikitin, Julia V. Sheldakova, Alexis V. Kudryashov, Active Optics Night N Ltd. (Russian Federation); Gilles Borsoni, AKA Optics SAS (France); Dmitrii Denisov, Valerii Karasik, Alexey Sakharov, Bauman Moscow State Technical Univ. (Russian Federation)

A device based on the SHWFS is considered for testing flat and spherical wide aperture optical components. The device is compared to traditional optical testing techniques. Its advantages and drawbacks are presented.

9754-37, Poster Session

Prototype of VNIR/SWIR hyperspectral imager based on curved prism
Yueming Wang, Shanghai Institute of Technical Physics (China)

VNIR/SWIR hyperspectral imager is a promising technology for earth observation. Up to now, most of hyperspectral imagers consist of two spectrometers, one for VNIR spectral range, and the other for SWIR detection. The detectors of the two spectrometers are Si-CCD and MCT FPA, respectively. However, the two spectrometer system suffers mis-registration. In many applications, mis-registration is unacceptable. Thanks for the technology of substrate-removed MCT, which enable MCT FPA responsive from 400nm to 2500nm. This paper will present the design, fabrication, integration and measurement of a prototype of VNIR/SWIR hyperspectral imager. The system is consist of TMA telescope, slit, VNIR/SWIR imaging spectrometer based on single curved prism, substrate-removed MCT FPA and electronics.

Advantage and disadvantage of the technology will be analyzed and presented. It is the biggest advantage that the system can acquire well-registered hyperspectral imagery. It is very important to real-time target detection because less computation is needed. Its transmission efficiency is higher than JPL’s multi-blazed convex grating. Volume and weight are larger and non-linear dispersion is its disadvantage.

9754-38, Poster Session

High temperature monitoring of an oxy-fuel fluidized bed combustor using femtosecond infrared laser written fiber Bragg gratings
Robert B. Walker, Huimin Ding, David Coulas, Dan Grobnic, Ping Lu, Stephen J. Mihailov, National Research Council Canada (Canada); Marc A. Duchesne, Robin W. Hughes, David J. McCalden, Ryan Burchat, Natural Resources Canada (Canada); Robert Yandon, Natural Resources Canada, CanmetENERGY (Canada).

Femtosecond Infrared (fs-IR) written fiber Bragg gratings (FBGs), have demonstrated great potential for sensing in extreme environments. This paper presents the fabrication and deployment of several fs-IR written FBG arrays, for monitoring the temperature distribution within a fluidized bed combustor.

Harsh environments are inherent to the advanced power plant technologies under development to reduce greenhouse gas emissions. The performance of new power systems are currently limited by the lack of sensors and controls capable of withstanding the high temperature, pressure and corrosive conditions present. With minimum emissions and maximum efficiency being two of the primary design criteria, sensors that can survive the rigors of such environments are seen as a goldmine of useful information.

Oxy-fuel fluidized bed combustion is a clean energy technology that can utilize a variety of fuels for producing steam and electrical power with zero emissions. It is now demonstrated at the 30 MWth scale and is available for deployment at the 330 MWe scale. National Resources Canada CanmetENERGY is currently developing a pressurized variant of this technology using under bed fines feeding requiring detailed, transient, thermal gradient data in the combustor and at the surface of boiler tubes.

Results of this work include: wavelength shift calibration data to ~1100°C, discussion of deployment strategies, comparison of different grating types, contrast of real-time FBG measurements with thermocouple data, as well as comments on reliability and other important considerations.

9754-39, Poster Session

Challenges of demonstrating quantum entanglement on board sounding rockets
Patrick Wade, Ctr. for Quantum Technologies (Singapore)

The Centre for Quantum Technologies will demonstrate the Small Photon Entangling Quantum System onboard a TEXUS sounding rocket by breaching the von Karman line. This marks a milestone for demonstration of entanglement correlations in space. For this demonstration to take place thermal management is a significant challenge – ambient conditions within a small payload space can reach 35 C while the structure of the rocket can reach 140 C during flight. Above 10 km convection is removed as an option for heat transfer. This paper discusses the thermal analysis of the experiment and different approaches to maintaining the experiment within its operating range. Data from the sounding rocket test is also presented.
9754-40, Poster Session

**Long-term measurements of SPR hydrogen sensor based on hetero-core optical fiber with Au/Ta2O5/Pd/Au multilayers**

Ken Takahashi, Ai Hosoki, Michiko Nishiyama, Soka Univ. (Japan); Hirotaka Igawa, Japan Aerospace Exploration Agency (Japan); Kazuhiro Watanabe, Soka Univ. (Japan)

Demands for using hydrogen have been increased due to usages as ecological and alternative energy resource. On the other hand, hydrogen easily causes an explosion above concentrations of 4 % in air and hence hydrogen sensors need rapidity and accuracy for detecting hydrogen. Conventional hydrogen sensors have mainly used palladium (Pd) which is known as a hydrogen detecting material with high sensitivities and selectivity to hydrogen. Generally, Pd largely absorbs hydrogen and forms Pd hydride, moreover, Pd experiences phase transition during which volume changes of Pd occur. As a result, these volume changes induce a deterioration which affects time responses and sensitivities of hydrogen sensors. To improve the deterioration, alloying Pd with other metals such as Au and Ag, has been utilized as preventing Pd from experiencing phase transition.

In this paper, we propose a long-term measurable hetero-core optical fiber hydrogen sensor based on surface plasmon resonance (SPR) with multilayers of Au/Ta2O5/Pd/Au in order to suppress the deterioration of Pd. Owing to confirm sensors' deterioration, several sensors were prepared with fixed thicknesses of 25-nm Au/60-nm Ta2O5/with stacks of annealed double layers of 1.4-nm Pd and 0.6-nm Au or 5-nm pure Pd, and compared in terms of the time response and sensitivities. Response times at the 1st and the 15th cycle were experimentally observed to be from 3 s to 6 s for annealed Pd-Au, in contrast, to be from about 16 s to 22 s for pure Pd at 4 % hydrogen concentration, respectively.

9754-41, Poster Session

**Temperature-stable LED-based light source without temperature control**

Marko Bosiljevac, Dubravko I. Babic, Univ. of Zagreb (Croatia); Zvonimir Sipus, Faculty of Electrical Engineering and Computing (Croatia)

We propose and demonstrate an optical system for stabilization of light-emitting diodes over temperature exhibiting output power variation below 50 ppm/C. Light-source output stabilization over temperature and time is ubiquitous in light-emitting components used in sensor and communication applications. The output control in such systems relies on a feedback control loop in which a fraction of the emitted light is fed back to a current-controlling amplifier to adjust for any changes in the output. In order to achieve a high degree of stability a specially-designed weakly-polarizing interference filter is inserted in the feedback loop and the polarization of the feedback light is resolved to provide a correction over temperature. The control is realized using analog electronics and the stability of the source is adjusted at manufacturing time.

Many medical, environmental, and industrial sensing applications could take advantage of uncooled temperature-stable optical sources that are incoherent and un-polarized as such sources do not produce interference fringes, speckle patterns, or intensity variations due to polarization. Our design does not use any temperature control and hence consumes less power than conventional temperature controlled sources. This makes it especially suitable for handheld and battery operated instruments. The demonstrated optical stabilization system does not employ a thermometer and can be implemented with lasers as well.

9754-42, Poster Session

**SFFT based phase demodulation for faster interference fringes analysis**

Chen-Yu Lee, National Taiwan Univ. (Taiwan)

Try to take advantages of the high-resolution CCD/CMOS developed over the years for real-time three-dimensional deformation/geometry metrology system development, Fourier transform (FT) based algorithms have been integrated to convert interference fringes to wrapped phase maps and then to unwrapped phase maps. All of which led to easy implementation of the algorithms developed over the years to achieve extremely efficient FT computation. Sparse Fast Fourier Transform (SFFT), particularly the one-time SFFT that includes multiple calculations of imaginary part, log, and phase difference in frequency domain, was implemented to further accelerate the computation time for the above-mentioned FT based operations.

Coupling the SFFT accelerated phase map computation approach with Michelson interferometer and Electronic Speckle Pattern Interferometer for near real-time three-dimensional deformation measurement led to the newly developed system. The direction of object deformation are revealed by performing FT to the interference fringes obtained with pre-introduced spatial carrier frequency, which provides a way to retrieve the phase maps by using a single rather than several intensity maps. With only one image frame needed, the interference fringes caused by the deformation could be recorded for off-line phase maps computation if the computation efforts are longer than the recording frame rate. To handle regions with vastly different signal-to-noise ratios, windowed FT was introduced. For phase unwrapping, least-squares method that leads to the use of Fourier transform to solve a Poisson's equation with Neumann boundary conditions was implemented. The benefit of using SFFT as compared to FT was demonstrated.

9754-44, Poster Session

**A pseudo optical frequency comb interferometry by an optical resonator and a high-speed swept-source for 2D single-shot tomography and profilometry**

Tuan Q. Banh, Saitama Univ. (Japan) and SevenSix, Inc. (Japan); Tatsutoshi Shioda, Saitama Univ. (Japan)

In the previous report, we demonstrated the 2D, long-range and single-shot tomography and profilometry using optical frequency comb interferometry combined with the spatial phase modulator and the CCD. The expanded measurement range was proportional to the finesse of the optical resonator. However, the total optical power of the optical frequency comb, which was generated by the broadband light source and the optical resonator, was relatively weak owing to the losses of the resonator. This reason causes the S/N ratio of the interference images was low for those samples that scattered or absorbed the lights. In this report, we propose an effective way to create optical frequency comb light source for our developed single-shot imaging system. A 4-kHz repetition swept-source with 1300 nm gain element is combined with 200 GHz FSR optical resonator. High-speed and discrete frequency-scanning laser with 200 GHz space is generated when the wavelength of the swept-source is scanned. The developed imaging system employs a CCD camera whose integration time is slower than the scan-rate of the swept-source so that the discrete frequency-scanning laser is acting as the pseudo optical frequency comb light source for our single-shot, long-range imaging system. A measurement of a 100 um step-height sample was taken as the evaluation the effectiveness of the pseudo optical frequency comb for the 2D single-shot tomography and profilometry.
9754-45, Poster Session

**Fiber Bragg grating based tunable sensitivity goniometer**

Srivani Padma, Umesh Sharath, Shweta Pant, Talabattula Srinivas, S. Asokan, Indian Institute of Science (India)

Goniometer has found extensive usage in diverse applications, primarily being medical field in which it is employed for obtaining the range of motion of joints during physical therapy. It is imperative to have a dynamic system to measure the range of motion which will aid for a progressive therapeutic treatment. Hence in the present study, a novel goniometer for real-time dynamic angle measurement between two surfaces with the aid of a Fiber Bragg Grating sensor is proposed. The angular rotation between the two surfaces will be identified by the two arms of the Fiber Bragg Grating Goniometer (FBGG), which is translated to the rotation of the shaft which holds these arms together. A cantilever beam is fixed onto the base plate whose free end is connected to the rotating shaft. The rotating shaft will actuate a mechanism which will pull the free end of the cantilever resulting in strain variation over the cantilever beam. The strain variation on the cantilever beam is measured by the Fiber Bragg Grating sensor bonded over it. Further, the proposed FBGG facilitates tunable sensitivity by the discs of varying diameters on the rotating shaft. Tunable sensitivity of the FBGG is realised by the movement of these discs by varying circumferential arc lengths for the same angular movement, which will actuate the pull on the cantilever beam. As per the requirement of the application in terms of resolution and range of angular measurement, individual mode of sensitivity may be selected.

9754-46, Poster Session

**Development of SPR temperature sensor using Au/TiO2 on hetero-core optical fiber**

Sho Kitagawa, Hiroshi Yamazaki, Ai Hosoki, Michiko Nishiyama, Kazuhiro Watanabe, Soka Univ. (Japan)

This paper describes a novel temperature sensor based on hetero-core structured surface plasmon resonance (SPR) fiber optic sensor with multilayer films of gold (Au) and titanium dioxide (TiO2) coated. Temperature condition is well known as an essential parameter in chemical plants for controlling production, quality and safety. There are several fiber optic temperature sensors developed for some advantages over conventional electrical sensors, such as immunity to electromagnetic interference, resistance to corrosion and lack of electrical contact. In this work, a hetero-core fiber optic SPR sensor is proposed for temperature measurement by means of measuring the slight refractive index change of TiO2 having a large thermo-optic coefficient. As a preliminary step, temperature characteristics of a hetero-core SPR sensor with an Au thin film coating was verified by comparing an experiment to theoretical calculations in different temperature conditions. As a result, it was found that a SPR resonant wavelength is hardly affected by a temperature property of the sensor, which implies that the proposed sensor may directly monitor the thermo-optic effect of TiO2. A SPR resonant wavelength of the proposed sensor responded to temperature was verified by a theoretical calculation and an experiment in the temperature conditions of -10 and 50 degrees. It was confirmed that the resonant wavelength is shifted by 1.8 nm. Moreover, the measured resonant wavelength was also shifted as much as that of theoretical results. Therefore, it is successfully concluded that the proposed sensor detect temperature directly depending on thermo-optic effect of TiO2.

9754-47, Poster Session

**Ellipsometry-like analysis of polarization state for micro cracks using stress-induced light scattering method**

Yoshitaro Sakata, Kazufumi Sakai, Kazuhiro Nonaka, Nao Terasaki, National Institute of Advanced Industrial Science and Technology (Japan)

Fine polishing techniques, e.g. the chemical mechanical polishing (CMP), are very important part of the manufacturing process for liquid crystal panel glass substrate. These techniques have mechanical interactions and these interactions, e.g. friction, occur between the abrasive and the substrate surface during polishing, which may cause formation of micro cracks on these products. In the glass substrate manufacturing, fine polishing-induced micro cracks may become obvious during a subsequent cleaning process if glass surfaces are eroded away by chemical interaction with the cleaning liquid. In general, non-destructive inspection techniques, e.g. the light-scattering technique, used to detect foreign matters on the glass substrate surface. However, it is difficult to detect micro cracks by these methods because the flaws remain closed under the surface. The presented authors propose a novel inspection technique for fine polishing-induced micro cracks by combining the light scattering method with stress effects (the stress-induced light scattering method; SILSM). SILSM can distinguish between micro cracks and tiny particles on the surface. The authors’ previous research reported SILSM can detect micro cracks under the surface of a fine polished glass substrate selectively. However, detail evaluation that change in the stress concentration provides effect to the crack tip of the micro crack is not carried out. In this study, SILSM applying to the fine polished glass substrate, change in the reflection coefficients and the polarization states at the crack tips between before and after applied stress are calculated and evaluated ellipsometry like using Jones matrix.

9754-48, Poster Session

**The authenticity in art: analysis of the optical characteristics of paintings**

Seonhee Hwang, Eunhee Kim, Kyujung Kim, Pusan National Univ. (Korea, Republic of)

We have recently studied a novel method of analysis to measure the characteristics of painting by using the optics, for the first time, so the method is non-destructive and non-invasive. The oil paintings have been painted a variety of colors over and over the drawing. A variety of colors on the surface have been measured by the white light and detector and presented three kinds of spectrum by colors. The surface of painting is rough and uneven, so its roughness has been detected by the line laser and CCD camera. The results of experiment could be used to build database of the original paintings, and it indicates that the data of original have the unique characteristics. Thus, the results of forgery are observed very different compared to the original. The database also could be used to restore the damaged works of art.

9754-50, Poster Session

**Remote sensing solutions of oil and gas exploration by hyperspectral Raman lidar**

Alexsandr S. Grishkanich, Valentiii Elizarov, Sergey Kascheev, Aleksandr Zhevlakov, ITMO Univ. (Russian Federation); Igor Sidorov, Univ. of Eastern Finland (Finland); Aleksandr I’linskii, All Russian Petroleum Research Exploration Institute (Russian Federation); Dmitriy Kosachiov, Gazprom (Russian Federation); Igor
Remote sensing field is seen as an active growth area for international community. With the future of remote sensing in mind, the objective of the project will be to extend the hyperspectral data analysis methods that have been developed to study variability information extraction. With developed image processing approaches, they will use to understand what new information can be obtained from hyperspectral data.

Ultra spectral resolution can be achieved by using a dual photomultiplier based on large-stigmatic holographic gratings. The tests were conducted in real flight conditions on a transcontinental gas pipeline. He performed aerial leak detection and measurement of a gas leak. The sensitivity and ultra-spectral resolution of the technique make it possible to differentiate lines of methane (283.31 and 284.42 nm), nitrogen (278.69 nm), and hydrogen sulfide (280.89 nm). In particular, with a wavelength difference of 4.62 nm between the CH4 and N2 molecules, the linear distance in the photomultiplier was 20.6 mm, that allowed to reliably separate the spectral lines.

The methane leaks were detected and the spatial distribution of methane concentrations in the zone of the local leaks was obtained in the test flight (100 to 450 m height) over the actual track of a gas pipeline. Unlike Raman spectroscopy, CARS employs multiple photons to address the molecular vibrations, and produces a signal in which the emitted waves are mutually coherent. As a result, CARS is orders of magnitude more effective than spectroscopy based on spontaneous Raman emission, and allows to measure the concentration level up to 100 ppb and to determine hydrocarbons in natural atmospheric conditions.

High-power quantum cascade lasers and their use in intracavity nonlinear generation (Invited Paper)

We will present our results on high power mid-IR generation from single-emitter QCL devices. Besides their use as high power sources, the large nonlinearity associated with the intersubband transitions of QC devices and the multi-stage engineering of the band structure makes QCLs a perfect tool for building multi-functional devices. The high power of the mid-IR generation, associated with the resonances built-in by design into the active material, allow for room temperature generation of multiple wavelengths, including frequency doubling to the lambda<3um range and difference frequency generation into the THz region of the spectrum.

In this talk we will review our most important high power mid-IR results across the mid and long-wave infrared (MWIR and LWIR) regions and show how they can be applied to the room temperature generation of light at frequencies otherwise unattainable by a standard direct-generation QCL design.

Stabilization of two frequency combs with a small relative fceo jitter using diode laser injection locking

We report a novel stabilization method for two frequency combs with a smaller relative fceo jitter using a selected single optical mode out of one frequency comb. The intention is to stabilize two frequency combs tighter so as to enhance the measurement performance of dual-comb-based spectroscopic, ranging, and bio-imaging systems. For the purpose, a single optical mode is selected out of one frequency comb by using a composite optical filtering and subsequent diode laser injection locking technique. The selected optical frequency yields a narrow relative linewidth less than 2.38 mHz and the frequency stability of 1.58×10^-17 at 10 s averaging time. By making interference between the selected single comb mode and the other frequency comb, a heterodyne beat signal is generated, which provides the relative frequency jitter information with a high resolution. With the aid of phase-locked-loop, the relative frequency jitter between two combs is well stabilized down to 1.52×10^-16 at 10 s averaging time, which is one order of magnitude better than the case with f-2f interferometers. This high relative stability between two frequency combs will improve the measurement performances of dual-comb-based precision metrology.
9754-24, Session 6
Structured illumination employing coherent radiation (Invited Paper)
Yakov G. Soskind, DHPC Technologies (United States); Michael Soskind, Rose Soskind, Rutgers, The State Univ. of New Jersey (United States)

Structured illumination plays an important role in several photonic applications, including non-contact 3D metrology, gesture recognition, autonomous navigation, and miniaturized projection systems for near-to-eye display and augmentation of the observer’s surrounding. Structured illumination patterns are traditionally produced in the form of regular or randomized patterns in the far field. By employing coherent radiation to produce structured illumination, some limitations of the traditional techniques are eliminated. The coherent radiation techniques can increase the spatial extent of the produced structured patterns. They also can result in a dynamic and efficient way of generating a variety of spatial structured patterns that will not require moving parts. The described techniques exploit coherent properties of laser radiation, and the produced patterns can be dynamically altered by adjusting the optical path delays within the propagating field.

9754-25, Session 6
High-speed universal polarization state generator
Alan She, Federico Capasso, Harvard Univ. (United States)

We have developed a general approach for polarization state generation (PSG) using only the control of the optical intensity of four spatially-separated polarization components. PSG is achieved by modulating four spatially-separated polarization components of an input laser beam in an analog or digital fashion to generate a laser beam with arbitrary state of polarization (SOP). Current methods of polarization state generation often rely on the addition of control systems to compensate for the lack of stability and repeatability of generated polarization states due to the use of moving parts, such as rotating wave plates or bending fibers. The approach here aims to improve speed and stability, while enabling compact and robust form in future device applications. The method described here allows for the theoretical limits on performance, such as speed and stability, of PSG to be completely dictated by the current level of technology of optical intensity modulation and hence decouples this endeavor from other previously dependent technologies such as control of optical path length, indices of refraction, birefringence, etc., opening up exciting prospects for polarization generation at extremely fast speeds and the ability to explore new wavelength regimes. Measurements of the performance of this approach, such as SOP settling time, SOP accuracy, degree of polarization accuracy, etc., are compared to the advertised specifications of existing commercial technologies. Polarization state generation has found applications in optics, telecommunications, and other areas of science.

9754-26, Session 6
Low-spatial-coherence broadband fiber source for speckle free imaging
Brandon Redding, Yale Univ. (United States); Peyman Ahmadi, Vadim Mokan, Martin F. Seifert, Nufenn (United States); Michael A. Choma M.D., Hui Cao, Yale Univ. (United States)

Amplified spontaneous emission (ASE) has been widely utilized to achieve broadband emission with high brightness. Unlike a lamp or a light emitting diode (LED), ASE sources typically possess high spatial coherence and high power per mode, which is advantageous in applications such as spectroscopy, optical sensing, and optical coherence tomography. However, the high spatial coherence of existing ASE sources has precluded their use in full-field imaging applications, where spatial coherence introduces artifacts such as speckle. The commonly used low spatial coherence sources such as lamps and LEDs do not provide the required power per mode for high speed, full-field imaging applications. Here, we present a novel fiber-based ASE source that combines low temporal and low spatial coherence, similar to an LED, with the high power per spatial mode associated with a laser. ASE is achieved by optical pumping of a multimode fiber with an extra-large mode area gain core while minimizing feedback to avoid lasing. The fiber ASE source provides 270mW of CW emission centered at the wavelength of 1055 nm with 74 nm 3dB bandwidth (full width at half maximum). The emission is distributed among as many as 70 spatial modes, enabling efficient speckle suppression when combined with spectral compounding. We also demonstrate speckle-free full field imaging using the fiber ASE source. By providing broadband, speckle free emission with 40dB higher power per mode than an LED, the fiber ASE source is ideally suited for high-speed, full-field imaging and coherent ranging applications.

9754-27, Session 6
Compact high-performance metasurface polarimeter
Jan Philipp Balthasar Mueller, Harvard Univ. (United States); Kristjan Leosson, Univ. of Iceland (Iceland); Federico Capasso, Harvard Univ. (United States)

Recently, work on surface plasmon-polariton (SPP) couplers demonstrated that subwavelength metal patterns may launch SPPs unidirectionally in a direction that depends on the handedness of circularly polarized incident light. The sensitization of the scattering properties of the nanostructure to polarization helicity results from the interference of the emission of many sub-wavelength spaced optical antennas depending on their spatial configuration and the phases at which they are driven by the incident light. We adopted this general principle to engineer a 2D subwavelength antenna array that directionally scatters light into a homogenous dielectric environment, rather than to couple to SPPs. By properly configuring the polarization states that are scattered in different directions - including polarization states with opposite helicities - we achieve polarization state measurements of a signal transmitted through the array by reading out the scattered field. The antennas constituting the array, which due to its subwavelength structure can be considered a "metasurface", are deliberately inefficient to avoid perturbing the signal and allow non-destructive in-line measurements. The polarization measurements using this new type of polarimeter were carried out across C-band wavelengths and show excellent agreement with measurements using a commercial, state of the art polarimeter.

9754-28, Session 7
Frequency-domain single-shot optical frequency comb tomography using VIPA
Takumi Miyaoaka, Tatsutoshi Shioda, Saitama Univ. (Japan)

We propose a novel Frequency-domain optical frequency comb (OFC) interferometry applied for the single-shot tomography with a combination of a virtually imaged phased array (VIPA) and CCD. This system can take a 2-Dimensional tomographic image with a capturing speed of the CCD. The VIPA outputs the frequency different OFCs whose peak interval depends on their output angles. The OFC interferometry generates multi-fringe orders, so that the dynamic range can be expanded by use of higher OFC interference fringe order. In addition, this system enables to zoom in or zoom out the images, because the measurement range is proportional to the OFC interference fringe order. We actually measured twelve interference signals (measured range 16mm, resolution 2.6µm). The dynamic range...
As a background, high-speed and high-resolution profilometry or tomography is required to be developed for industrial applications. Traditional low-coherence interferometer or SS-OCT is a popular measurement system, providing the high-resolution. But they need a mechanical moving parts or the excess data calculation to obtain the image. On the other hand, we have proposed the time-domain 2-dimensional imaging system by installing a spatial phased modulator and a CCD into an interferometer. It could take a single-shot tomographic image with a capturing speed determined by the CCD. Advantages of proposed Frequency-domain single-shot system using VIPA are to enable to measure a single-shot image in high-resolution, high-speed, and high-energy utilization efficiency. We will present the operation principle with simulation and experimental results.

90km distributed optical fiber disturbance sensing in OFDR

Tiegen Liu, Yang Du, Zhenyang Ding, Kun Liu, Junfeng Jiang, Tianjin Univ. (China)

We present a 90km distributed disturbance optical fiber sensor (DDOFS) based on the correlation analysis of the deskew filter OFDR signals with the sensing spatial resolution of 30m. In our method, we use a deskew filter to compensate the nonlinear phase of a tunable laser source (TLS) after the data acquisition. Comparing with the external clock method, the measurement range of our presented method is no longer limited to the path difference in the auxiliary interferometer, so the measurement range can be extended to 90km. For a given fiber, the Rayleigh backscattering (RB) amplitude or reflectivity can be consider as the characteristic information. The RB signals at the same location are separately measured twice. When there is no any disturbance, two local RB signals from different measurements are very similar or identical. In contrast, when a disturbance occurs, the two local RB signals from two separate measurements are different and the “similarity” is low. We use a “non-similar level” to quantitatively evaluate the “similarity”, which is the number of data points beyond the threshold value in the cross-correlation between two local RB signals in optical frequency domain. In our experiment, two Piezoelectric transducers (PZT) fiber stretchers are added to the fiber at positions of 90.2 km and 91.31 km respectively, to serve as two independent disturbance transducers. From the experimental results, we extract the positions and intensities of two disturbance waveforms distributed “non-similar level” as a function of fiber length. The “non-similar level” is in proportional to the disturbance intensity.

Femtosecond laser fabricated multimode fiber sensors interrogated by optical-carrier-based microwave interferometry technique for distributed strain sensing

Liwei Hua, Yang Song, Jie Huang, Clemson Univ. (United States); Baokai Cheng, Clemson Univ/COMSET (United States) and Clemson Univ/COMSET (United States); Wenge Zhu, Clemson Univ/COMSET (United States); Xiao Hai, Clemson Univ. (United States)

A multimode fiber (MMF) based cascaded Fabry-Perot interferometers (FPIs) system is presented and the distributed strain sensing has been experimentally demonstrated by using such system. The proposed 13 cascaded FPIs have been formed by 14 cascaded reflectors that have been fabricated on a grade index MMF. Each reflector has been made by drawing a line on the center of the cross-section of the MMF through a femtosecond laser. The distance between any two adjacent reflectors is around 100 cm. The optical carrier based microwave interferometry (OCMI) technique has been used to interrogate the MMF based cascaded FPIs system by reading the optical interference information in the microwave domain. The location along with the shift of the interference fringe pattern for each FPI can be resolved though signal processing based on the microwave domain information. The multimode interference showed very little influence to the microwave domain signals. By using such system the strain of 10-4 for each FPI sensor and the spatial resolution of less than 5 cm for the system can be easily achieved.

Silicon plasmonic-integrated interferometer sensor

Ahmad Bassam, The American Univ. in Cairo (Egypt); Qiaoqiang Gan, Univ. at Buffalo (United States); Mohamed A. Swilliam, The American Univ. in Cairo (Egypt)

We propose a novel structure with two input and output silicon waveguide ports separated by the Insulator-Metal-Insulator channel deposited on silicon nitride base. In principle, both the top surface insulator/metal interface and bottom surface can support SPPs decoupled modes. Once the SPP modes excited input silicon waveguide, the SPP signals from the two optical branches (the top and bottom interfaces) propagate to the output silicon waveguide. At the output waveguide both branches interfere with each other and modulate the far-field scattering. The top surface is considered as the sensing arm of this plasmonic Mach Zehnder interferometer (MZI). The bottom surface is considered as the reference arm of the sensor. High sensitivity and small footprint is achieved using this integrated simple plasmonic design. The combination of sensitive interferometric techniques and the optimization process of the design and the material yields to enhanced sensitivities up to 3000 nm/RIU.

A hemispheric hetero-core fiber optic tactile sensor for texture and hardness detection

Hiroshi Yamazaki, Michiko Nishiyama, Kazuhiro Watanabe, Soka Univ. (Japan)

This paper describes a hemispherical tactile sensor based on a hetero-core optical fiber for the purpose of texture and hardness detection in a small contact area. In recent years, tactile sensing technology has been developed to discriminate tactile information as much sensitively as human tactile function. Especially, fiber optic tactile sensors have been proposed as alternative methods to conventional electrical sensors due to some advantages of immunity to electromagnetic interference and structural features of optical fibers such as lightweight, thin size, and flexibility. Moreover, hetero-core fiber optic sensors developed in our laboratory is proved to have several attractive advantages of high sensitivity to soft bending, immunity to temperature fluctuation and cost-effective scheme. The hemisphere-shaped hetero-core fiber optic tactile sensor converts the applied force into the bending curvature on a hetero-core optical fiber. To evaluate the detection performance of minute-structured rough surface, the sensor was tested for scanning on a cloth with the periodic pattern. Additionally, it was confirmed that the ability of the sensor in hardness detection enables to measure the stiffness of a thick silicone rubber which contains a hard plastic lump. It was furthermore discussed that the above abilities of the sensor can be applied for precise discrimination of such household objects as several kinds of papers with different texture and hardness.
9754-33, Session 8

Simultaneous measurement of concentration of CO and temperature using an asymmetric microfiber incorporating a microfiber knot resonator

Min-Seok Yoon, Young-Guen Han, Hanyang Univ. (Korea, Republic of)

Carbon monoxide (CO) has been considered as the “silent killer” because it is colorless, odorless, tasteless and nonirritating. Since the affinity of CO for hemoglobin is about 240 times higher than that of oxygen, CO becomes toxic when encountered in concentrations above about 35 ppm. However, the sensing accuracy of the previous CO sensor is degraded in a thermal cycle environment. To overcome this drawback, it is required to investigate the simultaneous measurement technique of the concentration of CO and temperature.

In this paper, we investigate a simultaneous measurement of the concentration of CO and temperature using an asymmetrical microfiber with Rhodium complex overlay incorporating a microfiber knot resonator (MKR). We configure the Sagnac interferometer based on the asymmetrical microfiber with Rhodium complex overlay. Since the binding between CO and Rhodium complex increases the effective index of the Rhodium complex overlay, the resonant wavelength of the Sagnac interferometer will be changed, which is proportional to the concentration of CO. The MKR only responds to temperature, it is possible to simultaneously measure the concentration of CO and temperature.

9754-34, Session 8

Relative humidity sensor based on a micro-tapered long-period fiber grating

Jong Cheol Shin, Min-Seok Yoon, Young-Geun Han, Hanyang Univ. (Korea, Republic of)

The humidity sensors are widely implemented in a variety of applications, such as air conditioning, food manufacture and civil engineering. The fiber-optic humidity sensors have many advantages, such as immunity to electromagnetic interference, good stability, and greater resistance to corrosion. Various fiber-optic humidity sensing techniques, such as a long-period fiber gratings (LPFGs), a fiber Bragg gratings, and plastic optical fibers incorporating hydrogel, polyvinyl sulfonic acid (PVS), and hydrophilic gel were proposed. However, the previous humidity sensors have many disadvantages, such as high insertion loss, low accuracy and low sensitivity to humidity. Recently LPFGs inscribed in the tapered fiber have been proposed to improve their performance as fiber-optic sensors. Since tapered fibers have high fractional evanescent fields in air, strong evanescent field coupling in tapered fiber-based LPFGs is capable of improve their sensitivity to external environment change.

In this paper, we investigate a humidity sensor based on the microtapered long-period fiber gratings (MTFGRs) incorporating polyvinyl alcohol overlay. Since absorbing humidity of the PVA overlay changes effective index of the cladding mode of the MTFGRs, the resonant wavelength of the MTFGRs is consequently changed. The reduction of the waist diameter of the MTFGRs induces the evanescent field expansion of the cladding mode resulting in the improvement of humidity sensitivity of the MTFGRs. We believe that it is possible to improve the performance of the fiber-optic humidity sensors by controlling the waist diameter of the MTFGRs.

9754-35, Session 8

Fiber-optic vibration sensor for high-power electric machines realized using 3D printing technology

Bojan Igrec, Marko Bosiljevac, Zvonimir Sipus, Dubravko I. Babic, Smiljko Rudan, Univ. of Zagreb (Croatia)

The overwhelming majority of the world’s electric power is created by turbine-driven electric generators, while almost half of the energy in the world is consumed by electric motors. Many of these motors and almost all of power generators operate continuously, uninterrupted, and are brought off-line only for planned inspections and maintenance. Monitoring of vibration amplitude or acceleration is an essential element of machine protection, performance optimization, and prolonging machine’s life. In such environments, one prefers vibration sensors that have no conductive parts (like optical sensors) due to the presence of alternating high magnetic fields and voltages.

The objective of this work was to demonstrate a lightweight and inexpensive fiber-optic vibration sensor for high-power electric machines and similar applications. The target specifications are bandwidth 10 Hz to 200 Hz and acceleration range from 0.1g to 10g. In this paper, we report on the design and demonstrate the operation of a prototype fiber-optic vibration sensor made using 3D printing technology. The working principle is based on modulating the light intensity using a blade attached to a bendable membrane. The sensor prototype was manufactured using PolyJet Matrix technology with DM 8515 Grey 35 Polymer. The sensor shows linear response, expected bandwidth (> 200 Hz), and from our measurements we estimated the damping ratio for DM 8515 Grey 35 Polymer to be $\beta = 0.019$. The developed prototype is simple to assemble, adjust, calibrate and repair.

9754-36, Session 8

New dynamic system for measuring Stokes vectors and an application for low concentration glucose sensing

Quoc-Hung Phan, Yu-Lung Lo, National Cheng Kung Univ. (Taiwan)

A new dynamic system for full Stokes vectors measurement was developed. The proposed system comprised a high accuracy polarization scanning generator (HAPSG) and a high speed polarization state analyzer (HSPSA) was proposed. The HAPSG generated full state of polarization of light by using voltage driven electro-optics modulator without using any mechanical moving parts. The HSPSA was employed to record the intensity of output polarized lights in a high speed manner. The results show that the accuracy of Stokes vectors measurement of circular polarization state of light was slightly better than those of linear polarization state of light. The accuracy of proposed system was 10-4 for all Stokes vectors (S0, S1, S2, S3) measurement in full state of polarization of lights. An application of proposed system for low concentration Glucose in aqueous solution sensing with/without scattering effects was demonstrated. The sensitivity of the optical rotation angle of CB property to changes in the concentration of glucose sample was examined over the range from 0 to 0.5g/dL. The results confirm that the proposed system detected successfully glucose at fine concentration of 0.02g/dL. The linearly variation of the optical rotation angle and different glucose concentration at different scattering effect was obtained. In general, the new dynamic measurement system proposed in this study provided a fast and reliable method to measure all Stokes vectors and its potential applications in biological sensing.
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9755-1, Session 1

Advanced EO/IR technologies at DARPA MTO (Keynote Presentation)
Jay S. Lewis, Defense Advanced Research Projects Agency (United States)

Digital imaging devices, in becoming ubiquitous consumer products, have transformed society and the way that we interact with one another. This has been enabled by pixel scaling and improvements in silicon based detectors. Advances in infrared imaging technology have been slower due to market volume and technological barriers in detector materials, optics, and fundamental limits imposed by scaling laws. This paper will highlight the results of several DARPA imaging research programs ranging from visible to LWIR. A central theme will be the immense implications that compact imaging devices have for both Defense and National Security. By shrinking the package size of each infrared imager every warfighter may eventually have the capability to see through obscurants in day or night and in all weather conditions.

9755-2, Session 1

New metrics for economic complexity: Measuring the intangible fitness of countries and complexity of products (Keynote Presentation)
Luciano Pietronero, Sapienza Univ. di Roma (Italy)

Economic Complexity refers to a new line of research which portrays economic growth as a process of evolution of ecosystems of technologies and industrial capabilities. Complex systems analysis, simulation, systems science methods, and big data capabilities offer new opportunities to empirically map technology and capability ecosystems of countries, industrial sectors and companies, analyse their structure, understand their dynamics and measure economic complexity. This approach provides a new vision of a data driven fundamental economics in a strongly connected, globalised world.

In particular here we discuss the COMTRADE dataset which provides the matrix of countries and their exported products. According to the standard economic theory the specialization of countries towards certain specific products should be optimal. The observed data show that this is not the case and that diversification is actually more important. The situation is different for companies or sectors which seem instead to specialize only on few products.

The crucial challenge is then how to turn these qualitative observations into quantitative variables. We have introduced a new metrics for the Fitness of countries and the Complexity of products which is a sort of economic version of the Google Page rank approach. The direct comparison of the Fitness with the country GDP gives an assessment of the non-expressed potential of the country. This can be used as a predictor of GDP evolution or stock index and sectors performances. These results are also useful for risk analysis, planning of industrial development and strategies to exit from the “poverty trap”. Analogously the Complexity of products can be compared with its added value leading also to new information.

This approach also leads to the new concept of Complexity of Products and to the construction of a Network of Products. From this one can obtain a variety of new information related to development, investment and innovation. We will present specific results related to the area of high tech products and in particular Photonic and Quantum Sensing.

References

9755-3, Session 1

Superfluid 3He at microkelvin temperatures: the quasiparticle spectrometer and the vortex video camera (Keynote Presentation)
George Pickett, Lancaster Univ. (United Kingdom)

Superfluid 3He is the ultimate quantum model system with a whole range of quantum and topological properties. In this presentation I will concentrate on just two; first, quasiparticle generation, detection and visualization; secondly quantum turbulence (a good laboratory model for cosmic strings). We can put the two together by constructing a spectrometer whose quasiparticle beam can image vortices in the superfluid by the Andreev reflection of the beam by the flow fields around the vortex cores. This allows us to develop the vortex video camera (only 25 pixels so far) operating at ~100 microkelvin.

9755-4, Session 1

Sensors, nano-electronics and photonics for the Army of 2030 and beyond (Keynote Presentation)
Philip Perconti, W.C. Kirkpatrick Alberts II, Jagmohan Bajaj, Jonathan Schuster, Meredith Reed, U.S. Army Research Lab. (United States)

Recent advances in sensors, nano electronics and photonics have the potential to drastically increase the capabilities of the Army of 2030. The Army of 2030 must be more agile and expeditionary and will require new capabilities to avoid technological surprise while maintaining overmatch. Quantum phenomena can enable applications and exponential increases in performance that cannot be achieved through other, classical, means. Breakthroughs in this area have demonstrated the necessity of Army participation in advancing sensing, electronics and photonics research to realize new or enhanced capabilities, such as quantum-enhanced sensors for improved situational awareness and nano electronics for reduced size, weight, and power of Soldier-worn equipment. This paper presents recent research efforts at the Army Research Laboratory and discusses capability needs for the Army of 2030 and beyond.
9755-5, Session 2

Real-time spectroscopic sensing using a widely tunable external cavity-QCL with MOEMS diffraction grating (Invited Paper)

Ralf Ostendorf, Lorenz Butscheck, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); André Merten, Jan Grahame, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); Jan P. Jarvis, Stefan Hugger, Frank Fuchs, Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

External cavity quantum cascade lasers (EC-QCL) combine high brightness and wide spectral coverage of several hundred wavenumbers in the mid infrared wavelength region. The integration of Micro-Opto-Electro-Mechanical Systems (MOEMS) based gratings as wavelength selective elements in the external cavity allows for the development of very compact and particularly fast tunable laser sources, providing wavelength scan rates in the kHz range. The high scanning frequency of MOEMS based EC-QCLs pave the way for real-time optical spectroscopic sensing systems in the fingerprint region from 5 µm to 10 µm allowing for an instantaneously identification of chemical compounds. We present spectroscopic measurements performed with an EC-QCL combining a broadly tunable quantum cascade laser chip with a tuning range of more than 300 cm-1 and a resonantly driven MOEMS scanner with an integrated diffraction grating for wavelength selection. The gratings geometry was optimized to provide high diffraction efficiency over the wide tuning range of the QCL, thus assuring high power density and high spectral resolution in the MIR range. The MOEMS scanner has a resonance frequency of 1 kHz, hence allowing for two full wavelength scans, one up and the other downwards, within 1 ms. The capability for real-time spectroscopic sensing based on MOEMS EC-QCLs is demonstrated by transmission measurements performed on polystyrene reference absorber sheets as well as on gaseous samples of carbon monoxide. For the latter one, a large portion of the CO band containing several absorption lines in the range of 2100 cm-1 to 2300 cm-1 can be monitored in real-time.

9755-6, Session 2

Detection of hydrogen peroxide based on long-path absorption spectroscopy using a CW EC-QCL (Invited Paper)

Nancy P. Sanchez, Yajun Yu, Lei Dong, Robert J. Griffin, Frank K. Tittel, Rice Univ. (United States)

Hydrogen peroxide (H2O2) is an important gas species involved in multiple atmospheric processes including the formation of sulfate aerosol in the atmospheric aqueous phase by oxidation of S (IV) to S (VI) and the production of radical species such as the hydroxyl radical. Determination of atmospheric concentration levels of H2O2 via wet-chemistry methods has been reported. Although these techniques allow detection at the ppb level, potential artifacts associated with gas to liquid-phase transfer of H2O2 and particularly fast tunable laser sources, providing wavelength scan rates in the kHz range. The high scanning frequency of MOEMS based EC-QCLs pave the way for real-time optical spectroscopic sensing systems in the fingerprint region from 5 µm to 10 µm allowing for an instantaneously identification of chemical compounds. We present spectroscopic measurements performed with an EC-QCL combining a broadly tunable quantum cascade laser chip with a tuning range of more than 300 cm-1 and a resonantly driven MOEMS scanner with an integrated diffraction grating for wavelength selection. The gratings geometry was optimized to provide high diffraction efficiency over the wide tuning range of the QCL, thus assuring high power density and high spectral resolution in the MIR range. The MOEMS scanner has a resonance frequency of 1 kHz, hence allowing for two full wavelength scans, one up and the other downwards, within 1 ms. The capability for real-time spectroscopic sensing based on MOEMS EC-QCLs is demonstrated by transmission measurements performed on polystyrene reference absorber sheets as well as on gaseous samples of carbon monoxide. For the latter one, a large portion of the CO band containing several absorption lines in the range of 2100 cm-1 to 2300 cm-1 can be monitored in real-time.

9755-7, Session 2

Demonstration of a rapidly-swept external cavity quantum cascade laser for rapid and sensitive quantification of chemical mixtures (Invited Paper)

Brian E. Brumfield, Matthew S. Taubman, Mark C. Phillips, Pacific Northwest National Lab. (United States)

Accurate and rapid quantification of chemical mixtures is important for remote and open-path sensing applications relevant to atmospheric and industrial effluent monitoring. Laser absorption spectroscopy in the mid-infrared spectral region provides the sensitivity and specificity needed for quantification of many trace chemicals. For many measurements, a broadly-tunable mid-infrared laser source with a high wavelength tuning rate and narrow spectral resolution is needed. The broad wavelength coverage is necessary to measure broadband absorption spectra from large chemicals, while a high spectral resolution enables measurement of small chemicals with narrow absorption spectra. We have developed a rapidly-swept external cavity quantum cascade laser (EC-QCL) system for open-path trace-gas sensing of chemical mixtures that provides a combination of broad wavelength coverage, high wavelength tuning rate, and high spectral resolution for rapid quantification of chemical mixtures. The EC-QCL is swept over its entire wavelength tuning range (>100 cm-1) rapidly at frequencies up to 200 Hz, providing wavelength tuning rates of 2x10^-4 cm-1/sec at a spectral resolution of < 0.2 cm-1. The ability to rapidly measure changing chemical concentrations was demonstrated for multiple chemicals and mixtures at atmospheric pressure using an open-path multi-pass cell. The high sweep rate enabled concentration measurements of multiple chemicals with both broad and narrow spectral features on millisecond timescales, with ppb to ppm detection limits depending on absorption cross-section.

9755-8, Session 2

Quantum Cascade Laser based active hyperspectral imaging for standoff detection of chemicals on surfaces (Invited Paper)

Stefan Hugger, Frank Fuchs, Jan P. Jarvis, Quankui K. Yang, Marcel Rattunde, Ralf Ostendorf, Christian Schilling, Rachid Driad, Wolfgang Bronner, Rolf Aidam, Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); Thorsten Tybussek, Klaus Rieblinger, Fraunhofer Inst. for Process Engineering and Packaging IVV (Germany)

In this contribution we report on active hyperspectral imaging in the mid-infrared (MIR) using External Cavity Quantum Cascade Lasers (EC-QCLs) developed at Fraunhofer IAF as illumination sources. This technique is employed for contactless identification of solid and liquid contaminations on surfaces. It is fully eye safe and requires no sample preparation. While the main purpose of our present system is standoff-detection of explosives, the spectroscopic approach allows the detection of any substance that exhibits a sufficiently characteristic absorbance / reflectance spectrum within the spectral range of the laser. The area of interest is illuminated by the tunable EC-QCL, and the diffusely backscattered radiation is collected by an IR camera, synchronized with the spectral tuning of the laser. Thus, a hyperspectral data cube, containing
the spatially resolved spectroscopic information of the scene, is obtained. The sensitivity of the detection system was improved by beam shaping and measures taken to reduce speckle formation. The collected data are analyzed by appropriate algorithms, capable of detecting the target substances even on substrates with a priori unknown spectrum.

Residues of explosives such as PETN or TNT on the order of 10 µg could be detected over a few meters, while quantities of some 100 µg to 1 mg are detectable over up to 20 m. In addition to explosive detection, we will show results of MiR active hyperspectral imaging on biological samples.

9755-9, Session 3

High-power single-mode multiwavelength quantum cascade lasers (Invited Paper)

Jérôme Faist, ETH Zürich (Switzerland)

Quantum cascade laser active regions can be designed to operate with very broad gain curves, recently achieving close to an octave of frequency in the mid-infrared and Terahertz. We report operation of external cavity QCLs with very broad gain curves, as well as an array of surface-emitting laser with single mode operation combined with a collection optics on a single ridge. Single mode, high power (800mW) operation of a buried heterostructure photonic crystal laser will also be discussed.

9755-10, Session 3

High-power electrically-tunable quantum cascade lasers (Invited Paper)

Steven Slivken, Manijeh Razeghi, Northwestern Univ. (United States)

Mid-infrared laser sources (3-14 microns) which have wide spectral coverage and high output power are attractive for many applications. This spectral range contains unique absorption fingerprints of most molecules, including toxins, explosives, and nerve agents. Infrared spectroscopy can also be used to detect important biomarkers, which can be used for medical diagnostics by means of breath analysis. The goal is to produce a broadband mid-infrared source which is smaller, lighter, more robust, and less expensive than what is currently available.

Gain bandwidth alone, however, is not sufficient to make a compact sensor. Single mode output with rapid tuning is desirable. For dynamic wavelength selection, our group is developing multi-section laser geometries with wide electrical tuning (hundreds of cm-1). These devices are roughly the same size as a traditional quantum cascade lasers, but tuning is accomplished without any external optical components. When combined with suitable amplifiers, these lasers are capable of multi-Watt single mode output powers. This talk will describe our current research efforts and potential for high performance, broadband electrical tuning with the quantum cascade laser.

9755-11, Session 3

Quartz enhanced photoacoustic leak sensor for mechatronic components (Invited Paper)

Angelo Sampaolo, Pietro Patimisco, Marilena Giglio, Univ. degli Studi di Bari Aldo Moro (Italy); Paolo Pietro Calabrese, CNR IFN Bari (Italy); Leonardo Chieco, MASMEC S.p.A. (Italy); Gaetano Scamarcio, Univ. degli Studi di Bari Aldo Moro (Italy); Frank K. Tittel, Rice Univ. (United States); Vincenzo Spagnolo, Politecnico di Bari (Italy)

The safety of car engines represents one of the main issues and important valuation parameter for automobile customers. High standard of reliability requires accurate performance evaluation methods for any single mechatronic part. Differential pressure measurements are typically employed by the automotive industry for the testing of vacuum seals in mechanical components.

We will report the first leak sensor based on a quartz-enhanced photoacoustic (QEPAS) spectroscopic technique. A QEPAS sensor was integrated into a vacuum-seal test station for diesel engine injectors. The test station consisted of a piston making seal with a high-vacuum valve connected to the QEPAS sensor. We selected sulfur hexafluoride (SF6), as the target gas and employed a 1% SF6 in N2 mixture as a test gas carrier. An external-cavity quantum cascade laser emitting at 10.56 µm, coupled to a 300-µm bore diameter hollow core waveguide was used as the laser source. We characterized and calibrated the SF6 sensor employing certified leak standards. A minimum detection sensitivity of of 2.75 ppb for a 1s of integration time was achieved, which corresponds to a detectable leak flow of 3x10⁻⁵ standard cm³. A minimum detectable leak flow down to 3x10⁻⁷ standard cm³ could be achieved by using pure SF6 as gas carrier. We tested our sensor with five high vacuum valves; each of them characterized by defects of different sizes. The smallest defect (the insertion of a metallic wire of 20-µm diameter) produced a leak flow of 0.04 standard cm³, orders of magnitude higher than the minimum detectable flow.

9755-12, Session 3

Timing-frequency-modulated combs in Mid-IR and THz ranges (Invited Paper)

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

Frequency combs are important tools in spectroscopy and metrology. In mid-infrared and THz ranges of spectrum frequency combs can be reliably produced by quantum cascade lasers (QCL) without any additional intra cavity elements, save dispersion compensation. But these frequency combs differ from those produced by mode-locked laser in visible and near IR ranges. QCL combs are frequency modulated (FM) combs and in temporal domain they produce complex intensity patterns rather than short pulses. In this talk I will consider strategies for obtaining predictable FM combs with constant intensity and uniform distribution of power between spectral lines. These strategies include AM and FM modulation of current as well as chirped gratings coupled with saturable absorbers. With these techniques FM combs can also be changed into short pulse trains in temporal domain.

9755-13, Session 3

Linewidth broadening factor and gain compression in quantum cascade lasers (Invited Paper)

Louise Jumpertz, Télécom ParisTech (France); Wolfgang E. Elsässer, Technische Univ. Darmstadt (Germany); Mathieu Carras, mirSense (France); Kevin Schires, Frédéric Grillot, Télécom ParisTech (France)

In addition to the phase fluctuation induced by spontaneous emission, instantaneous carrier variations in semiconductor lasers generate coupling between optical gain and refractive index [1]. This coupling between phase and amplitude of the electric field in the optical cavity is driven by the linewidth broadening factor (LBF), which is responsible for the optical linewidth broadening, occurrence of nonlinearities or gain asymmetry, due to the curvature difference between the conduction and valence bands. This key parameter typically takes values between 2 and 6 in interband lasers with quantum well or quantum dot active media [2]. In quantum cascade lasers (QCLs), since the lasing transition occurs between two subbands of the conduction band that have therefore similar curvatures, the LBF was expected to be naught. However sub-threshold LBF was measured taking values from 0.5 to 0.5 [3] and the above-threshold LBF at room
temperature was found between 1 and 2 [4]. In this work, the LBF of a mid-infrared QCL emitting around 5.6 µm is measured using either wavelength shift under optical feedback or self-mixing interferometry, resulting in values from 0.8 to 3.7. Furthermore, a strong increase of the LBF with the pump current was observed, that can be explained by a relatively large gain compression in such structures, of the order of 10-15 cm3.

References

9755-14, Session 4
Interband cascade lasers with CW wallplug efficiency higher than 40% at low temperatures (Invited Paper)

Charles D. Merritt, William B. Biewley, Chadwick L. Canedy, Chul S. Kim, U.S. Naval Research Lab. (United States); Mijin Kim, Sotera Defense Solutions (United States); Igor Vurgaftman, Jerry R. Meyer, U.S. Naval Research Lab. (United States)

Recently, a narrow-ridge 10-stage interband cascade laser (ICL) emitting at lambda = 3.45 µm displayed a cw wall-plug efficiency (WPE) of 18%, only slightly lower than the best result ever reported for a mid-infrared quantum cascade laser (QCL). We show that the cw WPE of the ICL remains comparable to that of the QCL at lower temperatures, even using an ICL design that was not specifically optimized for cryogenic-temperature operation. To demonstrate this result, broad-area (150-um-wide) devices with 1-mm-long and 2-mm-long cavities and high-reflection/anti-reflection coatings were fabricated. At 80 K, the threshold current density for the 2-mm-long device was only 11 A/cm2, i.e. about 30 times lower than the corresponding QCL thresholds. The cw external differential quantum efficiency for the 1-mm-long cavity was 70% at 80 K and still above 65% at 150 K. These results imply an internal loss as low as 2 cm-1 at 80 K. The cw wallplug efficiencies are just over 40% up to 125 K and still > 35% at 175 K. Slope efficiencies are > 2.2 W/A at all temperatures less than or equal to 200 K. The 2-mm cavity lased in CW mode up to 250 K (with 10% WPE), although the intermediate-temperature performance of both devices suffered substantially from the epi-up mounting configuration. Hence while the maximum WPE for these ICLs did not quite reach the pulsed QCL record, it exceeded the highest-reported cw cryogenic WPE reported for a QCL (32% at 30 K).

9755-15, Session 4
Tunable mid-infrared single-mode interband cascade lasers (Invited Paper)

Sven Höfling, Julius-Maximilians-Univ. Würzburg (Germany) and Univ. of St Andrews (United Kingdom); Robert Weihs, Matthias Dallner, Julius-Maximilians-Univ. Würzburg (Germany); Julian Scheuermann, Michael von Edlinger, Lars Nähle, Marc O. Fischer, Johannes Koeth, nanoplus GmbH (Germany); Martin Kamp, Julius-Maximilians-Univ. Würzburg (Germany)

Interband cascade lasers (ICLs) have become a mature and competitive semiconductor laser source in the mid-infrared region. ICLs based on current epitaxial layers grown on GaSb can cover the 2.7 µm to >5.7 µm wavelength range operating in continuous mode wave. Growing ICLs on InAs substrates combined with semiconductor the emission range can be extended beyond 7 µm at room temperature in pulsed mode. We fabricated single mode emitting ICLs with distributed feedback gratings emitting between 2.8 and 5.2 µm. By a combination of current and temperature tuning around room temperature they are tunable over about 25 nm. Utilizing multi-segment ICLs with customized gratings the laser emission can be tuned over more than 150 nm and a continuous tuning range of 20 nm can be obtained. These results are very promising with regard to highly-sensitive and selective multi-gas detection.

9755-16, Session 4
Compact, low power consumption methane sensor based on a novel miniature multipass gas cell and a CW, room temperature interband cascade laser emitting at 3.3 µm (Invited Paper)

Lei Dong, Rice Univ. (United States) and Shanxi Univ. (China); Chunguang Li, Nancy P. Sanchez, Aleksander K. Gluszek, Robert J. Griffin, Frank K. Tittel, Rice Univ. (United States)

A compact, sensitive tunable-diode-laser-absorption-spectroscopy (TDLAS) based methane sensor will be reported. This sensor employs an interband cascade laser from Nanoplus and a novel, compact, dense pattern multipass gas cell (MGC) from Sentinel Photonics. The fundamental v3 band of methane, located near 3.29 µm, has absorption strength levels of 10-19 cm/mol and is optimum for sensitive CH4 detection at the 73R(1) absorption line, located at 3038.5 cm-1 (3.29 µm). This absorption line is interference-free from other species such as H2O and CO2 over a wide wavelength range, so that methane measurements can be performed at atmospheric pressure. The MGC has a small footprint of 17.5X5.5X3.5 cm3 with a >50 m effective path length due to its dense optical multipass pattern. In order to minimize the overall sensor system size, the methane sensor platform was constructed in two layers. The performance of CH4 sensor was evaluated. Continuous outdoor CH4 measurements lasting one week were carried out with the 3.29 µm, TDLAS sensor.

9755-17, Session 4
High-power CW GaSb type-I gain chips as single-frequency sources for widely-tunable spectroscopy in the mid-infrared (Invited Paper)


2-3 micron band is of particular importance for spectroscopy and sensing applications as it covers the absorption bands of numerous important gas molecules and liquids. Optical sensing based on tunable laser absorption spectroscopy (TDLAS) is an attractive candidate due to the possibility of using diode lasers as laser sources which enables the sensing system to be low-cost, small-footprint and low-power consumption. The key element for such a system is the light-source which needs to operate in CW at room-temperature, emit in single-frequency and be power efficient. Ideally, for system level integration, it is desired that it would be matched with high-sensitivity room-temperature detectors such as extended-GaInAs, which works up to 2500 nm. GaSb type-I lasers diodes and gain-chips are ideal candidates for this: they are manufactured on 5-inch industrial GaSb substrates, demonstrate input threshold powers < 10 mW and provide CW output powers as high as several 10s of mW in single-frequency.

In this work we present latest results achieved at Brolis Semiconductors on mid-infrared GaSb gain chips as high-output power narrow-linewidth...
continuous-wave single-frequency laser sources for ultra-widely tunable spectroscopy and sensing applications. > 40 mW CW output power with over 100 nm / chip tuning and < 1 MHz linewidth performance is demonstrated in the entire band from 1900 nm – 2450 nm covering most essential absorption features from CO, CO2, NH3, CH4 and N2O for environmental and medical applications. In addition, we report on complete single-frequency laser system with integrated gain-chip for high-resolution spectroscopy and sensor applications.

9755-18, Session 5
Towards low-loss, infrared, and THz nanophotonics and metamaterials: surface phonon polariton modes in polar dielectric crystals (Keynote Presentation)
Joshua D. Caldwell, U.S. Naval Research Lab. (United States)

The field of nanophotonics is based on the ability to confine light to sub-diffractional dimensions. Up until recently, research in this field has been primarily focused on the use of plasmonic metals. However, the high optical losses inherent in such metal-based surface plasmon materials has led to an ever-expanding effort to identify, low-loss alternative materials capable of supporting sub-diffractional confinement. One highly promising alternative are polar dielectric crystals whereby sub-diffraction confinement of light can be achieved through the stimulation of surface phonon polaritons within an all-dielectric, and thus low loss material system. Both SiC and hexagonal BN are two exemplary SPhP systems, which along with a whole host of alternative materials promise to transform nanophotonics and metamaterials in the mid-IR to THz spectral range. In addition to the lower losses, these materials offer novel opportunities not available with traditional plasmonics, for instance hyperbolic optical behavior in natural materials such as hBN, for instance enabling super-resolution imaging without the need for complex fabrication. This talk will provide an overview of the SPhP phenomenon, a discussion of what makes a ‘good’ SPhP material and recent results from SiC and the naturally hyperbolic material, hBN from our research group demonstrating record quality factors for deeply sub-diffractional resonators, 3D confined hyperbolic polaritons and super resolution imaging from an unpatterned slab of hBN.

9755-19, Session 6
Broadband terahertz time-domain spectroscopy with diffraction-limited spatial resolution (Invited Paper)
Matthieu Baillergeau, Thomas Nirrangen, José Palomo, Sukhdeep Dhillon, Jérôme Tignon, Kenneth Maussang, Juliette Mangeney, Lab. Pierre Aigrain (France)

Terahertz (THz) spectroscopy is a powerful tool for fundamental investigation of matter at THz frequencies as well as for a variety of applications such as security or medicine. Owing to the proliferation of 15 fs pulse lasers, ultrabroadband THz technology ranging typically from 0.1 THz to few tenth of THz is spreading rapidly. However, extending the spectral range of THz spectroscopy systems over multi-octave spanning frequency raises new issues. For instance, confining THz radiation to the ultimate diffraction limit in THz time domain spectroscopy, that is highly demanding for investigation of small objects, is a great challenge. Indeed, it requires generation of THz pulses with frequency-independent wavefront and divergence over multi-octave spanning frequency. Here we present an original concept relying on spherical-wavefront optical excitation of large-area interdigitated photoconductive antenna that enables manipulating the divergence and wavefront of THz emission. We experimentally and theoretically demonstrate that this spherical optical excitation scheme can provide frequency-independent divergence and wavefront of the THz emission over multi-octave spanning frequency. By exploiting these unique properties, we demonstrate broadband THz time domain spectroscopy system, ranging from 0.3 THz to 20 THz, with dynamic range of 60 dB and diffraction-limited focusing of the THz pulses. We highlight the significant improvement of the system dynamic range (up to factor x16) provided by our wavefront manipulation scheme.

9755-20, Session 6
Advances in THz quantum cascade lasers for on-chip frequency combs (Invited Paper)
Markus Roesch, Giacomo Scalari, Christopher B. Bonzon, Mattias Beck, Jérémy Faist, ETH Zürich (Switzerland)

Recently, on-chip, quantum-cascade laser based frequency combs are gaining increasing attention both in the Mid-IR and in the THz spectral regions. We present three new terahertz quantum cascade lasers emitting in the 2-4 THz spectral range and aimed at enhancing the performance of QCL-based THz, on-chip frequency combs. One laser device is based on the heterogeneous cascade concept and contains four different active regions. It is an evolution of the octave-spanning device recently demonstrated by our group and displays laser action from 2 THz up to 3.85 THz in pulsed and from 2.0 to 3.74 in CW with a regular power distribution between lasing modes and powers of the order of several mW. Two new active regions are also demonstrated based on a strongly diagonal transition in real space coupled with phonon extraction. The new design is based on our four-quantum well approach, by reducing the overlap of the upper state with the lower quasi-miniband. The dipole matrix element of the main radiative transition has been lowered down to 70% of the original value. Homogeneous cascade devices display bandwidths as wide as 700 GHz centered at 2.8 THz with threshold currents as low as 100 A/cm² and T_max=130 K. Since the doping has been increased by 30% the low threshold is a clear indication of a significant increase in the upper state lifetime. The intersubband transition not limited by lifetime broadening, an increase in the upper state lifetime does not sacrifice the broad bandwidth of our devices. The longer upper-state lifetime of the new designs is then very promising for both non-linear, CW frequency comb regime and for actively RF-modulated short pulse generation.

9755-21, Session 6
Terahertz homodyne self-mixing as a new tomographic tool (Invited Paper)
Till Mohr, Stefan Breuer, Dominik Blömer, Technische Univ. Darmstadt (Germany); Marcello Simonetta, Univ. degli Studi di Pavia (Italy); Sanketkumar Patel, Malte Schlosser, Technische Univ. Darmstadt (Germany); Anselm J. Deninger, TOPTICA Photonics AG (Germany); Gerhard Birkl, Wolfgang E. Elsässer, Technische Univ. Darmstadt (Germany); Guido Giuliani, Univ. degli Studi di Pavia (Italy) and Julight S.r.l. (Italy)

We present a novel and compact technique for the simultaneous generation and detection of THz waves, for spectroscopy and two-dimensional tomography. The experimental set-up includes a photoconductive antenna (PCA) that generates a THz wave exploiting the photonixing effect. Two continuous-wave (CW) single-mode lasers emitting around 794nm are superimposed onto the PCA. The generated CW THz wave is sent through the object under test and it is chopped and reflected back on its path by a rotating chopper wheel with metal blades.

The backward propagating THz wave is detected by the same PCA antenna, using a phase-sensitive technique called self-coherent detection, that
resonates with the well-known self-mixing technique in semiconductor lasers. A transimpedance amplifier, followed by a lock-in amplifier, measures the AC part of the current signal generated by the PCA. This homodyne self-mixing signal is demonstrated to be proportional to the vectorial electric field of the back-reflected THz wave. This method allows to measure also the phase of the THz wave, as demonstrated by the sine signal measured when the chopper is displaced longitudinally over several THz wavelengths. This technique is shown to be limited by either quantum or thermal noise, depending on the power of the emitted THz wave.

We demonstrate 2D tomography and spectroscopy of a hollow-core Teflon cylinder filled with 2-lactose, that is analyzed at two frequencies (0.19 and 0.54 THz). The analysis takes into account refraction effects into the sample, and it has potential to reveal properties of the substance that fills the cylinder.

9755-22, Session 6

Plasmonic resonances in carbon fibers observed with terahertz near-field microscopy (Invited Paper)

Irina A. Khromova, Univ. College London (United Kingdom) and ITMO Univ. (Russian Federation); Miguel Navarro-Cia, Imperial College London (United Kingdom); Igal Brener, John L. Reno, Sandia National Labs. (United States) and The Ctr. for Integrated Nanotechnologies (United States); Andrey Ponomarev, Saint-Petersburg State Polytechnical Univ. (Russian Federation); Oleg Mitrofanov, Univ. College London (United Kingdom) and The Ctr. for Integrated Nanotechnologies (United States)

Resonant plasmonic response of micro-scale structures at terahertz (THz) frequencies holds great potential for THz devices as it provides highly sought after tunability. Resonators made of doped semiconductors and materials with metallic behaviour, such as graphene, graphite, carbon nanotubes and a number of two-dimensional atomic crystals, support surface plasmons and can be used as tuneable elements for THz sensing and for frequency-selective THz components. Here we demonstrate experimentally that carbon micro-fibers support dipolar resonances of plasmonic origin.

Using the THz near-field time-domain spectroscopy and imaging technique we observed excitation of THz plasmons, which form a standing wave along the fiber length. We mapped enhanced resonant fields near individual fibers and measured their resonance characteristics in the THz frequency range. The results are compared to electromagnetic simulations.

The observed characteristics allow development of precise models for describing these fibers, for instance for modelling their collective response in THz absorbers. The dependence of the resonance properties on the plasma frequency and charge carrier scattering rate provides a framework for non-contact probing of THz conductivity in sub-wavelength size particles using the experimentally measured amplitude and frequency of the plasmonic resonance.

9755-23, Session 7

Antenna-coupled microcavity THz photodetectors (Invited Paper)

Carlo Sirriorti, Daniele Palaferri, Yanko Todorov, Angela Vasanelli, Univ. Paris 7-Denis Diderot (France); Lianhe H. Li, Edmund H. Linfield, Univ. of Leeds (United Kingdom)

Although the physics of QWIP active region is well understood, improving photon collection for this detector remains an issue due to the limited quantum efficiency and the rather restricting selection rule for light-absorption in intersubband transitions. In this context, novel photonic architectures, such as photonic crystals or double-metal microcavities have recently been proposed in order to increase the light in-coupling efficiency.

We have developed a different approach, which is inspired from our recent research on the ultra-strong light-matter coupling and consists of electrically connected patch antennas. These plasmonic antennas collect photons from the free space and also act as microcavities, thus increasing quantum efficiency. We have indeed observed that the photo-response of these devices is strongly enhanced when the microcavity becomes resonant with the intersubband resonance.

Our investigation shows that this design not only allows to increases the coupling of incident photons, but also improves the intrinsic detector performances, such as the BLIP (Background-Limited Infrared Performance) temperature, which rises from 13 K for conventional QWIP operating at 5 THz, to 21 K for antenna coupled devices at the same frequency. Indeed, the antenna has the peculiarity to absorb photons on an effective area larger than its physical dimensions. As the detector dark current is proportional to the device area, in our design the dark current is reduced in comparison to the photo-generated current. This concept can be further optimized by using LC resonator, such as split ring, rather than microcavities. In this case the volume of the absorbing material, where the photocurrent is generated, is commensurable with that of the circuit capacitor, therefore much smaller than the wavelength in any direction of the space. Three dimensional LC resonator that we are planning to implement in photodetectors will be discussed.

Our plasmonic devices bring important improvements in the performance of infrared detectors as they combine the properties of an antenna with that of a microcavity, thus enhancing photon collection and quantum efficiency respectively. Indeed, with a judicious choice of the density of elements per unit area, it is possible reach the critical coupling regime where all incident photons are absorbed by the detector. Finally, it is worth mentioning that our geometry is by no means exclusively related to QWIP, on the contrary it is a very general concept applicable to any other existing detector operating in the THz or mid-infrared spectral region.

9755-24, Session 7

Black-phosphorus terahertz photodetectors with selective and controllable plasmonic, bolometric, and thermoelectric response (Invited Paper)

Miriam S. Vitiello, Consiglio Nazionale delle Ricerche (Italy)

The ability to convert light into an electrical signal with high efficiencies and controllable dynamics, is a major need in photonics and optoelectronics. In the Terahertz (THz) frequency range, with its exceptional application capabilities in high data rate wireless communications, security, night-vision, biomedical or video-imaging and gas sensing, detection technologies providing efficiency and sensitivity performances that can be “engineered” from scratch, remain elusive. By exploiting the inherent electrical and thermal in-plane anisotropy of a flexible thin flake of black-phosphorus (BP), we devised plasmonic, thermoelectric and bolometric nanodetectors with selective, switchable and controllable operating mechanism. All devices operates at room temperature and are integrated on-chip with planar nano-antennas, which provide remarkable efficiencies through light harvesting in the strongly sub-wavelength device channel. The achieved selective detection (75-8 V/W responsivity) and sensitivity performances (signal-to-noise ratio > 500), unmatched in other THz detectors embedding two-dimensional nano-materials, are here exploited to demonstrate the first concrete application of a phosphorus-based active THz device, for pharmaceutical and quality control imaging of macroscopic samples, in real-time and in a realistic setting.
9755-25, Session 7

**Nanoplasmonics for enhanced terahertz technologies, single protein trapping and analysis, and quantum limits (Invited Paper)**

Reuven Gordon, Univ. of Victoria (Canada)

In this work, I will review our recent progress in achieving enhanced photoconductive THz technologies using nanoplasmonics. I will also review our progress on optical tweezers using nanoapertures in metal films for the trapping and analysis of single proteins, including their vibrational resonances in the 100 GHz regime. Finally, I will present our work on probing the ultimate quantum limits of plasmonic enhancement.

9755-27, Session 8

**On-chip microscopy, sensing and diagnostics (Invited Paper)**

Aydogan Ozcan, Univ. of California, Los Angeles (United States)

In this presentation I will discuss some of the emerging applications and the future opportunities/challenges created by the use of mobile phones and other consumer electronics devices as well as their embedded components for the development of next-generation imaging, sensing, diagnostics and measurement tools through computational photonics techniques. The massive volume of mobile phone users, which has now reached ~7 billion, drives the rapid improvements of the hardware, software and high-end imaging and sensing technologies embedded in our phones, transforming the mobile phone into a cost-effective and yet extremely powerful platform to run e.g., biomedical tests and perform scientific measurements that would normally require advanced laboratory instruments. This rapidly evolving and continuing trend on the use of mobile phones and other emerging consumer electronic devices including e.g., wearable computers, in advanced imaging and sensing experiments might help us transform current practices of medicine, engineering and sciences through democratization of measurement science and empowerment of citizen scientists, educators and researchers in resource limited settings and developing countries.

9755-28, Session 8

**Hybrid integrated photonic and plasmonic structures for sensing applications (Invited Paper)**

Ali A. Eftekhar, Hamed Mousavi, Georgia Institute of Technology (United States); Maysamreza Chamanzar, Univ. of California, Berkeley (United States); Ye Luo, Ali Adibi, Georgia Institute of Technology (United States)

The use of enhanced light-matter interaction in integrated photonic and plasmonic structures for highly sensitive sensing applications will be discussed. On one hand, the use of integrated nanoplasmonic structures for highly efficient coupling of light into plasmonic nanostructures will be demonstrated. On the other hand, the use of nanoplasmonic arrays for enhancement of light-matter interaction through the formation of Fano-type resonance for increasing the sensitivity of biosensors will be presented. Design methodologies along with fabrication procedures and experimental characterization results will be presented for both the understanding of the fundamental properties of these structures and their sensing performance.

9755-29, Session 8

**Recent advances in silicon photonics (Invited Paper)**

Laurent Vivien, Delphine Marris-Morini, Institut d’Électronique Fondamentale (France); Leopold Virot, MINATEC (France); Diego Pérez-Galacho, Pedro Damas, Carlos Alonso-Ramos, Institut d’Électronique Fondamentale (France); Jean-Michel Hartmann, CEA-LETI (France); Eric Cassan, Paul Crozat, Xavier Le Roux, Institut d’Électronique Fondamentale (France); Charles Baudot, Frederic Boeuf, STMicroelectronics (France); Jean-Marc Fédéli, CEA-LETI (France)

Silicon is the mainstream material in the electronic industry and it is rapidly expanding its dominance into the field of photonics. Indeed, silicon photonics has been the subject of intense research activities to pave the way for next generation of energy-efficient high-speed computing, information processing and communications systems. The trend is to use optics in intimate proximity to the electronic circuit, which implies a high level of optoelectronic integration. Over the last decade, the field of silicon photonics has advanced at a remarkable pace. Recent advances in silicon photonics will be presented including the development of silicon modulators based on plasma dispersion and Pockels effects, avalanche germanium photodetectors as well as their on-chip integration in silicon platform.

9755-30, Session 8

**Silicon and germanium mid-infrared photonics (Invited Paper)**

Goran Z. Mashanovich, Graham T. Reed, Milos Nedeljkovic, Jordi Soler Penadés, Colin J. Mitchell, Ali Z. Khokhar, Callum J. Littlejohns, Stevan Stankovic, Xia Chen, Li Shen, Noel Healy, Anna C. Peacock, Univ. of Southampton (United Kingdom); Carlos Alonso-Ramos, Univ. Paris-Sud 11 (France); Alejandro Ortega-Moñux, Juan Gonzalez Wangüemert-Pérez, Iñigo Molina-Fernández, Univ. de Málaga (Spain); Pavel Cheben, National Research Council Canada (Canada); Jason J. Ackert, Andrew P. Knights, McMaster Univ. (Canada); Frederic Y. Gardes, David J. Thomson, Univ. of Southampton (United Kingdom)

We present three main material platforms: SOI, suspended Si and Ge on Si. We report low loss SOI waveguides (rib, strip, slot) with losses of ~1dB/cm. We also show efficient modulators and detectors realized in SOI, as well as filters and multiplexers. To extend transparency of SOI waveguides, bottom oxide cladding can be removed. We have fabricated low loss passive devices in a suspended platform that employ subwavelength gratings. Ge on Si material can have larger transparency range than suspended Si. We have designed passive devices in this platform, demonstrated all optical modulation and carried out two photon absorption measurements. We have also investigated theoretically free carrier optical modulation in Ge.

9755-31, Session 8

**A Si-based plasmonic light-emitting tunnel junction source**

Hasan Goktas, Volker J. Sorger, The George Washington Univ. (United States)
The physical principle of light emission is based on inelastic scattering of hot electrons after tunneling through a thin insulating layer. This light-emitting tunnel junction utilizes combo cavity comprised of a photonic crystal nano-cavity and a sub-wavelength plasmon hybrid mode towards achieving enhanced light-matter-interactions. We demonstrate that the electro-luminescence efficiency is optimal for a metal thickness close to the skin-depth for visible and near infrared frequencies. Furthermore a grating increases the out-coupling efficiency by more than two orders of magnitude over a rough scattering metallic surface. Electrically this device is intriguing since the temporal modulation bandwidth is not capacitive limited, but depends on the tunnel barrier thickness. Thus, a THz fast modulation dynamic is expected from analyzing the tunnel current for sub 1-nm thin tunnel barriers. All measurements were carried out by electrically driving the device under ambient conditions at room temperature. In conclusion, the demonstration of a Silicon-based light source with ultrafast modulation capability and minuscule footprint is shows potential for next generation on-chip sources for optical interconnect applications. However some intriguing questions are still open by the time of this paper submission such as experimentally verifying the modulation bandwidth, determining the wall-plug efficiency of the device, and we are positive to provide such details at the conference.

9755-32, Session 8

Heterogeneously-grown tunable group-IV laser on silicon

Mantu K. Hudait, Michael Clavel, Luke F. Lester, Virginia Polytechnic Institute and State Univ. (United States); Dzianis Saladukha, Tomasz J. Ochalski, Felipe Murphy-Armando, Cork Institute of Technology (Ireland)

As data rates increase, it is becoming increasingly more challenging to transmit signals electrically. An enticing alternative is the integration of photonic devices with Si technology, and the monolithic integration of Si-based optoelectronics would be an obvious choice. However, the indirect bandgap of Si limits the realization of Si-based light emitters. Thus, the hybrid integration of III-V and Ge-based electronic and photonic devices with Si technology would revolutionize the technology needs in the near future. The III-V/Si hybrid laser currently produced by wafer bonding imposes strict design and process constraints with limited scalability of size and cost. A heterogeneously, directly-grown active material would alleviate these constraints and provide a more scalable solution. We have implemented a novel heterogeneously integration scheme of laser materials with a tunable wavelength utilizing a combination of strain-engineered Ge quantum well active region and III-V semiconductor waveguides on a Si substrate. In our hybrid III-V and Ge-on-Si integration approach, we have selected a substrate architecture that offers greater design flexibility with diverse material choices and lower defect density to produce heterogeneously grown lasers on Si. In this talk, a pathway to realizing this device goal will be described that involves a graded InGaAs buffer that enables highly tensile-strained Ge that exhibits a direct bandgap and wavelength tunable emission from 1.55μm to 2.1μm. Successful heterogeneous integration of tunable tensile-strained Ge quantum wells on Si paves the way for the design and implementation of heterogeneous devices on the Si.

9755-33, Session 9

Imperceptible active sensors for cyber-physical systems (Keynote Presentation)

Tsuquito Sekitani, Osaka Univ. (Japan)

In this talk, I will discuss the recent progresses and future prospects of large-area, ultraflexible, and ultrathin electronic sensors. Our works focus on integration technologies of thin-film electronics comprising ultrathin gel electrodes, thin-film amplifier, Si-LSI platform, thin-film battery, and information engineering, which are imperceptible active sensors. Here I would like to demonstrate the applications of imperceptible sensors for patch-type bio-signal monitoring sheet and real-time health monitoring system of civil infrastructures. These sensors serve as an important part of seamless cyberspace/real-world interfaces that are commonly referred to as cyber-physical systems (CPSS).

On the basis of our initial work on manufacturing different flexible organic devices, including TFTs, LEDs, and PIDs, we developed ultraflexible electronics for applications that use large-area sensors, actuators, memories, and displays. For example, by taking advantage of an ultraflexible and compliant amplifier that can amplify biological signals by 500, we developed 1-μm-thick multi-channel active matrix electrophysiology and electromyography monitoring systems. Ultrathin electronics with a total thickness of approximately 1 to 2 μm support a bending radius of less than 10 μm.

In addition to the above-mentioned biomedical application, I will also review a wide range of new applications, including real-time health monitoring of civil infrastructures using all-printed large-area sensor systems.

9755-95, Session 8

Ultra broadband excitation of plasmons using metallic self-organized crystal

(A Invited Paper)

Agnès Maître, Guillaume Binard, Univ. Pierre et Marie Curie (France); Clotilde M. Lethiec, Univ. Pierre et Marie Curie (France) and Northwestern Univ. (United States); Hugo Frederich, Univ. Pierre et Marie Curie (France); Eduardo Yraola, Univ. Autónoma de Madrid (Spain); Céline Bourdillon, Catherine Schwob, Univ. Pierre et Marie Curie (France); Fabrice Charra, Commissariat à l‘Énergie Atomique (France); Laurent Coolen, Univ. Pierre et Marie Curie (France); Ludovic Douillard, Commissariat à l‘Énergie Atomique (France)

A silica opal used as a periodic template and covered with an optically thick gold layer, constitute a metallic self organized crystal presenting discontinuities and cracks at mesoscopic scale. Thanks to its geometrical properties, plasmons, localized and propagating ones, can be excited on a large scale. At low power, resonant optical excitation can be achieved and detected by specular optical spectroscopy. In photo excitation electron microscopy (PEEM), a fs high power laser achieves high power unmatched plasmon excitation. Such experiment is complementary for different spectral and intensity domains, to previous resonant studies. Both experiments highlight the different mechanisms implied in plasmon excitation. Moreover PEEM are used as well to map the electronic density. PEEM experiment exhibits not only interference fringes corresponding to the beating between excitation laser and Surface Plasmon Polariton (SPP), but also the presence of high intensity hot spots. It demonstrates a coupling between SPP and localized plasmons.

References:


Radiation tolerance studies of long wavelength infrared InAs/GaSb detectors (Invited Paper)

Alexander Soibel, Sir Rafal, Arezou Khoshakhlagh, Jean Nguyen, Linda Höglund, Anita Fisher, Sam Keo, David Ting, Sarath Gunapala, Jet Propulsion Lab. (United States)

Superlattice detectors based on InAs/GaSb/AlSb material layers have demonstrated significant performance improvement in the last decade. As superlattice detectors and focal plane arrays (FPAs) become valuable candidates for space-based instruments, question of their radiation tolerance became important. In this work we investigated the effect of the proton irradiation on the performance of the long wavelength infrared InAs/GaSb photodiodes based on complementary barrier infrared detector design. We found that irradiation with 68MeV protons up to the total ionizing dose, TID=200kRad, results only a small decrease in quantum efficiency and no increase in operational bias of the photodiodes. However, the irradiation causes a significant increase in dark current. The analysis of dark current as a function of operating temperature and bias showed that the dominant contributor to the dark current in these devices changes from diffusion current to tunneling current when these detectors are irradiated. This change in the dark current mechanism can be attributed to an onset of surface leakage current, which indicates that radiation damage near the device side walls has a major contribution to the dark current increase. Moreover, thermal-cycling of the device made only a minor improvement in the device performance, indicating a proton displacement damage to the device structure.

Mid-infrared interband cascade photodetectors with high quantum efficiency (Invited Paper)

Zhao-Bing Tian, The Univ. of New Mexico (United States); Anjali Singh, Kevin Rigg, Northrop Grumman Electronic Systems (United States); Sanjay Krishna, The Univ. of New Mexico (United States)

Antimony-based Interband Cascade (IC) photodetector are emerging as a viable candidate for high-performance infrared applications, especially at High Operating Temperatures (HOT). In each stage of the IC detector, an InAs/Ga(In)Sb type-II superlattice (T2-SL) absorption region is sandwiched between electron and hole barriers, and multiple stages are electrically connected in series via the type-II broken-gap alignment between InAs and GaSb quantum-well structures. The asymmetric energy-band alignment and efficient carrier transport channel provide IC detectors with several unique device features, thus enabling IC detectors to have many highly-desirable device characteristics, such as zero-bias operation, low dark current, and High Operating Temperature. Our effort has led to the demonstration of mid-IR single pixel device operating up to 450 K under zero-bias, and these devices have achieved superior electrical performance compared to Mercury Cadmium Telluride (MCT) technology at higher operating temperatures. In this presentation, we will discuss our recent development of low-noise mid-IR IC photodetectors with high quantum efficiency. The device optoelectrical characteristics and test results will be presented, and most recent technical progress will also be reported. This work is partially supported by the Northrop Grumman Innovation Fund.

Recent progress in interband cascade IR photodetectors (Invited Paper)

Rui Q. Yang, The Univ. of Oklahoma (United States)

Interband cascade IR photodetectors (ICIPs) are multi-stage detectors with discrete absorbers separated by unipolar electron and hole barriers. In this multi-stage detector architecture, the absorber in each stage is designed with a thickness that is thinner than the diffusion length of carrier so that photo-generated carriers can be collected efficiently. This advantage has been validated with operation of ICIPs at high temperatures (>400 K). Furthermore, because of the thin absorber in each stage, the carriers travel only across a short distance. As such, ICIPs can respond quickly to high frequency modulation without sacrificing much of absorption efficiency owing to the multiple discrete absorber architecture in contrast to the conventional single-stage photodetectors. In this talk, we will report our recent investigations of ICIPs and their progress towards improved understanding and high device performance.

A low effective mass material system for quantum cascade detectors (Invited Paper)

Peter Reiningr, Tobias Zederbauer, Benedikt Schwarz, Hermann Detz, Donald MacFarland, Aaron M. Andrews, Werner Schrenk, Gottfried Strasser, Technische Univ. Wien (Austria)

In the recent years quantum cascade detectors (QCD) showed a tremendous performance improvement. Even further improvement can be achieved by finding new, better material systems. The most relevant material parameter for QCDs is the effective mass. A material with a small effective mass inherently has a higher absorption efficiency as well as a significantly smaller noise current density. In this work we introduce the InAs/AlAsSb material system for QCDs, which has an effective mass of the well material of m∗=0.021. Using this material system we demonstrate a QCD with a Johnson limited specific detectivity of D*=2.87 x 10^10 Jones at 80K and D*=2.75 x 10^7 Jones at 300K. A low effective mass benefits a QCD in two distinct ways. For a given doping density, the absorption coefficient is inversely proportional to the electron effective mass, i.e. the smaller the effective mass the larger the absorption and the higher the responsivity. The second consequence of the smaller effective mass is an improvement of the noise characteristics. At equilibrium the dominant noise mechanism for QCDs is Johnson noise. The noise spectral density is inverse proportional to the device electrical resistance, which again is inverse proportional to the scattering rates. The most dominant scattering mechanism for QCDs at 300K is LO-phonon scattering, where the scattering rate is directly proportional to the effective mass. Thus, the lower effective mass leads to a reduction of the scattering rates, which increases the device resistance and thus further improves the specific detectivity.

Radiometric and radiation tolerance characterization of IR photodiodes employing unipolar barrier detector architectures with bulk and T2SLS III-V absorbers (Invited Paper)

Vincent M. Cowan, Christian P. Morath, Eli Garduno, Geoffrey D. Jenkins, John E. Hubbs, Air Force Research Laboratory (United States)
Surface plasmonic resonance has been extensively researched. Significant
photodetector

type II strain-layer superlattice (T2SLS) III-V based absorbers is presented. Protons with an energy of 63 MeV were used to irradiate the detectors under test to a proton fluence of $7.5 \times 10^{11}$ protons/cm$^2$, corresponding to a TID of 100 kRads(Si), while the detectors were under-bias and held at 130 K. The performance of detectors yielded from a suite of growths were characterized by dark current, quantum efficiency and optical collection length measurements. The results show an increase in dark current, while yet maintaining roughly diffusion-limited performance, and a reduction in the quantum efficiency and optical collection lengths consistent with an increase in the trap density and degradation of minority carrier lifetime as shown from data collected via time resolved photoluminescence. An in-depth examination of the collective results from under bias experiments quantifying the performance degradation rates of III-V based, unipolar barrier infrared detectors with various designs, cutoff wavelengths and operating conditions due to 63 MeV proton irradiation is presented. Complementary proton induced minority carrier lifetime degradation results collected using time resolved photoluminescence will also be reported on.

9755-39, Session 11

Metamorphic InAsSbx/InAsSby heterostructures: new materials for infrared photonics (Invited Paper)

Gregory Belenky, Youxi Lin, Leon Shterengas, Dmitry V. Donetsky, Gela Kipshidze, Sergey Suchalkin, Stony Brook Univ. (United States); Wendy L. Sarney, Stefan P. Svensson, U.S. Army Research Lab. (United States)

We report on the design and fabrication of metamorphic periodic heterostructures containing InAsSb layers with controlled modulated Sb composition and predicted band alignments. The band gap energy of ordered alloys can be much smaller than that in bulk InAsSb of any Sb composition. The modulation period is determined by the thicknesses of the strain compensated, repeated InAsSbx/InAsSby pairs grown on a virtual GaInSb substrate with a chosen lattice constant. High resolution transmission electron micrographs of 4.3 nm period heterostructures with Sb compositions of $x = 31\%$ and $y = 61\%$ exhibited the targeted 6-7 and 8-9 monolayer thicknesses. The electron diffraction patterns showed dual As/Sb ordering: deliberate along the (002) and strain-induced Cu-Pt along the (111) directions. Varying the modulation period from 2.3 to 5.5 nm led to a shift of the 20 photoluminescence maximum from 12.9 $\mu$m to 19.6 $\mu$m. With the lattice constant as a design parameter, the growth of strain compensated InAsSbx/InAsSby on virtual substrates induces narrow bandgaps well below that allowed for bulk material. Modulation periods as low as 2.3 nm result in relatively wide electron and hole subbands, therefore bulk-like absorption and carrier transport properties are expected.

9755-40, Session 11

Surface plasmonic resonance enhanced type II strain-layer superlattice photodetector (Invited Paper)

Guiru Gu, Stonehill College (United States); Jarrod N. Vaillancourt, Applied NanoFemto Technologies LLC (United States); Xuejun Lu, Univ. of Massachusetts Lowell (United States)

Surface plasmonic resonance has been extensively researched. Significant enhancement has been reported in quantum dot infrared photodetector (QDIP). In this paper, we report an SPR enhanced type-II strain layer superlattice (SLS) mid wave infrared (MWIR) photodetector with reduced active layer thickness. The performance is compared with the reference SLS MWIR photodetector without the plasmonic structure.

9755-41, Session 11

Photoluminescence studies of InAs/InAsSb type-II infrared superlattices (Invited Paper)

Elizabeth H. Steenbergen, Air Force Research Lab. (United States); Jeremy A. Massengale, The Univ. of Oklahoma (United States); Yong-Hang Zhang, Arizona State Univ. (United States)

InAs/InAsSb type-II superlattices are of interest for infrared detector applications due to their longer minority carrier lifetimes than those of InAs/(In)GaSb superlattices. However, time-resolved photoluminescence of InAs(In)SbSb superlattices shows evidence of Shockley-Read-Hall recombination, indicating the presence of trap states due to defects. The photoluminescence technique is extremely sensitive to defects in materials and temperature and excitation dependence is used to examine recombination through different energy states present in these superlattices. Results will be presented for both n-type and p-type InAs/InAsSb superlattices.

9755-42, Session 11

InAs-based type-II superlattice long wavelength photodetectors (Invited Paper)

Fangfang Wang, Jianxin Chen, Zhicheng Xu, Yi Zhou, Li He, Shanghai Institute of Technical Physics (China)

We will report our recent works on InAs-based superlattice photodiode structures. InAs/GaAs superlattices were conventionally grown on GaSb substrates and have been achieved excellent successes. However since InAs has a smaller lattice constant than that of GaSb, InSb-like interface layers are usually employed to balance the strain. The longer the cutoff wavelength, the thicker InAs layer in each period and therefore the thicker InSb interface has to be used. This issue can be removed if the superlattice structure is grown on an InAs substrate. Moreover, by getting rid of InSb-like interface, one can raise the growth substrate of the superlattice layer which helps to improve the superlattice's electrical properties, such as minority carrier lifetime, which is a bottleneck for superlattice photo-detector's performances. High quality InAsGaSb superlattices on InAs substrates with sharp X-ray diffraction peaks have been obtained for the first time. The results show that the lattice mismatch of the superlattices to the InAs substrates is not sensitive to the InAs thickness in each T2SLSperiod. A p-i-n detector with a superlattice period of 22 ML InAs/7 ML GaSb showed a 100% cutoff wavelength of 11.5 $\mu$m at 77K. Its dark current density at -50mV bias is 4.0710-3A/cm$^2$ and a ROA of 12.37-cm$^2$ has been reached.

9755-43, Session 12

Metamaterial-based nanobiosensors and nanophotodetectors (Invited Paper)

Ekmel Ozbay, Bilkent Univ. (Turkey)

In this talk, we will present how metamaterials can be used for nanobiosensors and nanophotodetector applications. We will present a label-free, optical nano-biosensor based on the Localized Surface Plasmon Resonance (LSPR) effect that is observed at the metal-dielectric interface
Optimization of plasmonic grating resonators based on highly-doped semiconductors for sensing applications using 2D finite-difference time-domain simulations (Invited Paper)

Franziska B. Barho, María José Milla Rodrigo, Fernando González-Posada Florès, Thierry Taliercio, Univ. Montpellier 2 (France)

Sensing techniques based on surface plasmon resonance (SPR) sensing and surface enhanced spectroscopies (SES) exploit the sensitivity on the local refractive index and the electric nearfield exaltation. Operating SPR sensors in the mid-infrared (MIR) near the characteristic molecular absorption lines has been proposed in order to improve their sensitivity and selectivity [1]. For the development of such sensors, appropriated materials, such as highly doped semiconductors (HDSC), are required to overcome the limitations that gold and silver present in this spectral region [2].

Here we investigate simple periodic grating structures made of HDSC material, notably InAsSb on GaSb substrate. We use two-dimensional finite-difference time-domain (FDTD) simulations to study the characteristics of the plasmon modes as a function of the grating’s geometrical parameters. Optimization of the plasmonic resonator grating is performed with regard to SES and SPR sensing applications. We consider the electric field enhancement as well as the sensitivity on refractive index variation. The effects of different ribbon cross section shapes are also investigated to account for artefacts that could be introduced by technological processing.

We show an accurate control of the resonance wavelength of the localized surface plasmon modes in the MIR spectral region by adapting the ribbon’s geometry. The simple, gap-free structures allow field enhancement factors that gold and silver present in this spectral region [2].

We show a high control definition of the ribbon width, from 1000-to-100nm with an error below 9%, by using different wet-etching times. Besides, we find a clear correlation between the ribbon width and the LSP wavelengths. The LSP wavelength is monotonically blue-shifted when the ribbon width is decreased reaching an asymptotical value of the order of 10nm. Consequently, adjusting the ribbon width allows the accurate setting of the LSP wavelength. Additionally, a significant reflectance variation is exhibited when changing the environment. These results make InAsSb/GaSb HDSC very suitable for the development of highly sensitive and selective biosensing devices.

quantum and nonlinear optics [1-3].

A key phenomenon taking place in double well potentials is the spontaneous breaking of the inversion symmetry: a bifurcation from delocalized to localized states in the wells, which are mirror images of each other. Although few theoretical studies have addressed mirror-symmetry breaking in micro and nanophotonic systems, we provide here the first experimental evidence, using two evanescently coupled photonic crystal nanolasers [4]. We reveal a transition to spontaneously broken parity states in the form of a pitchfork bifurcation as long as the nonlinear interaction – the nonlinear nanolaser frequency shift– overcomes photon tunneling. Coexistence of these states is shown by switching them through short pulse perturbations in the cavities.

Our (spatially) bistable switchable nanolaser opens exciting prospects for the realization of scalable optical flip-flop memories based on symmetry breaking without any resonant driving beam. In addition, since the tunneling rate can be finely adjusted [5], we can predict such transitions with few intracavity photons for future nanolaser devices with strong quantum correlations.


9755-47, Session 12

Theoretical and experimental investigation of optically spin-injected VECSEL (Invited Paper)

Alexandre Joly, Thales Research & Technology (France); Julien Frougier, Unité Mixte de Physique CNRS/Thales (France); Ghaya Baill, Thales Research & Technology (France); Mehdi Alouini, Institut de Physique de Rennes (France); Jean-Marie George, Unité Mixte de Physique CNRS/Thales (France); Isabelle Sagnes, Lab. de Photonique et de Nanostructures (France); Daniel Dolfi, Thales Research & Technology (France)

We report theoretical and experimental analysis of spin-injected VECSELs. First, we present a vectorial model of laser polarization eigenstates evolution as a function of linear phase anisotropy; circular phase anisotropy and circular gain dichroism added by spin injection. A first laser configuration is presented for efficient optical spin injection at room temperature. It consists on a M-shaped laser cavity incorporating a high circular phase anisotropy. Then, we report linear phase anisotropy measurements of the VECSEL in oscillating conditions. The proposed technique relies on the measurement in the microwave domain of the beatnote between the oscillating mode and the amplified spontaneous emission of the cross-polarized non-lasing field lying in the following longitudinal mode. This technique is shown to offer extremely high sensitivity and accuracy enabling to track the amount of residual birefringence according to the laser operation conditions. We discuss the compensation of the residual linear phase anisotropy by controlling the birefringence of an intracavity electro-optical crystal. A 12-fold birefringence reduction is obtained. Besides, we study the modification of the laser polarization eigenstates with birefringence compensation: a rotation of the linear polarization state is observed when the total phase anisotropy is reduced. A circular polarization eigenstate is obtained at the minimum of the birefringence into the laser cavity, more favorable for anisotropy is reduced. A circular polarization eigenstate is obtained at

9755-48, Session 12

Dynamic control of chaotic resonators (Invited Paper)

Andrea Di Falco, Univ. of St. Andrews (United Kingdom); Roman Bruck, Univ. of Southampton (United Kingdom); Changxu Liu, King Abdullah Univ. of Science and Technology (Saudi Arabia); Otto L. Muskens, Univ. of Southampton (United Kingdom); Andrea Fratalocchi, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Planar Photonic Crystals (PhC) have a prominent role in modern integrated optics, because of the extreme design versatility, mediated by the ease of dispersion control and the existence of bandgaps. We recently used this versatility to fabricate and study chaotic optical PhC resonators. We have shown that the eigenvalues of a chaotic cavity tend to have the same value, and that this effect can be exploited for broadband energy storage. We have also shown that losses play a non-trivial role in chaotic dynamics, and can lead to localized states for light in time and space, akin to rogue waves. In these studies, the effect are controlled with careful choice of the topology, for example arranging the holes to form a uniform billiard cavity, or by using coupling waveguides of different width. Here we show that the degree of chaos supported by a microcavity can be controlled dynamically, using light itself. We start with a square (non-chaotic) cavity obtained on Silicon on Insulator. We then pump it from above with pulsed blue light and collect the transmission of a probe pulse in the near infrared, for different pump-probe delays. Since the pump is focused on a small region of the cavity, our study permits to assess the effect of pumping on different regions of the resonator. The analysis of these activity maps, confirmed by numerical modelling based on random matrices, demonstrates that nonlinear optics can be used to control reversibly the chaotic behavior of light in optical resonators.

9755-49, Session 13

Quantum photonics with color centers in diamond and nanophotonic structures (Invited Paper)

Simeon Bogdanov, Mikhail Y. Shalaginov, Jing Liu, Purdue Univ. (United States); Vadim V. Vorobyov, Photonic Nano-Meta Technologies (Russian Federation); Polina V. Kapitanova, ITMO Univ. (Russian Federation); Marcello Ferrera, Herriot-Watt Univ. (United Kingdom); Alexei Lagutchev, Purdue Univ. (United States); Alexey V. Akimov, Russian QuantumCtr. (Russian Federation); Pavel A. Belov, ITMO Univ. (Russian Federation); Alexander V. Kildishev, Joseph M. Irudayaraj, Alexandra Boltasseva, Vladimir M. Shalaev, Purdue Univ. (United States)

Color centers in diamond are crystalline defects that share many quantum properties with single atoms, being at the same time easier to manipulate and integrable into solid-state structures. These systems are very favorable for the realization of quantum devices such as nanoscale sensors, single-photon sources and quantum memories. Our research relies on the promising potential of the last developing field of nanophotonics in order to enhance or better harness the quantum properties of such systems. In particular, novel nanophotonic structures such as hyperbolic metamaterials and plasmonic waveguides are good candidates for increasing the color center’s spontaneous emission rate and controlling the directionality of their emission in a broad frequency range. In addition, the broadband optical Purcell factor in plasmonic systems can also be used to control the spin readout. Conversely, the color centers’ spin degree of freedom can be a powerful tool to evaluate the photonic density of states on the nanoscale. The use of CMOS-compatible nanostructured materials brings a new level of
functionality for a variety of integrated room-temperature quantum devices based on diamond color centers.

Is super-Planckian thermal emission possible in the far field? (Invited Paper)
Francois Marquier, Jean-Jacques Greffet, Institut d’Optique Graduate School (France); Patrick Bouchon, ONERA (France); Giovanni Brucoli, Institut d’Optique Graduate School (France)

It has been predicted and observed that radiative heat transfer between two surfaces separated by nanometer scale gaps can exceed the flux exchanged between two black bodies [1]. This is often referred to as super-Planckian flux. This raises the question of the possibility of super-Planckian emitters into the far field. As many infrared sources are thermal sources, super-Planckian emitters would be of practical interest. It has been shown [2,3] that the power radiated by a finite size emitter can be increased by a factor n^2 by bringing a solid immersion lens in contact with the emitter. This observation does not exceed the Planckian prediction. There have been publications suggesting that photonic crystals or metamaterials could achieve super-Planckian emission [4,5]. In this contribution, we report a general proof of the Kirchhoff law. As a consequence, it appears that the emitted flux is the product of the absorption cross section by the black body radiance for any source of arbitrary size made of materials satisfying reciprocity. This result encompass most photonic crystals and metamaterials. It follows that super-Planckian emission in the far field is not possible.

The expression of the emission can be extended to anisothermal bodies. Indeed, we introduce a local emissivity density which is equal to the local absorptivity. This result had been derived for periodic one dimensional systems previously. Here, we introduce a general derivation valid for any shape and any combination of reciprocal materials.

Integrated spectral and displacement sensors based on nanomechanical photonic crystals (Invited Paper)
Zarko Zobenica, Rob W. van der Heijden, Maurangelo Petruzella, Francesco M. Pagliano, Tian Xia, Leonardo Midolo, YongJin Cho, Frank W. M. van Otten, Andrea Fiore, Technische Univ. Eindhoven (Netherlands)

Nanophotonic structures featuring narrow optical resonances, such as high-quality factor photonic crystal cavities, enable spectral sensing with high resolution. When the optical cavity is coupled to a moveable structure, this also translates into high-sensitivity displacement sensing. While these optomechanical sensors are in principle integrated, low-power and extremely compact, their optical read-out is usually realized with an external electro-optical circuit. Moreover, for many applications, an actuation functionality is needed. In this talk we will introduce a novel nanophotonic sensing structure, where the actuation, sensing and read-out are integrated in the same device. It is based on electromechanically-tuneable double-membrane photonic crystal cavities, where the resonant wavelength of the cavity is sensitive to the separation between the membranes. The output is provided directly in the form of a current, removing the need for external optical read-out. It can be used to measure the spectrum of incident light, to determine the wavelength of a laser line with pm-range resolution, or equivalently to measure tiny displacements. Additionally, the integrated actuation makes it suitable for applications where motion control is needed.

Optical Helmholtz resonators (Invited Paper)
Patrick Bouchon, Paul Chevalier, ONERA (France); Fabrice Pardo, Lab. de Photонique et de Nanostructures (France); Riad Haidar, ONERA (France)

Designing nanotenna that could strongly and efficiently concentrate incident light into deep subwavelength volumes is a key issue to locally enhance the electric field and thus produce strong light-matter interactions. Many existing designs are inspired by structures widely used in the radiofrequency domain such as bowtie or Yagi-Uda antennas. Here, we rather use an analogy between acoustics and electromagnetism to model plasmonic and photonic resonators, brute force numerical simulation is extensively used, to compute key physical quantities (cross sections, Purcell factor). However, one need to repeat many independent computations, when parameters such as wavelength, polarization, ... are changed. Besides, much knowledge about the physical mechanisms at play remains hidden.

To go beyond, we have developed a modal method [1,2] that permits to obtain easily an accurate prediction using only a few modes (if not only one) of the resonator. We can expand the fields on the quasi resonator modes of the resonator [2], whose eigenfrequency is complex. Once the modes have been found numerically, and properly normalized, their excitation coefficient is known analytically, even for three-dimensional, open and dispersive problems.

Apart from simplifying the calculation of canonical systems (nanoparticle on substrate, plasmonic nano-antenna, ...), this formalism permits to handle more complex situations. At the conference, we will present this toolbox and discuss it on a few examples and applications: the hybridization of one plasmonic resonator with a quantum dot [3] or other nanoresonators, the design of devices for plasmonic sensing [4].

Enhanced second-harmonic generation from magnetic resonance in AlGaAs nanoantennas (Invited Paper)

Costantino De Angelis, Andrea Locatelli, Luca Carletti, Davide Rocco, Univ. degli Studi di Brescia (Italy); Oleksandr Stepanenko, Giuseppe Leo, Ivan Favero, Univ. Paris 7-Denis Diderot (France); Aristide Lemaître, Lab. de Photonique et de Nanostructures (France); Giuseppe Marino, Nicolas Olivier, Anatoly V. Zayats, King’s College London (United Kingdom)

All-dielectric nanoantennas offer unique opportunities for the study of nonlinear effects due to very low losses in combination with multipolar characteristics of both electric and magnetic resonant optical modes [1,2]. The nonlinear optical effects of magnetic origin can have fundamentally different properties compared with those of electric origin. When nonlinearities of both electric and magnetic type are present, the nonlinear response can be substantially modified and is accompanied by nonlinear mode mixing and magnetoelectric coupling, which has only been studied at microwave frequencies to date.

The only investigation of the nonlinear optical response generated from a magnetic resonant optical mode in an all-dielectric antenna has been conducted on Si nano disks [3]. However, in that case, operation in the third window of optical fiber communication is limited by two-photon absorption (TPA) and volume second order nonlinear interactions are absent because of centro-symmetry of Si. In this perspective III-V materials such as GaAs or AlGaAs offer a strong potential to efficiently observe second order nonlinear effects such as Second-Harmonic Generation (SHG), which up to now have been studied only in metal based nanoantennas [4]. Furthermore, by engineering the AlGaAs alloy composition, TPA at wavelengths close to 1.55 μm can be avoided. Finally, AlGaAs monolithic nanoantennas might benefit from the direct integration of diode lasers on a GaAs chip.

Here we present theoretical and experimental results on the linear and nonlinear scattering of AlGaAs-on-aluminum-oxide monolithic nanodisks. We illustrate the design of nanodisks exhibiting the magnetic dipole resonance in the near-IR wavelength range and we report an analysis of the optical nonlinear response generated from volume second order nonlinearity in all-dielectric nanoantennas. Our results show that AlGaAs nanoantennas have a strong potential to enhance the SHG from all-dielectric nanostructures.


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measurements in 2D devices with dimensions comparable to the electron and phonon mean free paths (~100 nm) which show quasi-ballistic thermal transport and significant phonon-edge scattering in narrow devices [3,4]. Finally, we will describe thermoelectric (e.g. Peltier) effects observed during device operation and how these could be leveraged to enable energy-efficient electronics and energy harvesters [5]. In general, the 2D properties will be discussed both from a fundamental point of view and in the context of device applications.


9755-58, Session 15

Structural and electrical properties of MoS2 grown by sulfuration of PVD sputtered MoO3 and Mo precursor films (Invited Paper)

Shanee Pacley, Air Force Research Lab. (United States); Jianjun Hu, Michael Jespersen, Univ. of Dayton Research Institute (United States); Albert Hilton, Wyle Aerospace (United States); Adam R. Waite, Univ. of Dayton Research Institute (United States); Elizabeth A. Moore, Wyle Aerospace (United States); Jacob Brausch, Air Force Research Lab. (United States) and Univ. of Dayton Research Institute (United States); Emory Beck-Millerton, Andrey A. Voevodin, Air Force Research Lab. (United States)

Monolayer molybdenum disulfide (MoS2), a 2D semiconducting dichalcogenide material with a bandgap of 1.8-1.9 eV, has demonstrated promise for future use in field effect transistors and optoelectronics. Various approaches have been used for MoS2 processing, the most common being chemical vapor deposition. During chemical vapor deposition, precursors such as Mo, MoO3 and MoCl5 have been used to form a vapor reaction with sulfur, resulting in thin films of MoS2. Currently, MoO3 ribbons and powder, and MoCl5 powder have been used. In addition, sputtering of Mo produces continuous MoS2 films as well. In this paper, we compare the structure and electrical properties of MoS2 grown by sulfuration of pulse vapor deposited MoO3 and Mo precursor films. Our transmission electron microscopy results show a more uniform and continuous film growth for the MoS2 films produced from Mo when compared to the films produced from MoO3. This uniform and continuous growth was also shown in the Raman mapping imaging for the films grown using Mo precursors. The X-ray photoelectron spectroscopy results show that the MoS2 films produced using both precursors were stoichiometric. Correlations between Mo and MoO3 layers, and resulting 2D MoS2 film chemistry and structure are discussed.

9755-59, Session 15

Development of a research platform for uniform, large-area transition metal dichalcogenides (Invited Paper)

Jacob H. Leach, Gregg Dodson II, Paul Gentry, Eugene Shishkin, Robert Metzger, Keith R. Evans, Kyma Technologies, Inc. (United States)

Transition metal dichalcogenides (TMDs) constitute an exciting new class of 2-dimensional materials which have a number of attractive properties which make them potentially useful in a myriad of possible applications ranging from sensors and detectors to flexible electronics, photonics, and piezotronics. While impressive inroads have been made recently in both the understanding of the physical properties as well as realization of device fabrication techniques and performance for many of the TMDs, a stable synthesis platform for growth of relevant 2D-TMD crystals in large areas is not available. In this work, we will discuss our efforts toward realizing a large-area capable TMD synthesis tool in terms of its design, simulation of growth within the tool, and realization of state-of-the-art films from the tool.

9755-60, Session 15

Probing topological insulators surface states via plasma-wave terahertz detection (Invited Paper)

Leonardo Viti, Consiglio Nazionale delle Ricerche (Italy); Dominique Coquillat, Univ. Montpellier 2 (France); Antonio Politano, Univ. della Calabria (Italy); Konstantin A. Kokh, V.S. Sobolev Institute of Geology and Mineralogy (Russian Federation); Ziya S. Aliev, Mahammad B. Babanly, Azerbaijan National Academy of Sciences (Azerbaijan); Oleg E. Tereshchenko, Institute of Semiconductor Physics (Russian Federation) and Novosibirsk State Univ. (Russian Federation); Wojciech Knap, Univ. Montpellier 2 (France) and Institute of High Pressure Physics (Poland); Evgenui V. Chulkov, Ctr. de Fisica de Materiales (Spain) and National Research Tomsk State Univ. (Russian Federation) and Saint Petersburg State Univ. (Russian Federation); Miriam S. Vitiello, Consiglio Nazionale delle Ricerche (Italy)

Topological insulators (TIs) represent a novel quantum state of matter, characterized by an insulating bulk surrounded by gapless boundary states. Beside the intriguing theoretical description, the topological surface states (TSS), arising at the boundaries of a three dimensional TI, open a new interesting scenario thanks to their gapless band structure and to the fact that the time reversal symmetry prevents carriers from back scattering. Thus TSS are capable, in principle, to outperform the electrical properties of graphene itself and represent, then, an ideal material platform for exploring new applications in optoelectronics, spintronics, low-power electronics and quantum computing.

Unveiling the existence of topological surface states is a very challenging task since the TSS properties are usually mixed up with those of bulk-states. Here, we devise a tool to unveil TSS and to probe their related plasmonic effects by exploiting terahertz (THz) radiation. By engineering Bi2Te(3-x)Sex stoichiometry, and by gating the surface of nanoscale field-effect-transistors, exploiting thin flakes of Bi2Te2.2Se0.8 or Bi2Se3, we provide the first demonstration of room-temperature THz detection mediated by overdamped plasma-wave oscillations on the “activated” TSS of a Bi2Te2.2Se0.8 flake. The reported detection performances allow a realistic exploitation of TSS for large-area, fast imaging, promising superb impacts on THz photonics.

9755-61, Session 16

From black phosphorus to phosphorene (Invited Paper)

Peide Ye, Purdue Univ. (United States)

Phosphorus is one of the most abundant elements preserved in earth, constructing with a fraction of 0.1% of the earth crust. In general, phosphorus has several allotropes including white, red, and black phosphorus. Black phosphorus, though rarely mentioned, is a layered semiconductor as shown in Figure 1 and have great potentials in optical and
9755-62, Session 16

**Bridging the gap: layered black phosphorus for electronics and optoelectronics (Invited Paper)**

Fengnian Xia, Yale Univ. (United States)

Black phosphorus recently emerged as a promising new 2D material due to its widely tunable and direct bandgap, high carrier mobility and remarkable in-plane anisotropic electrical, optical and phonon properties. It serendipitously bridges the zero-gap graphene and the relatively large-bandgap transition metal dichalcogenides such as molybdenum disulfide (MoS2). In this talk, I will first cover the basic properties of few-layer and thin-film black phosphorus, followed by a discussion of recent observation of highly anisotropic robust excitons in monolayer black phosphorus. Finally, I will present a few potential applications of black phosphorus such as radio-frequency transistors and wideband photodetectors.

9755-63, Session 16

**Theory of 2D lateral semiconductor heterojunctions (Invited Paper)**

Henry Yu, Alex Kutana, Boris I. Yakobson, Rice Univ. (United States)

Two-dimensional (2D) materials have shown remarkable electronic properties since their emergence. In order to harness these properties in a workable device one has to form a heterojunction. While vertically stacked junctions of 2D materials have been widely explored, lateral junctions have been made only recently [1]. In this work we investigate electronic properties and potential applications of 2D lateral coplanar heterojunctions. Common knowledge applicable to bulk heterojunctions is no longer valid in such 2D case, and a new physical picture must be established. Our results show that extensive and non-localized charge transfer is a general trait of a 2D junction. Based on the new description, we further obtained scaling laws for the built-in potential, doping and depletions length. As a result of charge delocalization, typical length scale of a 2D junction is shown to be 2-3 orders of magnitude greater than a traditional one. Such delocalization may cause ordinary device design unworkable, but does not prevent the possibilities of applications with a new mindset. Therefore, we suggest implications of our results to device applications. The extensive charge transfer determines the lower bound of capacitance for coplanar heterojunctions. The non-localized charge, resulting in non-localized field, may offer a platform for splitting electron-hole pairs, for potential solar cell device. We also explore other electronic and photonic applications of these systems, such as tunneling and light emitting diodes.


9755-64, Session 16

**Spin filtering and magnetic coupling across ferromagnet-graphene-ferromagnet heterostructures (Invited Paper)**

Enrique Cobas, U.S. Naval Research Lab. (United States)

Graphene’s unique nature and properties have made it alluring for in-plane charge and spin transport devices. It has been investigated as a potential conductive transparent electrode for displays, an interconnect material, a channel material for THz devices and spin valves, a channel for chemical and biological sensors, and more. Its interfaces and out-of-plane transport have only more recently become a topic of research. Among the more interesting theoretical predictions is a giant spin-filtering effect at the out-of-plane interface between graphene and certain ferromagnetic crystals. Graphene’s unique band structure makes it a tunnel barrier for electrons with momentum away from the K point. Combined with metallic crystal surfaces where electrons with momentum K have only minority-spin polarization, the interface becomes a spin-filter and should exhibit magnetoresistances far exceeding any current technology. We have confirmed that a single graphene layer can function as a tunnel barrier contact between ferromagnetic metals and multi-layer graphene produces the predicted minority spin filtering. We have further demonstrated spin transport and precession in silicon channels and silicon nanowires using graphene tunnel contacts. Finally, we have also realized scalable arrays of high-quality graphene junction devices with high magnetoresistance and very low impedance. This combination of these features is critical for fast-readout, low-power magnetic random access memory as well as for spin-logic schemes and low-power magnetic field sensors.

9755-65, Session 16

**Atomic layer epitaxy for quantum well nitride-based devices (Invited Paper)**


Control of material properties on the nanoscale is a key enabler for using quantum size effects to achieve higher efficiency and added functionality in sensing technologies. The development and control of single and multiple quantum well structures in III-nitride semiconductors has been essential in the commercial success of LED and LD devices. Although tremendous advances have been made in III-nitride alloy growth, conventional growth techniques are challenged in achieving alloy compositions over the entire stoichiometric range without phase separation with atomic level thickness control. Atomic layer epitaxy (ALEp), a pulsed growth technique similar to atomic layer deposition, provides resolution of some of these challenges. In ALEp the use of surface limited growth mechanisms and lower temperatures enables growth of epitaxial layers over the full III-N stoichiometric range with the atomic thickness control needed for state of the art device structures.

The development and characterization of nitride QW structures by ALEp for device applications will be presented. Previous work demonstrated the growth of epitaxial thin films (4-10nm) covering the full range of binary and ternary III-N compositions by ALEp. In this work, ALEp-grown QW structures will be presented. Optical characteristics will be discussed. Characterization of interfaces between layers and layer composition are investigated with atom probe tomography. Structural characterization of nitride films with electron channeling contrast imaging will be presented to image dislocations in the material. By understanding the structure of crystalline ALEp films with nanoscale thickness, the unique properties of these materials can be advanced for quantum sensing applications.
Recent advances in Sofradir IR on II-VI photodetectors for HOT applications (Invited Paper)


SOFRADIR is the worldwide leader on the cooled IR detector market for high-performance space, military and security applications thanks to a well mastered Mercury Cadmium Telluride (MCT) technology, and recently thanks to the acquisition of III-V technology: InSb, InGaAs, and QWIP quantum detectors. As a result, strong and continuous development efforts are deployed to deliver cutting edge products with improved performances in terms of spatial and thermal resolution, low excess noise and high operability. The actual trend in quantum IR detector development is the design of very small pixel, with high operating temperature (HOT).

To maintain the detector performances and operability at high temperature, the number of pixels exhibiting extra noise like 1/f and RTS noise must be limited. This paper presents the recent developments achieved at Sofradir in terms of HOT MCT extrinsic p on n technology, blue MW band (cut-off wavelength of 4.2μm at 150K) and extended MW band (cut-off wavelength of 5.3μm at 130K). Comparison between optimized and non-optimized technology will be presented in terms of NETD temperature dependency, 1/f noise and the corresponding impact on RFPN (Residual Fixe Pattern Noise) and its stability up to 170K will be shown. Correlation with RTS and DLTS studies will be discussed.

Optically-addressed visible/MWIR two-color photodetectors based on monolithically-integrated CdTe nBn and InSb PIN sub-photodetectors (Invited Paper)

Zhao-Yu He, Shi Liu, Calli Campbell, Maxwell B. Lassise, Ying-Shen Kuo, Zhi-Yuan Lin, Yong-Hang Zhang, Arizona State Univ. (United States)

Very recently, we have demonstrated CdTe and CdTe/MgCdTe heterostructures on lattice-matched InSb substrates with minority carrier lifetime longer than 2.7 μs and interface recombination velocity lower than 1 cm/s. All these numbers are either very close to or better than the best values reported for the well-studied GaAs/AlGaAs and GaAs/GalnP heterostructures. Using the novel optical addressing approach published in Ref. 1, we report here the design and demonstration of an optically-addressed two-color, single-polarity, and two-terminal photodetector consisting of monolithically-integrated and lattice-matched CdTe nBn and InSb PIN sub-photodetectors. The CdTe nBn sub-photodetector with an 820 nm cut-off and the InSb PIN sub-photodetector with a 5.5 μm cut-off are electrically connected through a highly conductive (≈ 0.1 Ω·cm) n-CdTe/p-InSb heterovalent interface. ZnTe is selected as the barrier layer for the CdTe nBn sub-photodetector because it has a nearly perfect band alignment to CdTe to achieve an nBn structure design, namely – 1 eV conduction band offset and = 0.1 eV valence band offset. Optical-addressing has been realized using an optical bias from a 633 nm CW laser. The response mode of the photodetector can be switched between the infrared and visible bands by turning on and off the optical bias at 77 K. More device performance, including the dark current, the spectral responsivities, the linearity of the photocurrent vs. the light power, and the optical crosstalk will be presented at the conference.

Monolithic quantum cascade lasers (Keynote Presentation)

Kwok Keung Law, Naval Air Warfare Ctr. Weapons Div. (United States)

Quantum cascade lasers (QCLs) are becoming main stream devices that are being incorporated into a variety of systems and sensing applications. Many advances have been made recently in mid-wave infrared and long-wave infrared quantum cascade lasers (QCLs) technologies. We will discuss in this presentation Naval Air Warfare Center Weapons Division’s efforts on significantly improving QCLs’ performance, affordability and reliability by means of monolithic integrations.

Determiministic temporal chaos from a mid-infrared quantum cascade laser subjected to external optical feedback (Invited Paper)

Frédéric Grillot, Louise Jumperz, Kevin Schires, Télécom ParisTech (France); Mathieu Carras, mirSense (France); Marc Sciamanna, CentraleSupélec (France)

Quantum cascade lasers (QCLs) are unipolar semiconductor lasers offering access to wavelengths from the mid-infrared (IR) to the terahertz
domain and promising impact on various applications such as free-space communications, high-resolution spectroscopy, LIDAR remote sensing or optical countermeasures [1,2]. Unlike bipolar semiconductor lasers, stimulated emission in QCLs is obtained via electronic transitions between discrete energy states inside the conduction band [2]. Recent technological progress has led to QCLs operating in pulsed or continuous wave mode, at room temperature in single- or multi-mode operation, with high powers up to a few watts for mid-IR devices [2,3]. This spectacular development raises multiple interconnections on the stability of QCLs as little is known on their dynamical properties. Very recently, experiments based on optical spectrum measurements have unveiled the existence of five distinct feedback regimes without, however, identifying the complex dynamics dwelling within the QCL [4]. In this paper, we provide the first experimental evidence of a route to chaos in a QCL emitting at mid-IR wavelength. When applying optical feedback with an increasing strength, the QCL dynamics bifurcate to periodic dynamics at the external cavity frequency and later to chaos without an undamping of relaxation oscillations, hence contrasting with the scenarios known in interband laser diodes [5].

References

9755-72, Session 19
Mid-infrared near-field investigations of semiconductor multilayers and of quantum cascade lasers coupled to metal nanostructures for single-mode emission (Invited Paper)
Yannick De Wilde, Institut Langevin (France)
The metal tip of a scanning probe constitutes a sub-wavelength scatterer, which can be used to map the electromagnetic near-field and measure its spectrum with a spatial resolution of tens of nanometers at mid-infrared wavelengths. In this presentation, we will firstly demonstrate the use of a mid-infrared scattering near-field microscope to investigate semi-conductor stacks made of doped/undoped InAs multilayers. Heavily doped semi-conductor layers behave as metals in the infrared. They can therefore support plasmonic modes confined at the interface which they exhibit with air or with the undoped semi-conductor layers. The surface plasmons modify the electromagnetic local density of states (EM-LDOS), which we have probed via measurements of the near-field thermal emission on the cleaved edge of a semi-conductor stack, in order to access the 300 nm semi-conductor layers individually. Secondly, we will present the near-field investigation of mid-infrared quantum cascade (QC) lasers. The implementation of an array of linear metallic nano-antennas on the top surface of the ridge of a QC laser is sufficient to result in a single mode emission of the laser. Scanning near-field investigations on the top surface of the device in operation have been performed to find out how the mode inside the laser cavity couples with the array of antennas.

ACKNOWLEDGMENTS
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9755-73, Session 19
Room-temperature continuous-wave operation of a terahertz molecular laser optically pumped by a quantum cascade laser (Invited Paper)
Jean-François Lampin, Institut d’Electronique de Microélectronique et de Nanotechnologie (France); Antoine Pagies, Guillaume Ducournau, Institut d’Electronique de Microélectronique et de Nanotechnologie (France)
It has been demonstrated in the 60’s and 70’s that laser oscillation in the THz range can be achieved by electrical or optical pumping of a low-pressure molecular gas at room temperature. Population inversion is obtained between two vibrationally excited states of the molecules. Nevertheless THz gas lasers are still bulky, heavy and necessitate dangerous high voltages which prevent their widespread use. We demonstrate here a THz gas laser pumped by a compact solid-state quantum cascade laser (QCL) instead of a bulky CO2 gas discharge laser. The unique properties of mid-infrared (MIR) QCLs allow us to obtain efficient CW laser oscillations on several tens of lines with only one kind of molecule. The low-pressure gas is contained in a specially designed high-Q metal cavity. The MIR power threshold is very low: a few mW are sufficient to obtain laser oscillation in the THz range. On the strongest lines the prototype generates an output power of about 40 µW and has a conversion efficiency of 0.6 mW/W. The generated spectrum was also measured thanks to subharmonic heterodyne conversion in the microwave range. A very small linewidth was obtained (< 1 MHz) and the central frequency was coherent with the expected values coming from molecular databases with a relative error below 10^-6. To our knowledge this is the first THz gas laser pumped by a solid-state source and it opens the way for compact, simple and efficient THz sources.

9755-74, Session 19
THz nonlinear optics with quantum cascade lasers: optical sideband generation up to room temperature (Invited Paper)
Sarah Houver, Armand Lebreton, Lab. Pierre Aigrain (France); Maria Amanti, Carlo Sirtori, Univ. Paris 7-Denis Diderot (France); Lianhe H. Li, Edmund H. Linfield, Giles Davies, Univ. of Leeds (United Kingdom); Jérôme Tignon, Sukhdeep Dhillon, Lab. Pierre Aigrain (France)
High-intensity THz sources has shown significant development over the last decade, permitting access to the new fields of nonlinear THz physics and spectroscopy. However, the sources remain expensive, large, and require a considerable operational know-how. We have recently demonstrated that it is possible to exploit the THz fields generated by a compact semiconductor source, the quantum cascade laser (QCL) [1], for THz nonlinear optics. By exploiting resonant nonlinearities of interband and intersubband transitions, we have shown [2, 3] nonlinear frequency mixing between a near infrared (NIR) pump and a THz beam within a QCL cavity i.e. sideband generation. Although relatively high efficiency and high order sideband generation have been demonstrated, these previous studies were inherently limited to cryogenic temperatures owing to the utilisation of THz QCLs. In this work, by appropriate design of the QCL and the resonance excitations, we demonstrate the resonant nonlinear process and sideband generation up to room temperature between a resonant near-infrared beam and the emission of a mid-infrared (MIR) QCL [4]. We further show that, although the phase-mismatch is large, this is compensated by the resonant nonlinearity and the fact the absorption becomes a more dominant process on the nonlinear process.
As well as the application of QCLs to nonlinear optics, this work can be applied to all-optical communication networks for large wavelength shifts between telecommunication bands and to the detection of MIR QCL emission using mature NIR techniques.


9755-96, Poster Session

Microwave radiation absorption and Shubnikov: de Haas oscillations in semimetal InAs/GaSb/AISb composite quantum wells

Maya P. Mikhailova, Anatoly I. Veinger, Igor V. Kochman, Petr V. Semenikhin, Ioffe Physical-Technical Institute (Russian Federation); Karina V. Kalinina, Ioffe Institute (Russian Federation); Robert V. Parfeniev, Vyacheslav A. Berezovets, Ioffe Physical-Technical Institute (Russian Federation); Alice Hospodka, Jiří Pangrác, Eduard Hulicius, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Magnetotransport, optical, spin-dependent and topological properties of the composite InAs/GaSb/AISb quantum wells (CQWs) based on the broken-gap heterojunctions are actively studied during last two decades as promising materials for spintronics and nanoelectronics applications. In this paper we report first study of absorption of microwave radiation and Shubnikov-de Haas oscillations in semimetal InAs/GaSb/AISb CQWs at low temperatures 2.7 - 20 K and in magnetic field H < 14 kOe. CQWs were grown by MOVPE on n+-GaSb (100) substrates with various widths of InAs QWs (15 nm or 12.5 nm) and GaSb (10 nm or 8 nm) surrounded by AISb barriers (30 nm) and GaSb cap layer (3 nm). Method of electron paramagnetic resonance spectroscopy was used and derive microwave power (dP/dH) was measured (f = 10 GHz). Intensive oscillations were observed at H > 7 - 14 kOe. Temperature and orientation dependence of Shubnikov-de Haas oscillation amplitudes were recorded. 2D-electron concentration was obtained from the filling factor dependence on inverse magnetic field. Cyclotron frequency and non-parabolicity of effective mass were evaluated for the samples with different QW widths. Unusual anisotropy of angular dependence of the oscillation amplitudes on orientation of CQW samples in magnetic fields was observed in the angle range from 0° up to 180°. Obtained results allow us to conclude that this effect can be explained by an inversion asymmetry which is the feature of substances with lack of inversion center.

9755-98, Poster Session

Superconducting single-photon detector with the capability of photon-number resolving and photon positioning

La Bao Zhang, Pen Gu, Xu Tao, Chao Wan, Min Gu, Lin Kang, Pei Heng Wu, Nanjing Univ. (China)

Superconducting nanowire single photon detectors (SNSPDs) have been characterized to be with a high sensitivity, short dead time, and low time jitter. But the ability of photon number resolving and photon positioning usually are rarely mentioned. In many fields, such as linear optics, fluorescence imaging, quantum computation, etc., the detector is required to have the ability to distinguish photon number and photon position. Based on a series structure of SNSPDs, we designed and fabricated a new photon-number resolving detector, which has 3 nanowire units, each nanowire unit connected to a resistor RP in parallel. The newly experimental results show that the detector can distinguish 2n-1 photons as well as their positions. Meanwhile, the system detection efficiencies (SDEs) of detector are greater than 40% at a wavelength of 1550nm and a temperature of 2.4 K.

9755-99, Poster Session

Dark current analysis in InGaAs-based mesa structured photodiode arrays

Halit Dolas, Serdar Kocaman, Middle East Technical Univ. (Turkey)

Short wavelength infrared (SWIR) band can provide many opportunities in infrared detection such as passive night vision due to good match to night glow, room temperature operation, compact machinery and high contrast/high resolution applications. We study on dark current optimization of lattice matched InP/In0.53Ga0.47As heterojunction p-i-n photodiodes at low bias regime both experimentally and theoretically. While planar structured detectors are more suitable for low dark current applications, we focused on mesa structured detectors considering their positive sides for future applications as dual color detection and high frequency performance due to lower capacitance. Test detector pixels with different perimeter/area ratios are processed onto epitaxial layers grown by Molecular Beam Epitaxy. I-V characteristics of test detectors are measured at room temperature and detailed I-V-T characterization is also performed. Based on the results, bulk and surface dark current components are differentiated and ohmic, diffusion, generation and recombination and trap assisted tunneling current mechanisms are taken into account to fit to the bulk component: Effect of absorbing In0.53Ga0.47As layer doping (n-type) on dark current is theoretically estimated and epitaxial layers with changing absorbing layer doping levels are produced. Doping levels are confirmed with C-V and Hall Effect measurements. Detector’s ROA values are estimated and optimum doping level as well as optimum biasing point that maximizes ROA value is obtained. In the light of these results, detectors with 25 µm pixel pitch and 640×512 format are fabricated. Wavelength depended spectrum, peak responsivity and peak detectivity values are measured. Experimental results are in good agreement with theoretical data.

9755-100, Poster Session

Diamond-based field sensor for nEDM experiment

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We have demonstrated EIT (Electromagnetically Induced Transparency) in the ground state of an NV center ensemble and are also investigating the existence of EIT associated with the excited state as well. NV centers in our diamond samples were created by electron irradiation followed by annealing in vacuum at 1000° C. Total internal reflection was used in a cleaved diamond chip to achieve a high optical depth of 4 at 77 K. Using an EOM, sidebands were generated in a red laser beam (637 nm). As the sidebands were scanned across the zero field splitting of the ground state, a broad anti-hole was observed around 2.87 GHz. The red laser ionizes the NV- centers to the neutrally charged, NV0 centers. We have demonstrated high contrast (around 8%) using a green laser which increases the NV0 to NV- ratio. We are also investigating the presence of excited state EIT features. Unlike the ground state however, the excited state transitions have a strong dependence on the local strain in the crystal and are thus harder to detect in a strain averaged ensemble.
Mid-infrared quantum cascade laser integrated with distributed Bragg reflector

Hiroyuki Yoshinaga, Jun-ichi Hashimoto, Hiroki Mori, Yukihiro Tsuji, Makoto Murata, Mitsuru Ekawa, Tsukuru Katsuyama, Sumitomo Electric Industries, Ltd. (Japan)

Quantum cascade lasers (QCLs) are promising as compact light sources in the mid-infrared region. In order to put them into a practical use, their relatively high threshold currents should be reduced. Facet reflectivity increase by distributed Bragg reflector (DBR) is effective for this purpose, but there have been few reports on DBR-integrated QCLs (DBR-QCLs). In this paper, we report a successful operation of a DBR-QCL in 7.7 µm wavelength region.

With the fabrication, an n-InP buffer layer, a core region consisting of AlInAs/GaInAs superlattices, an n-InP cladding layer, and an n-GaInAs contact layer were successively grown on an n-InP substrate using MOVPE in the first growth. Then, the wafer was processed into a mesa-stripe, and it was buried by an Fe-doped InP current-blocking layer to form a buried-heterostructure (BH) waveguide. After that, a DBR in which semiconductor-walls and air-gaps were alternately arranged was formed at the end of the cavity by dry-etching the epitaxial layers of the air-gap regions, and thus a DBR-QCL was fabricated.

A DBR-QCL chip (Mesa-width:10.7 µm, Cavity-length:1.5 mm) which had a DBR-structure consisting of 2 pairs of a 37/4-thick semiconductor-wall/37/4-thick air-gap at the rear end and a cleaved facet at the front end oscillated successfully under pulsed condition at 300 K. This is the first report on the InP-based DBR-QCL to our knowledge. The threshold current was 447.6 mA, which was about 20% smaller than that (560.9 mA) of the conventional QCL having no DBR-structure. This result clearly shows that the DBR-structure is effective for threshold current reduction of QCL.

Optimization of the epitaxial design of high current density resonant tunneling diodes for terahertz emitters

Razvan Baba, Univ. of Glasgow (United Kingdom); Ben J. Stevens, The Univ. of Sheffield (United Kingdom); Toshikazu Mukai, ROHM Co., Ltd. (Japan); Richard A. Hogg, Univ. of Glasgow (United Kingdom)

The THz spectrum attracts attention due to its potential in high wireless data rates with advantages in security and reduced interference. Resonant tunneling diodes (RTDs) have been coupled to antennas to radiate THz at room temperature, demonstrating 1.55 THz through harmonics. The InGaAs/AlAs/InP material system is advantageous in terms of high electron mobility, suitable band-offsets, and low resistance contacts.

We explore the design of high performance RTDs in this material system using a numerical simulator. In addition to well width and composition, barrier width, emitter and collector doping scheme, we explore a number of more advanced designs to maximize the extractable power of a Triz emitter, which is proportional to the product of the voltage and current span of the hysteretic region of the V-I characteristics of the RTD.

Since operating current densities are high, >1 MAc-m-2, catastrophic failure limits device area and current, so the operating voltage needs minimizing whilst maximizing the extractable power. We describe the interplay of parameters and highlight the importance of the emitter and collector doping scheme. For example, a variation of the unintentionally doped entry spacer layer thickness can be used to fine-tune the 1st quasi-bound state level (E1) and reduce the peak bias, whereas a thinner exit spacer broadens the resonance linewidth. Grading the QW such that the conduction band forms a more rectangular profile around resonance lowers E1 and increase Jpk, working around the reduction in density-of-states with increasing indium concentrations. An optimized structure utilizing asymmetric barriers, and a graded well is discussed.

Wide-field imaging of magnetic devices using solid state spins in diamond

Robert E. Scholten, David A. Simpson, The Univ. of Melbourne (Australia); Jean-Philippe Tetienne, The Univ. of Melbourne (France); Julia McCoey, Kumaravelu Ganesan, Liam Thomas Hall, Steve Petrov, Lloyd C. H.ollenberg, The Univ. of Melbourne (Australia)

Imaging of magnetic materials has been a key ingredient in the spectacular development of magnetic data storage. Important imaging criteria include spatial and time resolution, but also sensitivity, sample damage, field of view, cost and simplicity of use. Techniques based on electron or x-ray microscopy provide high spatial resolution down to a few nanometers, but require expensive complex apparatus, dedicated sample preparation and often vacuum environments. Magnetic force microscopy (MFM) and magneto-optical Kerr microscopy (MOKE) are routinely used for rapid characterization of magnetic devices but the magnetic tips used in MFM can impact the fragile magnetization states of the sample, and MOKE microscopy is restricted to materials that exhibit a measurable Kerr response. The development of a universal magnetic imaging technique which can be applied to any material producing a stray magnetic field and which operates with sub millisecond temporal resolution is highly desirable.

In this work, we demonstrate the magneto-optical response of an array of electronic spins in diamond for imaging sub-micron magnetization patterns from thin ferromagnetic films. Using optically detected magnetic resonance, we demonstrate wide-field magnetic imaging over 100 x 100 µm with a diffraction-limited spatial resolution of 440 nm and a temporal response of 10 ms under ambient conditions. In addition, we present an all-optical magnetic imaging approach which functions in the absence of an applied microwave field. Our technique establishes diamond-based wide-field microscopy as a new method for rapid, sensitive characterization and imaging of magnetic phenomenon in a host of magnetic materials.
photic devices with high efficiency, e.g., lasers, electro-optical modulators, and solar cells. To extend the functions of the materials system, diluted nitride and bismide has been paid attention over the past decade. They can largely decrease the band gap of the alloys, providing the greater tunability of band gap and strain status, eventually suppressing the non-radiative Auger recombinations. On the other hand, selective oxidation for AlGaaS is a vital technique for vertical surface emitting lasers. That enables precisely controlled oxides in the system, enabling the optical and electrical confinement, heat transfer, and mechanical robustness.

We introduce the above functions into GaAs nanowires. GaAs/GaAsN core-shell nanowires showed clear redshift of the emitting wavelength toward infrared regime. Further, the introduction of N elongated the carrier lifetime at room temperature indicating the passivation of non-radiative surface recombinations. GaAs/GaAsBi nanowire shows the redshift with metamorphic surface morphology. Selective and whole oxidations of GaAs/AlGaAs core-shell nanowires produce semiconductor/oxide composite GaAs/AlGaOx and oxide GaOx/AlGaOx core-shell nanowires, respectively. Possibly sourced from nano-particle species, the oxide shell shows white luminescence.

9755-77, Session 21

InAs/GaAs quantum dot infrared photodetectors monolithically grown on silicon substrates (Invited Paper)

Jiang Wu, Qi Jiang, Siming Chen, Mingchu Tang, Univ. College London (United Kingdom); Yurii I. Mazur, Gregory J. Salamo, Univ. of Arkansas (United States); Huiyun Liu, Univ. College London (United Kingdom)

Mid-infrared detectors in the 3–5 mm and 8–12 mm regime can be applied to a wide range of applications, including free-space communication, surveillance, and detection of chemical and biological agents. The state-of-the-art HgCdTe and III-V photodetectors have high quantum efficiencies but cannot be fabricated on large-scale substrates. The demand for high resolution focal plane arrays favours monolithic integration of detector arrays on a single Si substrate, which has been challenging HgCdTe as well as most III-V materials. In this paper, we present the direct integration of III-V quantum dot infrared photodetectors directly grown on Si substrates by molecular beam epitaxy. High quality InAs/GaAs quantum dots with low dislocations are achieved by optimizing the GaAs buffer layers on Si substrates. The optical and structural qualities of the quantum dot infrared photodetectors are characterized by photoluminescence and transmission electron microscopy measurements. Photoresponse at the mid-infrared spectral region has been demonstrated for the first time from the quantum dot infrared photodetectors monolithically grown on the Si substrates. The direct integration of quantum dot infrared photodetectors on Si substrates will benefit from the mature Si process technology and enable cost-effective large format mid-infrared focal plane arrays.

9755-78, Session 21

Miniature multispectral quantum-dot infrared photodetector for optical remote chemical sensing (Invited Paper)

Xuejun Lu, Univ. of Massachusetts Lowell (United States); Jarrod N. Vaillancourt, Applied NanoFemto Technologies LLC (United States)

In this paper, we report an surface plasmonic resonance (SPR) enhanced quantum dot infrared photodetector (QDIP) with on-chip multispectral sensing capability. The chip is packed in a standard TO-66 hermetically sealed package with thermal-electric-cooling. Chemical sensing of below 1 ppm level is demonstrated.

9755-79, Session 21

Performance analysis of polarization sensitive mid-infrared photodetector using anisotropic quantum dot (Invited Paper)

Jitendra Kumar, Satish K. Singh, Indian School of Mines (India)

In this study, normal incidence polarization sensitive photodetector has been proposed based on intraband transition of holes in valence band using InGaAs/GaAs quantum dots. The in-plane elongated dots have been considered for the analysis to get the polarization sensitive absorption for normal incidence of light. The dimensions of the dots and transitions are chosen such that the peak detection wavelength comes in mid-infrared spectral region. We have calculated the detector parameters such as absorption coefficient, quantum efficiency, photoconductive gain, photocurrent and dark current. The calculated absorption coefficient and photoconductive gain are found of the order of $10^{-4} \text{m}^{-1}$ and $10^{-5}$, respectively.

The impact of number of quantum dot layers on these parameters has been analyzed. We have found that increasing the number of quantum dot layers enhances the quantum efficiency and decreases the dark current of the device, but simultaneously photoconductive gain reduces drastically and because of this photocurrent of the devices also reduces. In spite of very low quantum efficiency of the photodetector with single QD layer, it can produce a significantly high detectable photocurrent due to large photoconductive gain of the device.

9755-80, Session 21

Hybrid-cavity quantum electrodynamics with quantum-dot circuits (Invited Paper)

Takis Kontos, Jérémie J. Viennot, Matthieu C. Dartiailh, Ctr. National de la Recherche Scientifique (France); Laure E. Bruhat, Ecole Normale Supérieure (France); Matthieu P. Desjardins, Audrey Cottet, Ctr. National de la Recherche Scientifique (France)

In this work, we aim at using the cavity quantum electrodynamics techniques to probe or manipulate the electronic states of quantum dot circuits. In this context, the coherent coupling of a single spin to photons stored in a superconducting resonator is an important milestone. Using a circuit design based on a nanoscale spin-valve, we implement an artificial spin-orbit interaction and coherently hybridize the individual spin and charge states of a double quantum dot made in a single wall carbon nanotube while preserving spin coherence. This scheme allows us to increase by five orders of magnitude the natural (magnetic) spin-photon coupling, up to the MHz range at the single spin level. Our coupling strength yields a cooperativity which reaches 2.3, with a spin coherence time of about 60ns. We thereby demonstrate a mesoscopic device which could be used for non-destructive spin read-out and distant spin coupling [1].

We have very recently extended such an architecture to Cooper pair splitters which could be used to study spin entanglement in condensed matter. We observe a vacuum Rabi splitting of the photonic mode when brought in resonance with transitions of the Cooper pair splitter. The implications on the coherent Cooper pair injection in such devices will be discussed.

CdSe and CdSe/CdS/Au heterostructures: in situ synthesis and self-assembly (Invited Paper)
Elena Shevchenko, Richard D. Schaller, Argonne National Lab. (United States)

Hybrid systems consisting of semiconductor and noble metals are considered to be promising materials in photocatalysis since the photoinduced generation of charge carriers in nanocrystals can lead to chemical transformation of molecular species. Detailed understanding of the interactions between constituents in multicomponent heterostructures is critical for further progress in material design and establishing structure-property correlations. Understanding charge transfer processes is important for design of efficient catalysts. The majority of the studies on charge transfer in semiconductor/noble metal heterostructures are conducted on end point systems. We will present in situ study of the nucleation and growth of Au on CdSe/CdS nanorods using synchrotron SAXS technique and time-resolved spectroscopy. We will discuss the evolution of the structural and optical properties of CdSe/CdS/Au heterostructures formed under UV illumination and in the darkness. Our data indicate similar photoluminescence (PL) quenching and PL decay profiles in both types of samples. Via transient absorption and PL, we will show that such behavior can be consistent with rapid (faster than 3 ps) hole trapping by gold sulfur sites at the surface of semiconductor nanoparticles. This dominant process was overlooked in previous end-point studies on semiconductor/metal heterostructures. We will also report on the self-assembly in anisotropic semiconductor nanostructures and discuss the possibility of lasing in such structures.

Photoluminescence of sequential infiltration synthesized ZnO nanostructures (Invited Paper)
Leonidas E. Ocola, Argonne National Lab. (United States); David J Gosztola, Angel Yanguas-Gil, Hyo Seon Suh, Argonne National Laboratory (United States); Aine Connolly, Vassar College (United States)

For the past several years there have been ongoing efforts to incorporate zinc oxide (ZnO) inside polymethyl methacrylate (PMMA), in the form of nanoparticles or quantum dots, to combine their optical properties for multiple applications. We have investigated a variation of atomic layer deposition (ALD), called sequential infiltration synthesis (SIS), as an alternate method to incorporate ZnO and other oxides inside the polymer. Energy dispersive spectroscopy (EDS) results show that we synthesize ZnO up to 300 nm inside a PMMA film using the SIS process. Photoluminescence data shows that we achieve a factor of 400X increase in photoluminescence (PL) intensity when comparing a blank Si sample and a 270 nm thick PMMA film, where both were treated at the same time with 12 cycles of (H2O/DEZ). We have proven that this is not just an effect of increased surface area by obtaining the PL spectra of the same PMMA sample after burning off the organic components in an oxygen rich furnace at 500 oC. The data from this sample is only 5X more intense than the blank Si sample. In addition, the annealing removed the oxygen vacancies as the visible PL peak is no longer present.

PMMA is a well-known ebeam resist. We can expose and develop patterns useful for photonics or sensing applications first, and then convert them afterwards into a hybrid oxide material with enhanced photonic, or sensing, properties. This is much easier than micromachining films of ZnO or other similar oxides because they are difficult to etch.

CdTe quantum dots fluorescent probes for determination of 2,4-dichlorophenol (DCP) compounds based on the Fe(III)PcTs-BuOOH catalysis system (Invited Paper)
Yilin Tong, Xuecai Han, Hongqi Li, Hankou Univ. (China)

A new fluorescent probe based on CdTe quantum dot fluorescence was established and studied for the determination of contaminant 2,4-dichlorophenol (DCP) compounds. In the presence of 4-AAP, DCP was catalyzed by iron(II) phthalocyanine (Fe(II)Pc), the reaction product dye was generated, which quench the fluorescence of CdTe quantum dots. t-BuOOH was added in the system to be as oxidizing agent, greatly accelerate the oxidation effect of DCP. The water soluble CdTe quantum dot was prepared. The effects of reaction conditions on the fluorescence and catalysis oxidation of DCP were studied and the optimal reaction conditions were obtained. In the concentration range of 1.0?10^-6mol/L~9.0?10^-6mol/L and 1.0?10^-5mol/L~1.3?10^-4mol/L, there is a good linear relationship between the change value of CdTe quantum dot fluorescence intensity P0/P and DCP concentration. This method has good repeatability and ability of resisting disturbance.

Operation of molecular devices and machines on surfaces (Invited Paper)
Saw Wai Hla, Argonne National Lab. (United States)

A recent emergent research direction is the development of complex molecular machines suitable to operate on solid surfaces. Unlike biological counterparts, the synthetic molecular machines may tolerate a more diverse range of conditions, and thus be advantageous for the complex functions with low power consumption suitable to operate in solid state devices. Development of such molecular devices requires testing their operation mechanisms. We use low temperature scanning tunneling microscopy, spectroscopy, and molecular manipulation schemes to investigate fundamental operations of synthetic molecular switches and molecular motors on metallic surfaces. Using inelastic electron tunneling process, individual molecules can be switched from one state to another in a controlled manner [1-4]. Controlled directional rotation of molecular motors can also be performed using the same technique. By adding dipole active rotator arms to molecular motors, communication between the motors is established via dipolar interactions. Synchronization of molecular motors can be achieved depending on the symmetry of the molecular assemblies on surfaces and thus opening future development of solid state compatible complex molecular machines for potential applications [5].


Semiconductor nanocrystals: energy transfer and biosensing applications (Keynote Presentation)
Richard D. Schaller, Argonne National Lab. (United States)

Colloidal semiconductor nanomaterials offer size-tunable energy gaps, large photoluminescence quantum efficiencies at room temperature, scalable synthesis, and low cost solution processing. Owing to these characteristics,
significant interest exists in the development of these materials for use in chemical and biological sensing applications. First, we examine energy transfer between particles as a function of geometry and find ultrastable energy transfer for the scenario of nanoplatelet-to-nanoplate. FRET between CdSe nanoplatelets of differing thickness can occur more rapidly than Auger annihilation, which suggests novel applications for lasing as well as for solar energy conversion. We have made use of nanoparticles in biological sensing applications where the large absorption cross-sections and high optical stability offer high sensitivity and long-term performance. Using these materials, conjugated to immunological components, we report a selective, stable, fast and sensitive all-optical pathogen detection assay.

9755-86, Session 24

Examples of modern quantum sensing and metrology with new results on photon-added coherent states (Invited Paper)

Jerome A. Luine, Northrop Grumman Aerospace Systems (United States); Anjali Singh, Northrop Grumman Electronic Systems (United States); Bryan Gard, Louisiana State Univ. (United States); Jonathan Olson, Louisiana State Univ. (United States)

Quantum sensing and metrology is the application of non-classical resources to the measurement of physical quantities with precision or accuracy beyond that allowed by classical physics. For many years non-classical resources such as atomic energy quantization, Josephson Effect, and Quantum Hall Effect have been used to define the fundamental units of time, voltage, and resistance, respectively. In recent years non-classical resources such as quantum squeezing and entanglement have been exploited to expand the range of physical phenomena measured with unprecedented precision or accuracy. In this presentation we will summarize some of the recent research on advanced quantum sensing and metrology. We also discuss recent analyses of beating the amplitude signal-to-noise ratio standard quantum limit for photon-added coherent states of light. These analyses take into account imperfect photon addition and detection processes.

9755-87, Session 24

Quantum state engineering and measurement with AlGaAs devices (Invited Paper)

Sara Ducci, Claire Autebert, Guillaume Boucher, Yacine Halioua, Qifeng Yao, Univ. Paris 7-Denis Diderot (France); Aristide Lemaitre, Carmen Gomez Carbonell, Ivan Favero, Giuseppe Leo, Lab. de Photonique et de Nanostructures (France)

Nonclassical states of light are key components in quantum information science; in this domain, the maturity of semiconductor technology offers a huge potential in terms of ultra-compact devices including the generation, manipulation and detection of many quantum bits. Among the different semiconductor platforms AlGaAs present the advantage of high second order nonlinearity and a direct band-gap having already led to the generation, manipulation and detection of many quantum bits. AlGaAs devices offer a huge potential in terms of ultra-compact devices including the generation, manipulation and detection of many quantum bits. Among the different semiconductor platforms AlGaAs present the advantage of high second order nonlinearity and a direct band-gap having already led to the generation, manipulation and detection of many quantum bits. Therefore, we have developed the first demonstration of an AlGaAs source emitting highly indistinguishable and energy-time entangled photons by spontaneous parametric down conversion (SPDC) process within the same device. In this talk we report the first demonstration of an AlGaAs source emitting highly indistinguishable and energy-time entangled photons by spontaneous parametric down conversion (SPDC) process within the same device. In this presentation we will show the control of the pump beam’s incidence spot and angle in a transverse pump configuration corresponds to phase space displacements of conjugate collective continuous variables of the biphoton opening the possibility to generate Schrödinger cat states. On the other hand we will discuss the reconstruction of both amplitude and phase of the joint spectrum.

9755-88, Session 24

Light-matter interaction: conversion of optical energy and momentum to mechanical vibrations and phonons (Invited Paper)

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

Reflection, refraction, and absorption of light by material media are, in general, accompanied by a transfer of optical energy and momentum to the medium. Consequently, the eigen-modes of mechanical vibration (phonons) created in the process must distribute the acquired energy and momentum throughout the material medium. However, unlike photons, phonons do not carry momentum. What happens to the material medium in its interactions with light, therefore, requires careful consideration if the conservation laws are to be upheld. In this presentation we address the mechanism by which the electromagnetic momentum of light is carried away by mechanical vibrations.

9755-89, Session 24

Technology study of quantum remote sensing imaging (Invited Paper)

Siwen Bi, Institute of Remote Sensing and Digital Earth (China)

At first the paper summarizes the demand background and application development of the remote sensing science technology. And it describes the research situation at home and abroad of quantum remote sensing and correlated imaging technology. Then it introduces the advantages of quantum remote sensing contrast with conventional remote sensing, which expounds quantum remote sensing imaging experiments and the development of the quantum remote sensing prototype. Base on these researches the paper elaborates the project of satellite-based quantum remote sensing active imaging. At last, it summarizes 15 years of the development of the quantum remote sensing and looks to the future.

KEY WORDS: Quantum Remote Sensing; Imaging Experiments; Prototype; Satellite-based Project; High Resolution

9755-90, Session 24

DFB-ridge laser diodes at 894nm for cesium atomic clocks (Invited Paper)

Nicolas von Bandel, Michiel Garcia, Michiel Lecomte, Alexandre Larrue, Yannick Robert, Olivier Driss, III-V Lab. (France); Florian Gruet, Univ. of Neuchâtel (Switzerland); Renaud Matthey, Univ. of Neuchâtel (Switzerland); Gaetano Milet, Univ. of Neuchâtel (Switzerland); Michel Krakowski, III-V Lab. (France)

Time-frequency applications need high accuracy and high stability clocks.
Compact industrial optically pumped Cesium beam standards are promising to address various demands. However, the stability of these clocks relies strongly on the performances of laser diodes that are used for optical pumping and detection. This issue has led the III-V Lab to commit to the European Europadies "LAMA" project that aims to provide competitive compact optical cesium clocks. We have designed, fabricated and tested Distributed-Feedback laser diodes (DFB) at 894nm (D1 line of Cesium) and 852nm (D2 line). The use of D1 line for pumping will provide simplified clock architecture compared to D2 line pumping thanks to simpler atomic transitions and larger spectral separation between lines in the 894nm case. The laser modules should provide narrow linewidth (<1MHz), very good reliability in time and be insensitive to optical feedback. The new development of the 894nm wavelength is grounded on our previous results for 852nm DFB. We show results from Al-free active region with InGaAsP quantum well Ridge DFB lasers.

We obtain the D1 Cs line (894.4 nm) at 64°C and 150mA (optical power of 40mW) with a high side mode suppression ratio. The wavelength evolution with temperature and current are respectively 0.06nm/K and 0.0035nm/mA. The laser linewidth is less than 1MHz. The Relative Intensity Noise (RIN) and the frequency noise are respectively less than 10-12 Hz-1 @ f ≥ 10 Hz and 109 Hz/Hz @ f = 10 Hz.

9755-92, Session 25

Hollow-core waveguide for single-mode laser beam propagation in the spectral range of 3.7-7.3 µm (Invited Paper)

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Hollow-core waveguides (HCWs) are optical fibers for single mode beam delivering in the mid-infrared spectral range. A HCW is composed of a hollow glass capillary tube with a circular cross-section geometry and metallic/dielectric layers deposited inside the bore. The spectral response of an HCW is determined by the thickness of the dielectric layer, while the bore diameter and the optical coupling conditions between the fiber and the light source determine the quality of the output beam profile. HCWs with bore diameters d ≤ 30 times the wavelength provided low-loss mid-IR beam propagation with a single spatial mode. In particular, HWGs with a bore size d = 300 µm were successfully employed in the 9-11 µm spectral range, while reducing d to 200 µm allows providing single mode operation down to 5.1 µm.

In this work, we investigated the possibility of extending HCW single mode operation to shorter wavelengths, by employing HCWs with d = 200 µm and internal silver/silver iodine layers, designed to improve the spectral response down to 3 µm. We used HCWs having different lengths (15, 30 and 50 cm) and quantum cascade laser sources operating in the spectral range 3.7-7.3 µm. Despite the limited spatial quality of the input laser beams, by optimizing the launch conditions of the beam at the waveguide entrance, low propagation losses close to theoretically prediction were obtained. Single-mode output beam profiles with good spatial beam quality were achieved down to 3.7 µm.

9755-93, Session 25

Mid-infrared dual-comb spectrometer based on QCL technology

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We develop a spectrometer for laboratory and industrial applications based on semiconductor quantum cascade laser frequency combs. The platform's key features are an unmatched combination of bandwidth (100 cm⁻¹), resolution (100 kHz), speed (10 µs) and robustness (no moving parts). This opens the door to beforehand not addressable applications. The broadband yet high-resolution and high-brightness nature of the source allows measuring samples which are otherwise opaque to less bright sources with broad absorption features even when masked by complex background absorption.

Recent development in the field of dual-comb spectroscopy based on QCL frequency combs mainly concentrated on using free-running QCL combs. This resulted in strong drifts of fcoe and frep in the multi-heterodyne measurement. These drifts can be corrected for in the digital domain using well-known signal-processing algorithms. The clear advantage of
such an approach is the simplicity of the optical setup. However, one main drawback is the increased power consumption due to the demanding signal-processing speeds. With the vision of portable applications in mind, this may become a major problem. We investigate the possibility to stabilize the multi-heterodyne signal by various techniques such as master-slaving or RF-injection. We thoroughly compare the spectroscopy relevant noise-characteristics of the stabilized and the free-running setup.

9755-94, Session 26
Design and fabrication of Fe2O3 plasmonic nanostructures (Invited Paper)
Naresh C. Das, Joshua MacClure, Kyle Grew, Deryn D. Chu, U.S. Army Research Lab. (United States)

Recently the use of Fe2O3 nano plasmonic structure for energy harvesting has received renewed interest among many researchers [1]. Among the various semiconductor photo-electrode materials, hematite (Fe2O3) has received much attention due to its favorable optical band gap (-2.2 eV), excellent chemical stability in high pH media, natural abundance, and low cost [2]. However, Fe2O3 exhibits a relatively poor absorbivity of photons near its band-edge due to an indirect band gap, poor electronic conductivity (PEC), and picosecond recombination of excited states, thus leading to a photo-generated hole diffusion length of ~2-4 nm [3]. These non-ideal optoelectronic properties hinder the transport of photo-generated carriers and increase the recombination rate, which results in a lowering of the PEC efficiency compared to theoretically predicted values. Controlling the nanostructure of Fe2O3 may provide an effective technology for overcoming the aforementioned problems of Fe2O3 due to the geometry and mechanism-dependent semiconductor structure [4]. The shape of the Fe2O3 structures with cone, cylinder, sphere, etc. features alters the electric field dependent absorption and transport processes.

In this study, we use an inductively coupled plasma (ICP) etching process to define various Fe2O3 nano-structured films. After depositing the Fe2O3 film using e-beam evaporator we use either e-beam lithography or optical lithography to define pattern the plasmonic nanostructures. We use Ar plasma process and vary the ICP power, pressure and substrate temperature etc. to optimize the etching process. Scanning electron (SEM) and atomic force (AFM) microscopy tools determine the surface morphology of the nanostructures, whereas ellipsometer and UV-Vis spectrometer elucidate the optical properties. We find that in order to achieve a smooth surface and reasonable etch rate, the substrate temperature should be between 15-18 °C and the ICP power between 800-1000 W. Detailed processing and characterization results of Fe2O3 nano plasmonic structures will be presented in a full paper.

9755-104, Session 26
Optomechanical sensing of forces and liquids with miniature disk resonators (Invited Paper)
Biswaup Guha, Eduardo Gil Santos, Univ. Paris 7-Denis Diderot (France); Aristide Lemaître, C. Gomez, Lab. de Photonique et de Nanostructures (France); Giuseppe Leo, Sara Ducci, Ivan Favero, Univ. Paris 7-Denis Diderot (France)

Optomechanical systems based on nano-photonic devices are pushing forwards the art of precision motion measurement and quantum mechanical control [1]. Here, we present applications of such systems in a different context, showing that they can bring conceptual and technical novelty when it comes to measure force fields and liquids. To that purpose, we employ miniature Gallium Arsenide optomechanical disk resonators [2] (typically 500 nm to 5 um radius and 200 to 300 nm thickness) where high-Q optical whispering gallery modes couple to high frequency (100 MHz-3GHz) mechanical modes. These resonators confine both optical and mechanical energy in a miniature interaction volume, leading to a giant optomechanical coupling g0 [3,4].

With these advantageous features in hands, I will discuss how optomechanical interactions can help us to measure and analyze electromagnetic forces of different types with enhanced resolution. I will also show how physical interactions with a surrounding liquid can be probed with unprecedented sensitivity and speed [5].

References
Optical antennas: spontaneous emission faster than stimulated emission (Invited Paper)
Eli Yablonovitch, Univ. of California, Berkeley (United States)

Antennas emerged at the dawn of radio for concentrating electromagnetic energy into a small volume $< \lambda^3$, allowing for nonlinear radio detection. Such coherent detection is essential for radio receivers, and has been used since the time of Hertz. Conversely, an antenna can efficiently extract radiation from a sub-wavelength source, such as a small cellphone. Likewise, antennas can accelerate spontaneous emission from a small quantum dot or molecule, whose emission rate can become faster than stimulated emission. Antennas interact equally, with real electromagnetic fields, as well as the quantum zero point field fluctuations that are responsible for spontaneous emission. Regrettably, antenna physics is hardly addressed within the Physics curriculum. Whether from Jackson, the Feynman Lectures, or Yariv, it's hard to learn the true beauty of antenna science.

This talk will commence with a pedagogic description of the three most important parts of antenna physics: 1. The Radiation Resistance; 2. The Electromagnetic Capture Cross-Section; 3. The Wheeler Limit on antenna Q. These properties are encapsulated in an antenna equivalent circuit that provides us with physical understanding. Since antennas are intended to work at frequencies well below the plasma frequency, plasmonic effects are usually inerts to the underlying antenna properties.

Electrically tunable metafilm devices (Invited Paper)
Mark L. Brongersma, Geballe Lab. for Advanced Materials (GLAM) (United States)

No Abstract Available

Recent advances in cavity optomechanics (Invited Paper)
Tobias J. Kippenberg, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

No Abstract Available

Design and characterization of dielectric subwavelength focusing lens with polarization dependence
Sung Woon Kim, Lin Pang, Yeshiahu Fainman, Univ of California San Diego (United States)

We introduce and develop design, fabrication and characterization methodology for engineering the effective refractive index of a composite dielectric planar surface created by controlling the density of deeply subwavelength low index nanoholes (e.g., air) in a high index dielectric layer.
Metasurfaces have attracted a growing interest for their ability to artificially tailor any electromagnetic response on various spectral ranges. In particular, thermal sources with unprecedented abilities, such as directionality or monochromaticity, have been achieved with spatially uniform far field properties. However, the modulation of the emissivity at the wavelength scale remains a challenge and is at the crux of a new generation of emitters. Here, we study a metasurface made of a non periodic set of optical antennas that spatially and spectrally controls the emitted light up to the diffraction limit. Each antenna acts as a subwavelength single emitter for a given polarization and wavelength. Their juxtaposition below the diffraction limit spectrally encodes the emissivity in both polarizations, and on a wider scale encodes hyperspectral and polarized images. This opens up many promising straightforward applications such as optical storage, anti-counterfeit devices and hyperspectral emitters for biochemical sensing.

9756-10, Session 3

Quarter-wavelength metamaterial antireflection coating

Wonkyu Kim, The Univ. of Alabama in Huntsville (United States); Joshua Hendrickson, Air Force Research Lab. (United States); Junpeng Guo, The Univ. of Alabama in Huntsville (United States)

A metamaterial structure consisting of 1D metal/air-gap subwavelength nanograting is investigated for antireflection coating on germanium substrate in the infrared regime. For incident polarization perpendicular to the subwavelength metal lines, the metamaterial exhibits effective dielectric property and Fabry-Perot like plasmon-coupled optical resonance results in complete elimination of reflection and enhancement of transmission. It is found that the metamaterial antireflection structure does not require a deep subwavelength grating period, which is desirable for device fabrication. Also, it is found that the thickness of the anti-reflective metamaterial layer scales approximately as a quarter of the anti-reflection wavelength.

9756-11, Session 3

Modeling refractive metasurfaces in series as a single metasurface

Fatima Toor, Ananda C. Guneratne, The Univ. of Iowa (United States)

Metasurfaces are boundaries between two media that are engineered to induce an abrupt phase shift in propagating light over a distance comparable to the wavelength of the light. Metasurface applications exploit this rapid phase shift to allow for precise control of wavefronts. The phase gradient is used to compute the angle at which light is refracted using the generalized Snell’s Law. In practice, refractive metasurfaces are designed using a relatively small number of phase-shifting elements such that the phase gradient is discrete rather than continuous. Designing such a metasurface requires finding phase-shifting elements that cover a full range of phases (a phase range) from 0 to 360 degrees. We demonstrate an analytical technique to calculate the refraction angle due to multiple metasurfaces arranged in series without needing to account for the effect of each individual metasurface. The phase gradients of refractive metasurfaces in series may be summed to obtain the phase gradient of a single equivalent refractive metasurface. This result is relevant to any application that requires a system with multiple metasurfaces, such as biomedical imaging, wavefront correctors, and beam shaping.
Ultrafast switching in nonlinear dielectric metasurfaces with magnetic resonances

Polina P. Vabishchevich, Maxim R. Shcherbakov, Alexander S. Sorokhov, Lomonosov Moscow State Univ. (Russian Federation); Katie E. Chong, Duk-Yong Choi, Isabelle Staudie, Andrey E. Miroshnichenko, Dragomir N. Neshev, The Australian National Univ. (Australia); Andrey A. Fedyanin, Lomonosov Moscow State Univ. (Russian Federation); Yuri S. Kivshar, The Australian National Univ. (Australia)

All-optical signal processing is one of the important directions of photonics aimed at achieving high-speed signal processing functionalities that can potentially operate at the line rate of fiber optic communications. All kinds of nanostructures have been suggested for ultrafast all-optical switching but many of such approaches suffer from slow efficiency and losses, especially when metal elements are used. As a promising alternative to metallic structures, high-permittivity all-dielectric nanoparticles and nanostructures that utilize localized magnetic resonant Mie modes can be used. The main idea of this work is to design and fabricate a magnetic-resonance-based nanoscale all-optical switch. The samples under study comprise arrays of 130-nm-thick nanodisks with radii from 105 nm to 140 nm made of hydrogenated amorphous silicon as a material with large nonlinearities and fast carrier recombination times. In z-scan experiments a nonlinear self-modulation of up to 60% and a spectral resonance shift by 6 nm when pumping the metasurface at picosecond-per-disk powers were detected. Both I-scan and pump-probe measurements were conducted to unambiguously separate two-photon absorption contributions from the photogenerated free carrier and thermal contributions. The pump-induced modulation of the probe beam is a pulse-limited instantaneous process with the modulation time of 65 fs due to two-photon-absorption. Finally, we have provided a recipe to suppress undesirable contributions from free carriers by tailoring the Mie-type resonance position, thus making such dielectric metasurfaces the fastest nanoscale switches reported thus far.

A wide-range tunable reconfigurable graphene-based THz nanopatch Antenna

Hasan Goktas, Yuming Ren, Volker J. Sorger, The George Washington Univ. (United States)

Here we show a RF antenna design featuring a highest tunable and reconfigurable range. We utilize the physical properties of graphene towards delivering ultra-wide tunable antennas of micron-scale dimension for emerging internet-of-things technologies. We aim for 10-100x improvements in frequency-to-size scaling & data bandwidth while demonstrating highest tunability for short-range communication links. Current THz antennas are bulky and do not allow for miniaturization while keeping the frequency low due to a linear dispersion relation. Here, we utilize the plasmonic character of graphene to address the dispersion-size-frequency challenge of current THz antennas, which also enable an effective index of the antenna field tunable via changing the chemical potential. This effect is instantaneous (fs-timescale) and allows for 140+ % of frequency tuning range. In addition a variety of physical tuning options for an suspended graphene-based THz antenna considered including i) Chemical Potential via the complex conductivity, and further the effective index of the graphene plasmons are influenced by the chemical potential on graphene, which can be tuned via a capacitive gate voltage. iii) Joule Heating: Passing a current through graphene heats the strip, which changes the complex conductivity. iv) ITO Permittivity Change: We previously demonstrated refractive index tuning in ITO via the Drude model. Applications of reconfigurable these antennas are able to drive a new generation of RF devices. This novel antenna can be implemented in health-care, security screening, or swarm-like drone technology.

Enhanced light collection of photons by all solid-state architectures

Oliver Benson, Humboldt-Univ. zu Berlin (Germany)

Nanoscopic light sources down to the size of a single emitter are key elements of highly integrated electro-optical nanostructures. A major problem is how to direct and collect the emission with high efficiency. Ideally, even the emission rate can be enhanced by the Purcell effect. In this presentation we introduce concepts based on all solid-state architectures. A first approach concerns diamond-based emitters (nitrogen vacancy or silicon vacancy centers), which can be integrated in plasmonic or dielectric antenna structures. A second strategy utilizes growth of layered structures with tailored dispersion. In this way hyperbolic metamaterials with directly integrated infrared emitters can be fabricated. We describe the assembly and fabrication of these different structures and discuss their enhanced optical functionality.

Hybrid multilayer nanophotonic material platform and devices

Ali Asghar Eftekhar, A. H. Hosseinkinia, Majid Sodagar, Hesam Moradinejad, Amir H. Atabaki, Ali Adibi, Georgia Institute of Technology (United States)

Hybrid multi-layer nanophotonic platforms enable to integrate different functionalities that cannot be achieved in a single material platform. We present passive multi-layer material platforms based on three-dimensional integration of different photonic materials such as multi-layer silicon on isolator (SOI) and hybrid silicon/Silicon nitride (SiN) materials.
furthermore demonstrate low-loss coupling between different material layers based on inter-layer grating coupling and evanescent adiabatic coupling and demonstrate a series of new devices that are enabled by such material platforms.

9756-19, Session 5

Optomechanics in single-crystal diamond
(Invited Paper)

Paul E. Barclay, Univ. of Calgary (Canada)

We present recent progress in performing optomechanics experiments from single crystal diamond nanophotonic devices. These devices have ultra-low mechanical dissipation and strong optomechanical coupling, and can be used to study nonlinear nanomechanical effects, for sensing experiments, and for coupling nanomechanical resonances to diamond impurities such as NV centres.

9756-20, Session 5

Integrated III-V photonic crystal-Si waveguide platform with tailored optomechanical coupling

Viktor Tsirkin, Alessandro Surrente, Ctr. National de la Recherche Scientifique (France); Fabrice Raineri, Lab. de Photonique et de Nanostructures (France) and Univ. Paris 7-Denis Diderot (France); Grégoire Beaudoin, Rama Raj, Isabelle Sagnes, Isabelle Robert-Philip, Lab. de Photonique et de Nanostructures (France); Rémy Braive, Lab. de Photonique et de Nanostructures (France) and Univ. Paris 7-Denis Diderot (France)

Optomechanical systems, in which the vibrations of a mechanical resonator are coupled to an electromagnetic radiation, have permitted the investigation of a wealth of novel physical effects. To fully exploit these phenomena in realistic circuits and to achieve different functionalities on a single chip, the integration of optomechanical resonators is mandatory. Here, we propose a novel approach to heterogeneously integrated arrays of two-dimensional photonic crystal defect cavities on top of silicon-on-insulator waveguides. The optomechanical response of these devices is investigated and evidences an optomechanical coupling involving both dispersive and dissipative mechanisms. By controlling the optical coupling between the waveguide and the photonic crystal, we were able to vary and understand the relative strength of these couplings. This scalable platform allows for unprecedented control on the optomechanical coupling mechanisms, with a potential benefit in cooling experiments, and for the development of multi-element optomechanical circuits in the framework of optomechanically-driven signal-processing applications.

9756-21, Session 5

Demonstration of hetero optomechanical crystal nanobeam cavities with high mechanical frequency

Zhilei Huang, Kaiyu Cui, Guoren Bai, Yongzhuo Li, Xue Feng, Fang Liu, Wei Zhang, Yidong Huang, Tsinghua Univ. (China)

Optomechanical crystal is a combination of both photonic and phononic crystal. It simultaneously confine light and mechanical motion and result in strong photon-phonon interaction, which provide a new approach to deplete phonons and realize on-chip quantum ground state. It is promising for both fundamental science and technological applications, such as mesoscopic quantum mechanics, sensing, transducing, and so on. Here high optomechanical coupling rate and efficiency are crucial, which depends on the optical-mechanical mode-overlap and the mechanical frequency (phonon frequency), respectively. However, in the conventional optomechanical-crystal based on the same periodical structure, it is very difficult to obtain large optical-mechanical mode-overlap and high phonon frequency simultaneously.

We proposed and demonstrated nanobeam cavities based on hetero optomechanical crystals with two types of periodic structure. The optical and mechanical modes can be separately confined by two types of periodic structures. Due to the design flexibility in the hetero structure, the optical field and the strain field can be designed to be concentrated inside the optomechanical cavities and resemble each other with an enhanced overlap, and at the same time, high phonon frequency can be obtained. A record high optomechanical coupling rate of 1.3 MHz and a record high phonon frequency of 5.8GHz are estimated theoretically. The proposed cavities are fabricated as cantilevers on silicon-on-insulator chips. The measurements indicate that a mechanical frequency as high as 5.66 GHz is obtained in ambient environment, which is the highest frequency demonstrated in one-dimensional structure.

Diamond optomechanical crystals

Michael J. Burek, Harvard Univ. (United States); Justin D. Cohen, Sean M. Meenehan, California Institute of Technology (United States); Thibaud Ruelle, Srijan Meesala, Harvard Univ. (United States); Oskar J. Painter, California Institute of Technology (United States); Marko Loncar, Harvard Univ. (United States)

Single-crystal diamond – renowned for its optical and mechanical properties – is also rich in lattice defects revealing the optical activity of their electronic and vibrational transitions. The past two decades have seen tremendous advances in our ability to prepare and control the quantum states of these solid state atom-like systems, including the manipulation of the diamond nitrogen vacancy center electronic spin by mechanical oscillators via strain-based coupling. The latter has accelerated development of nanoscale mechanical and photonic systems in diamond for future on-chip hybrid quantum architectures that rely on coherent spin-phonon-photon interactions for spin transduction and quantum state transfer. Herein, we demonstrate such a system: diamond optomechanical crystals, where the co-localization of photons and phonons in a quasi-periodic diamond nanostructure enables coherent coupling of wavelength scale...
optical cavities to mesoscopic mechanical excitations via the radiation pressure of light. Fabricated diamond optomechanical crystals support optical and mechanical resonances at ~195 THz and 6 GHz, respectively, with corresponding quality-factors (Q) on the order of Qo ~ 10^5 and Qm ~ 10^3. The measured single-photon optomechanical coupling rate was approximately 100 kHz. Due to diamond's large bandgap and lack of two- and multi-photon absorption, the intracavity photon population was driven beyond 150,000 photons, exceeding an cooperativity of ~1 at room temperature, enough to observe large amplitude optomechanical self-oscillations. Diamond atom-like defects coupled to such monolithic diamond optomechanical crystals may ultimately provide a coherent interface between optical, mechanical, and electronic quantum systems, enabling studies such as quantum nonlinear optomechanics and spin-squeezing.

9756-22, Session 6

Confinement and interaction of elastic and electromagnetic waves in phoxonic crystal cavities (Invited Paper)

Yan Pennecl, Said El Jallal, Bahram Dijafari-Rouhani, Univ. des Sciences et Technologies de Lille (France)

Phoxonic crystals are periodic structures that can exhibit dual phononic and photonic band gaps, thus allowing the simultaneous confinement of both acoustic and optical waves inside the same defect such as a cavity or a waveguide. Then, one can expect an enhancement of the phonon-photon interaction for the purpose of novel optomechanical devices, in particular for the modulation of light by acoustic waves.

We study theoretically the optomechanic interaction in different two-dimensional, slabs, and strips phoxonic crystals cavities taking into account both mechanisms that contribute to the acousto-optic interaction, namely the photoelastic and moving interface effects. The strength of the acousto-optic coupling is evaluated and analyzed for each phonon-photon pair by calculating either the modulation of the photonic frequency by the acoustic mode or the so-called coupling rate. The contributions of the photoelastic and moving interfaces effects can have similar or very different magnitudes. Moreover, they can be in phase and add together or be out of phase and partly cancel each other. We can notice that, due to symmetry reasons, only acoustic modes having a specific symmetry can couple to photonic modes. We also discuss the influence of the material properties as concerns the photoelastic effect since the latter strongly changes when the optical frequency approaches the energy of the direct band gap. Finally these coupling features are extended to the field of plasmonics with a calculation of the modulation of the plasmonic mode due to the elastic vibrations of the cavity excited at one of its acoustic resonances.

9756-23, Session 6

Thermal and mechanical features of Si-based 2D phononic crystal membranes

Bartlomiej Graczhokowski, Markus R. Wagner, Marianna Sledzinska, Juan S. Reparaz, Institut Català de Nanociència i Nanotecnologia (ICN2) (Spain); Alexandros El Sachat, Institut Català de Nanociència i Nanotecnologia (ICN2) (Spain) and Univ. Autònoma de Barcelona (Spain); Francesc Alzina, Institut Català de Nanociència i Nanotecnologia (ICN2) (Spain); Clivia M. Sotomayor Torres, Institut Català de Nanociència i Nanotecnologia (ICN2) (Spain) and Catalana de Recerca i Estudis Avançats (Spain)

Research over the last 10 years has shown that nanoscale phononic crystals (PnCs) can be efficiently applied for the control of hypersound and engineering of the thermal transport in solids. The thermal conductivity can be significantly decreased with respect to that of the bulk, e.g., down by two orders of magnitude for Si-based PnCs. In this study we consider two types of 2D PnCs, solid-air and solid-solid, made of thin Si membranes. The results obtained by Brillouin spectroscopy show how the volume reduction or local resonances, both accompanied by a periodicity, modify the dispersion of GHz acoustic phonons. The experimentally observed features, such as zone folding, frequency bad gaps, and 3D localization are compared with results of finite element method calculations. Regarding the heat transport in such materials, in contrast to previous studies, we use a novel and non-contact technique based on Raman thermometry, where two lasers are used to heat and probe the sample. The results obtained for a wide range of temperatures show a clear reduction of thermal conductivity as a function of porosity of the holey PnCs. A comparative study of membranes with and without a periodic array of Al pillars touches the still open question regarding the role of phonon dispersion of PnCs on the thermal conductivity. Moreover, we address the important issue, in the viewpoint of potential applications, of the influence of air convective cooling on the heat dissipation in PnCs.

9756-24, Session 6

Design of high-quality pillar-based phononic crystal structures

Razi Dehghannasiri, Reza Pourabolghasem, Ali Asghar Eftekhar, Ali Adibi, Georgia Institute of Technology (United States)

A theoretical design for a waveguide/resonator device operating at the GHz frequency range based on the pillar-based phononic crystal (PnC) membranes is presented, and the experimental evidence is provided for the waveguiding property of the proposed structure. The details of the design and optimization process including the careful selection of the geometrical dimensions of the structure as well as the frequency of operation (i.e., 1050 MHz) is provided. It is shown that the experimental results are in reasonable agreement with the results predicted by the finite element simulations.

9756-25, Session 6

Integrated phononic crystal structures using surface acoustic waves

Reza Pourabolghasem, Razi Dehghannasiri, Ali Asghar Eftekhar, Ali Adibi, Georgia Institute of Technology (United States)

Ease of fabrication, compatibility with the back-end CMOS process, and higher robustness of surface acoustic wave (SAW) devices as compared with he slab-based devices make them a promising candidate for commercial applications. In this talk, we will present pillar-based surface SAWs at GHz frequencies that are fully compatible with CMOS fabrication and can be easily integrated or complemented with CMOS circuitry. We will discuss the details of bandgap formation and optimization of the phononic crystal unit cell to open up large phononic bandgap at GHz frequencies. Efficient waveguiding of phonons in these SAW-based phononic crystal structures will also be discussed.

9756-26, Session 7

Fundamental bounds for nonlinearity-based optical isolation (Invited Paper)

Dimitrios Sounas, Andrea Alù, The Univ. of Texas at Austin (United States)

Reciprocity is the symmetry in wave transmission when traveling in opposite directions and, as a consequence of time-reversal symmetry, is a fundamental requirement in many systems. On the other hand, breaking
Shedding light on the spin properties of photons and their potential applications, integer spin is a fundamental property of photons, with two eigenstates corresponding to the two circular polarization states of light. In general, a spin-one particle has three spin eigenstates, however, for photons the third, zero spin eigenstate is forbidden by relativity. This raises an interesting and important question: Is it possible to engineer photonic environments harnessing an enlarged spin space?

Our solution to this question is based on an analogy between “real” spin and the so-called “pseudospin”, which describes the distribution of a light field between different microscopic states, such as the sublattices of a photonic lattice. Thereby, pseudospin is a general concept, appearing in any photonic system with conical intersections.

Conical diffraction is a signature of conical intersections of energy bands in a system’s dispersion relation [1] and the simplest type of conical intersection is called “Dirac cone”. It appears in the electron band structure of graphene and, similarly, in the spatial spectrum of honeycomb photonic lattices [2]. Here, propagation of light with the spectrum near Dirac cone mimics the evolution of relativistic spin- particles.

In this contribution, we overcome the limitation of the spin space to only two states and experimentally demonstrate the generic impact of higher pseudospin states on wave dynamics, in particular on conical diffraction. We investigated light propagation in a two-dimensional Lieb lattice [3,4] inscribed in fused silica glass, displaying a generalization of Dirac cones to higher-order conical intersections hosting integer pseudospin eigenstates [5]. With this results, we present a significant advance to photonics, by opening up a “third dimension” to the spin of light.

resolution of 60nm. We also demonstrate the possibility to image spatial heterogeneities within crystalline ferroelectric BaTiO3 nanoparticles (70-500nm size), evidencing the existence of a centrosymmetric shell that is predicted from structural analyses but not detectable by traditional nonlinear optical microscopy.

9756-30, Session 7

**Time-harmonic optical chirality in inhomogeneous space**

Philipp Gutsche, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Lisa V. Poulikakos, ETH Zürich (Switzerland); Martin Hammerschmidt, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Sven Burger, Frank Schmidt, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany) and JCMwave GmbH (Germany)

Optical chirality has been recently suggested to complement the physically relevant conserved quantities of the well-known Maxwell’s equations. This time-even pseudoscalar is expected to provide further insight in polarization phenomena of electrodynamics such as spectroscopy of chiral molecules.

The two circular polarization states of propagating plane waves are chirality eigenstates and can be distinguished from one another with the help of optical chirality. This offers the possibility to introduce polarization states of electromagnetic energy in a chiral polarization basis.

Optical chirality density and the corresponding flux in conjunction with the common energy density and Poynting flux are used to compute the left and right circular polarized energy coefficients. We introduce this extended view on established electromagnetic energy by defining a complex energy number which illustrates the new polarization basis representation.

Previously, the continuity equation of optical chirality was stated for homogeneous lossless media only. We extend the underlying theory to arbitrary setups and analyse piecewise-constant material parameters in particular. The newly introduced complex energy number shows that the notion of chirality conversion in analogy to absorbed energy is required for the generalized conservation law.

Our implementation in the Finite Element solver JCMsuite is presented and applied to illustrative examples. This serves as a comprehensible introduction of the novel tool of chirality conservation for the analysis of time-harmonic simulations of nano-optical devices.

9756-31, Session 7

**Inverse design engineering of all-silicon polarization beam splitters**

Lars H. Frandsen, Ole Sigmund, Technical Univ. of Denmark (Denmark)

On the venture to reduce the size of integrated optical devices while keeping a high level of performance, inverse design engineering (iDE) has shown to be an attractive concept to remove geometrical restrictions and to allow a larger parameter space to be included in the design phase, thus, paving the way for objective-driven ultra-compact and optimal design solutions. However, IDE typically leads to a complex and subwavelength nanostructuring of the semiconductor photonic devices and sets tough requirements to the fabrication procedure, which normally requires state-of-the-art electron-beam lithography. This is presently not compatible with mass-fabrication technologies such as deep-UV lithography and, hence, for IDE to be of practical interest for photon integration in a not-so-distant future, the dependency of the device performance in respect to the device and feature sizes introduced in the IDE should be investigated.

Utilizing the iDE method of topology optimization, we have realized an all-silicon ultra-compact polarization beam splitter (PBS) and fabricated it in silicon-on-insulator material utilizing state-of-the-art electron beam lithography. The device footprint of the PBS is 1.8 micron x 2.8 micron and experimentally performs with an insertion loss lower than -0.9 dB and a high -14-30 dB extinction ratio for both polarization modes in the full measured wavelength range from 1520 nm to 1620 nm. As an example for future IDE devices, we investigate the device performance of the PBS as a function of the device and feature sizes in order to approach an optimal design that is compatible with e.g. deep-UV lithography.

9756-32, Session 8

**In-situ visualization of intercalation-driven nanoparticle phase transitions using plasmon-EELS (Invited Paper)**

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

A number of energy-relevant processes rely on nanomaterial phase transitions induced by solute intercalation. However, many of these phase transitions are poorly understood, since observing them in nanomaterials - and in particular in individual nanoparticles – can be extremely challenging. This presentation will describe a novel technique to investigate intercalation-driven phase transitions in individual nanoparticles, based on in-situ environmental transmission electron microscopy (TEM) and plasmon electron energy loss spectroscopy (EELS). As a model system, this presentation will focus on the hydrogenation of palladium nanoparticles. We use the plasmon-EEL signal at varying hydrogen pressures as a proxy for hydrogen concentration in the particle. First, we investigate the hydriding properties of single-crystalline particles, free from defects and grain boundaries, and free from elastic interactions with the substrate. We obtain single particle loading and unloading isotherms for particles ranging from approximately 10 nm to 50 nm, allowing us to address outstanding questions about the nature of phase transitions and surface energy effects in zero-dimensional nanomaterials. We find that hydrogen loading and unloading isotherms of single crystals are characterized by abrupt phase transitions and macroscopic hysteresis gaps. These results suggest that thermodynamic phases do not coexist in single-crystalline nanoparticles, in striking contrast with ensemble measurements of Pd nanoparticles.

Then, we extend our single-particle techniques to explore the hydriding properties of polycrystalline and multiply-twinned nanoparticles, including Pd nanorods and icosahedra. In contrast to single-crystalline nanoparticles, these particles exhibit sloped isotherms and narrowed hysteretic gaps. Based on these results, we develop a model to deconvolve the effects of disorder and strain on the phase transitions in nanoscale systems. Lastly, we describe techniques to generate high-resolution plasmon-EELS (and hence phase) maps of nanoparticles. These mapping studies promise unprecedented insight into the internal phase of nanomaterials, and can be complemented with diffraction and dark-field imaging studies. We will discuss how these results could be used to interpret the thermodynamics of Li-ion insertion in battery electrodes, hydrogen absorption in state-of-the-art metal hydride catalysts, or ion exchange reactions in quantum dot syntheses.

9756-33, Session 8

**Enhanced spontaneous emission from individual quantum dots coupled to lithographically defined metallic nano-antennas**

Armin Regler, Technische Univ. München (Germany); Konrad Schraml, Walter Schottky Institut (Germany) and Technische Univ. München (Germany); Anna A. Lyamkina, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation); Glenn Glasshagen, Technische Univ. München
9756-37, Session 8

Optical harmonics generation in metal/dielectric heterostructures in the presence of Tamm plasmon-polaritons

Boris I. Afionogov, Lomonosov Moscow State Univ. (Russian Federation); Anna A Popkova, Vladimir O. Bessonov, Lomonosov Moscow State Univ (Russian Federation); Andrey A. Fedyanin, Lomonosov Moscow State Univ. (Russian Federation)

The Tamm plasmon-polariton (TPP) is the surface electromagnetic mode at the interface between a one-dimensional photonic crystal (PC) and a metal film. Experimentally TPPs manifest themselves as sharp resonances in transmission spectra and their spectral position can be tuned by varying the thickness of the topmost layer of a PC. Optical harmonic generation (OHG) is a powerful noninvasive tool used to study surfaces and buried interfaces in condensed matter systems. In case of materials, possessing cubic or isotropic symmetry the main part of the second-harmonic (SH) signal is generated at the surfaces and interfaces, so localization of the electromagnetic field leads to the enhancement of the SH generation from such structures. Three cases were studied in this work. The first one corresponds to the resonant pump (fundamental radiation is in resonance with the TPP). In that case, the enhancement factor of the SHG from PC/metal structure is shown to be as high as 200. The second case corresponds to the off-resonant pump and resonant second harmonic. The enhancement factor of the SHG is reported to be nearly 50. The third one corresponds to the double resonant case: pump is in the resonance with the TPP, and the third harmonic (TH) is in resonance with the 3rd order TPP. In that case, the THG is enhanced up to 3000 times. All enhancement factors are given in comparison to the OH signal from bulk metal films at the same pump intensity, which proves the possibility of using this technique in applications related to the imaging and probing of buried interfaces.

9756-35, Session 8

Nanometers to centimeters: novel optical nano-antennas with an eye to scaled production

Timothy D. James, The Univ. of Melbourne (Australia) and Australian National Fabrication Facility (Australia); Jasper J. Cadusch, Stuart K. Earl, Evgeniy Panchenko, Paul Mulvaney, The Univ. of Melbourne (Australia); Timothy J. Davis, Commonwealth Scientific and Industrial Research Organisation (Australia); Ann Roberts, The Univ. of Melbourne (Australia)

Optical nano-antennas have been the focus of intense research recently due to their ability to manipulate electromagnetic radiation on a subwavelength scale, and there is major interest in such devices for a wide variety of applications in photonics, sensing, and imaging. Significant effort has been put into developing highly compact, novel, next-generation light sources, which have great potential in realizing efficient sub-wavelength single photon sources and enhanced biological and chemical sensors. We have developed a number of innovative optical antenna designs including elements of chiral metasurfaces for enabling circularly polarized emission from quantum sources, new designs derived from Radio Frequency (RF) elements for quantum source enhancement and directionality, and nanostructures for investigating plasmonic dark-modes that have the ability to significantly reduce the Q-factor of nano-antennas.

A challenge, however, remains the development of a scalable nanofabrication technology. The capacity to mass-produce nano-antennas will have a considerable impact on the commercial viability of these devices, and greatly improve research throughput. Here we present recent progress in the development of scalable fabrication strategies for producing of nano-antennas and antenna arrays, and their application to enhancing and controlling radiation by quantum sources such as quantum dots and probing subradiant modes of nanoparticle ensembles.

9756-38, Session 9

Latest progress in spaser and its biomedical applications (Invited Paper)

Mark I. Stockman, Georgia State Univ. (United States)

No Abstract Available

9756-39, Session 9

Design of a plasmonic-organic hybrid slot waveguide integrated with a bowtie-antenna for terahertz wave detection

Xingyu Zhang, Univ. of Texas at Austin (United States) and Hewlett-Packard Labs. (United States); Chi-Jui Chung, The Univ. of Texas at Austin (United States); Harish Subbaraman, Omega Optics, Inc. (United States); Zeyu Pan, Chin-Ta Chen, The Univ. of Texas at Austin (United States); Ray T. Chen, The Univ. of Texas at Austin (United States) and Omega Optics, Inc. (United States)

Electromagnetic (EM) wave detection over a large spectrum has recently attracted significant amount of attention. Traditional electronic EM wave sensors use large metallic probes which distort the field to be measured and also have strict limitations on the detectable RF bandwidth. To address these problems, integrated photonic EM wave sensors have been developed to provide high sensitivity and broad bandwidth. Previously we demonstrated a compact, broadband, and sensitive integrated photonic EM wave sensor, consisting of an organic electro-optic (EO) polymer refilled...
silicon slot photonic crystal waveguide (PCW) modulator integrated with a gold bowtie antenna, to detect the X band of the electromagnetic spectrum. However, due to the relative large RC constant of the silicon PCW, such EM wave sensors can only work up to tens of GHz. In this work, we propose a new generation of EM wave sensors based on EO polymer refilled plasmonic slot waveguides in conjunction with bowtie antennas to cover a wider electromagnetic spectrum from 1 GHz up to 10 THz, including the range of microwave, millimeter wave and even terahertz waves. This antenna-coupled plasmonic-organic hybrid (POH) structure is designed to provide an ultra-small RC constant, a large overlap between plasmonic mode and RF field, and strong electric field enhancement. A taper is designed to bridge silicon strip waveguide to plasmonic slot waveguide. Simulation results show that our device can have an EM wave sensing ability up to 10 THz. To the best of our knowledge, this is the first POH device for photonic EM wave detection.

9756-42, Session 10

Hybrid nanoantennas for nonlinear optics and biosensing (Invited Paper)
Stefan A. Maier, Imperial College London (United Kingdom)

This presentation will give an overview of our recent work on optical nanoantennas based on metal or dielectric nanostructures, or hybrids thereof. Topics covered will include highly enhanced nonlinear light generation, resonance tuning via controlled phase changes of the constituent materials, and surface-enhanced spectroscopies based on fluorescence and Raman scattering. In particular, conventional plasmonic nanoantennas will be compared to dielectric ones, in terms of achievable field enhancement, emission enhancement, and local heat generation. The dielectric nanoantenna system is poised to develop into an interesting complimentary platform to nanoplasmonics.

9756-43, Session 10

Experimental investigation on the lensing and Talbot effects of finite-sized 2D periodic metallic nanoaperture arrays
Yiting Yu, Northwestern Polytechnical Univ. (China); Hans Zappe, Univ. of Freiburg (Germany); Weizheng Yuan, Northwestern Polytechnical Univ. (China)

The finite-sized two-dimensional (2D) periodic metallic nanoaperture arrays, named as the “patches” by Odom and co-workers (Nano Lett., 2010, 10: 4111.), were demonstrated to behave as broadband plasmonic microlenses. In our previous report (Plasmonics, 2013, 8: 723), both the lensing and Talbot effects were presented for the similar devices. Here, an extended experimental investigation of the influences of structural parameters, including the fill factor, device size, lattice distribution, and nanoaperture shape, on the far-field optical transmission properties through the finite-sized 2D periodic metallic nanoaperture arrays is given. Both the lensing effect and the Talbot effect are characterized and analyzed. Light intensity patterns of Talbot revivals at various Talbot distances containing abundant subwavelength hotspots are obtained, and the average size of the hotspots are derived and compared. The results show that the lattice distribution has a large impact on both the lensing effect and Talbot effect. The fill factor seems having a little role on the focusing behavior, but will lead to the enlarged hotspots when it increases. A larger array size results in a broader focal point, but reveals no obvious influence on the average size of the hotspots. Different nanoaperture shapes exhibit no big difference for both effects. Besides, the competitive relationship between the Talbot effect and the lensing effect is demonstrated. To well understand the optical transmission features through periodic metallic nanoaperture arrays provides new opportunities for the potential applications such as nanofabrication, optoelectronics, and high-resolution imaging.
Polarization switchable two-color plasmonic nano-pixels for creating optical surfaces encoded with dual information states

Esmaeil Heydari, Zhibo Li, Jonathan M. Cooper, Alasdair W. Clark, Univ. of Glasgow (United Kingdom)
In this paper we demonstrate tunable, polarization-dependent, dual-color plasmonic filters based upon arrays of asymmetric cross-shaped nano-apertures. Acting as individual color emitting nano-pixels, each aperture can selectively transmit one of two colors, switched by controlling the polarization of white-light incident on the rear of each pixel. By tuning the dimensions of the pixels we build a polarization sensitive color palette at resolutions far beyond the diffraction limit. Using this switchable color palette we are able to generate complex optical surfaces encoded with dual color and information states; allowing us to embed two color images within the same unit area, using the same set of nano-apertures.

Driving research into sub-wavelength plasmonic color pixels has been their potential to improve upon the organic dye-based filters which provide color selectivity for all current image sensors, their use as a new, non-fading, nano-scale ‘printing’ technology, and their potential to provide small-footprint optical storage/encoding solutions. Typically, these plasmonic color filters are tuned to operate efficiently at a single wavelength. Our approach enables a single nano-aperture to encode dual color selectivity. These new pixel types hold the potential to improve upon current plasmonic pixel technology by enabling smaller, more versatile filter sets for imaging applications (where a single array can function at two selectable filtering regimes within the same unit area, rather than building two separate arrays), while also having potential applications in display technologies, image ‘printing’, storage, anti-counterfieting, and biosensing.

Nanoscale highly selective plasmonic multi-channel demultiplexer

Mohamed A. Swillam, Abdulilah A. Azzazi, The American Univ. in Cairo (Egypt)
A highly selective plasmonic demultiplexer based on a plasmonic slot waveguide platform is proposed. The structure is optimized as an add drop multiplexer/demultiplexer. The optimal design is targeting minimum FWHM. The device is optimal quad multiplexer/demultiplexer has FWHM of 9.8 nm for each channel with a high output transmission near the 1550 nm.

The device is optimal multiplexer/demultiplexer has FWHM of 9.8 nm for each channel with a high output transmission near the 1550 nm. The proposed structure is simple, can be easily fabricated. The proposed structure can be easily scalable for multichannel applications.

Refractive plasmonics: new material platforms for nanophotonics (Invited Paper)

Vladimir M. Shalaev, Nathaniel Kinsey, Purdue Univ. (United States); Urcan Guler, Nano-Meta Technologles, Inc. (United States); Jongbum Kim, Alexandra Boltasseva, Purdue Univ. (United States)
Designing plasmonic metamaterials with versatile properties that can be tailored to fit almost any practical need promises a range of potential breakthroughs. However, to enable these new technologies based on plasmonics, grand limitations associated with the use of metals as constituent materials must be overcome. In the structures demonstrated so far, too much light is absorbed in the metals (such as silver and gold) commonly used in plasmonic metamaterials. The fabrication and integration of metal nanostructures with existing semiconductor technology is challenging, and the materials need to be more precisely tuned so that they possess the proper optical properties to enable the required functionality. Our recent research aims at developing novel plasmonic materials (other than the metals used so far) that will form the basis for future low-loss, CMOS-compatible devices that could enable full-scale development of the plasmonic and metamaterial technologies. In this work, we replace metals in plasmonic metamaterials by new plasmonic ceramics such as transition metal nitrides, whose properties resemble those of gold. However, unlike gold, these materials have adjustable/tunable optical properties, they are cost-effective, robust, refractory (withstanding very high temperatures) and compatible with standard semiconductor processing. Here, we will demonstrate that transition metal nitrides and transparent conducting oxides’ addition to the short list of plasmonic materials paves the way to a new class of data recording systems and CMOS-compatible, on-chip hybrid nanophotonic devices with unprecedented compactness, speed, and efficiency as well as to novel energy conversion schemes.
This Report suggests to make use of the process of bimetal hybridization in copper, capability of oxidation/sulfidization of silver, and weak SPR of gold. Faces a number of obstacles that are due to the high chemical activity of bulk counterparts. However, application of the NPs in, e.g., SERS devices plasmon resonance (SPR) that makes a difference from their conventional what is more, due to the large local-field enhancement near the surface nanoparticles (NPs) of noble metals (Cu, Ag, and Au) embedded into a

Electronic Technology (Russian Federation)

G. Gromov, Andrey I. Savitsky, National Research Univ. of Physics and Technology (Russian Federation); Dmitry I. V. Melnikov, National Research Univ. of Electronic Technology (Russian Federation) and Univ. of Illinois in

In the recent decade, there has been a great revival of interest to composite materials for label-free single-molecule detection. Nature Mater. 2013, 12, 304

We focus the second part of the presentation on the demonstration of optical meta-effects and reconfigurability in metamaterials built from nano-elements for building reconfigurable metamaterials at visible and ultraviolet frequencies. Among them, semi-metallic nano-elements (Bi, Ga, Sb) are especially relevant due: i) to their solid-liquid phase transition that can be activated by thermostatic, laser, Joule or plasmonic heating, ii) the strong optical contrast between the nanoparticles with solid interband polaritonic phase and liquid plasmonic phase in the ultraviolet and visible. We focus the second part of the presentation on the demonstration of optical meta-effects and reconfigurability in metamaterials built from nano-Bi.


(2) Kravets, V.G. et al.; Singular phase nano-optics in plasmonic metamaterials for label-free single-molecule detection. Nature Mater. 2013, 12, 304


that is due to inherent features of the bimetal alloy.

A simple and inexpensive approach to the preparation of Ag/Au
nanoparticles is by using a magneto-sputtering tool. However, the effect of the preparation on optical properties of this bimetal nano-composite still requires more detailed studies. In this Report, our primary target is to determine the correlation between optical properties of the Ag/Au nanoparticle and annealing of the continuous bimetal double-film. Apart of that, we are also going to tackle here a number of issues that occur at bimetal-vapor condensation in a vacuum and that have not been so far addressed properly.

9756-69, Poster Session

Extraordinary optical transmission through nanohole arrays blocked by gold umbrella-like tap

Youwen Liu, Huidan Xue, Jiming Wang, Nanjing Univ. of Aeronautics and Astronautics (China)

The extraordinary optical transmission (EOT) of light through nanohole arrays has been paid much attention since this phenomenon was first reported by Ebbesen et al.. Surface plasmons (SPs) play vital important roles in this kind of phenomenon, owing to the interaction of the incident lights and the free electrons in the metal.

In this contribution, we propose a new structure with an umbrella-like tap blocking the nanohole, and use the finite difference time domain (FDTD) method to investigate the its optical transmission property. The Au film of 40 nm thickness is covered on the SiO2 substrate and the two-dimensional hole array has a period of 200 nm x 200 nm with hole diameter of 70 nm. Each gold umbrella-like tap consists of a pillar of 64 nm height and a cap of 40 nm thickness and 100 nm diameter. A giant transmission efficiency of 88% could be attained, which is much higher than the transmission efficiency of mushroom capped structure without pillar in the hole. The distributions of the simulated electric field further show this umbrella-like tap can improve light coupling from free space to a subwavelength hole.

The transmission spectra can be sensitively influenced by the change of the parameters of the proposed structure, such as hole and pillar diameters, cap thickness and diameter. The simulated results are presented and discussed in detail. Such a nano-scale structure blocked by umbrella-like tap will have a promising future in nanoplasmonic applications.

9756-70, Poster Session

Broadband meta-hologram composed of Z-shaped nano-antennas

Sang-Eun Mun, Yohan Lee, Joonsoo Kim, Seoul National Univ. (Korea, Republic of); BYOUNGHO LEE, Seoul National University (Korea, Republic of)

Holograms using metasurfaces composed of ultrathin subwavelength structures have recently been researched due to the capability of completely manipulating the phase information of light. Metasurfaces consist of monolayer of artificial nano-antennas which do not exist in nature and offer interesting functionality for controlling wavefront of light. The various types of metasurfaces which consist of an array of plasmonic nanorods have been used to make holograms. Especially, geometric metasurfaces such as metal nanorods, nanoparticles and V-shaped antennas show the ability to control the phase profile of incident electromagnetic field based on the geometric nature of their phase distribution. However, issues including diversity of structure, high efficiency and types of meta-hologram still remain.

We propose a reflective type hologram by a plasmonic metasurface composed of Z-shaped nano-antennas. The proposed metasurface renders precise phase modulation with spatially varying orientation, which attributes to the increase of the level of phase distribution. The geometric property of Z-shaped nano-antenna has different plasmonic resonance mode for the
orthogonal linear polarized incidence that makes different phase delay for orthogonal input. Besides, it keeps high polarization conversion efficiency about 80% in a broad bandwidth between 540 nm and 1500 nm. We use a gold metal plane as a ground mirror and put a dielectric spacer as a cavity structure, which allows high reflectivity with a phase delay due to the Fabry-Perot resonance. Meta-hologram using this metasurface has opened the possibility of variety of structures and expansion to near-infrared region, which is expected to be applied to the more complicated meta-hologram applications.

9756-71, Poster Session

Enhanced low-absorptive molecular detection by using metal slot antenna arrays

Kwang Jun Ahn, Fabian Rotermund, Ajou Univ. (Korea, Republic of)

Label-free chemical and biological detection and active transmission/reflection control of light using metallic antennas are very promising applications. While the former is usually accomplished by measuring antenna’s resonance peak shift caused by the refractive index of targeted substances, the latter depends on the reduction of the resonant transmission/reflection by the absorption of surrounding materials. The fundamental design and performance criteria of antenna’s sensitivity for a material detection is well understood by the figure of merit (FOM), the resonance peak shift per unit change of the refractive index (nm/RIU) with respect to the spectral width of the resonance peak. The sensitivity explained by the FOM inspires the antennas containing the Fano resonance in order to utilize its relatively narrow spectral width. A similar consideration is also requested for the decrease of the resonance peak value but has not been systematically discussed so far.

Here, we derive an analytical form of the light transmitted through (reflected from) an array of slot antennas fabricated in a thin metal film, and investigate the decrease of the transmission peak by the absorption of the material embedded in a slot antenna array. The numerical results from our models are compared with finite difference time domain simulations. We demonstrate that an ultrasensitive detection of molecules can be accomplished in a near infrared frequency regime, when the attenuation length of light at the resonance wavelength of the slot antenna array is a comparable order of the spectral width of the resonant transmission/reflection peak.

9756-72, Poster Session

The optical characteristics of 1D lamellar photonic crystal with PS-b-P2VP block copolymer

Jin Youb Lim, Dong-Myung Shin, Hongik Univ. (Korea, Republic of)

The lamellar-forming 1-dimensional photonic films were prepared by three different molecular weight, but nearly symmetric poly(styrene-b-2-vinyl pyridine) (PS-b-P2VP) block copolymers. Propylene glycol monomethyl ether acetate (PGMEA) was used as solvent to spin-cast the films. The films were submerged into ethanol to swell P2VP block. As the molecular weight of the block copolymer increases, the film shows red-shifted color, because of longer periodic distance. In addition, the color of the films in ethanol was tuned by blending the PS-b-P2VP block copolymers.

9756-73, Poster Session

Directional switching of surface plasmon polaritons by vanadium dioxide-gold hybrid antennas

Sun-Je Kim, Kyookkeun Lee, Seoul National Univ. (Korea, Republic of); Seung Yeol Lee, Seoul National Univ (Korea, Republic of); Byoungho Lee, Seoul National Univ. (Korea, Republic of)

Surface plasmon polariton (SPP) has received a lot of research interests due to its ability to overcome the diffraction limit of light and possibility for integrated ultrafast nano-photonic circuits. Plasmonic elements have been proposed which can manipulate SPP signals by controlling geometric parameters of structures and polarization of incident light. Several works have utilized active materials whose optical properties can be tuned electrically and optically. Vanadium dioxide (VO₂) is one of such active materials. Due to its unique phase transition characteristics, dielectric constant of VO₂ in optical frequency changes from positive to negative value, as its temperature exceeds critical value, about 70 degree Celsius. In this paper, we propose novel type of dual SPP gap antennas which can excite SPPs directionally and switch the direction according to the temperature. The proposed device consists of a VO₂-insulator-metal resonator and a metal-insulator-metal resonator with slightly different antenna width. Phase of SPPs generated by VO₂ gap antenna changes as the temperature increases, so that interference of SPPs from both gap antennas makes directional excitation and its launching direction can be switched. Directional intensity distinction ratios of coupled SPPs changes from about 1:5 to 7:1 as VO₂ transits from the semiconductor phase to the metallic phase. We expect that this result can be applied to various optical devices which can manipulate optical near-field and far-field, such as active plasmonic circuit elements and thermal plasmonic sensors.

9756-76, Poster Session

Fabrication of two-dimensional visible wavelength nanoscale plasmonic structures using hydrogen silsesquioxane-based resist for use in optical biosensing systems

Kyle Smith, Akshitha Gadde, Anand Kadiyala, Jeremy M. Dawson, West Virginia Univ. (United States)

In recent years, the global market for biosensors has continued to increase in combination with their expanding use in areas such as biodetection, home diagnostics, biometric identification, etc. A constant necessity for inexpensive, portable bio-sensing methods, while still remaining simple to understand and operate, is the motivation behind novel concepts and designs. Labeled visible spectrum bio-sensing systems provide an instant feedback that is simple and easy to analyze. In comparison, label-free bio-sensing systems and other detection modalities like electrochemical, frequency resonance, thermal change, etc., all require larger amounts of analyte and/or additional processing steps to convey the final result. Further decrease in the detection limit can be achieved through the addition of plasmonic structures. Nano-structures that operate in the visible spectrum have feature sizes typically in the order of the operating wavelength, calling for high aspect ratio nanoscale fabrication capabilities. In order to achieve these dimensions, electron beam lithography (EBL) is used due to its accurate feature production. Hydrogen silsesquioxane (HSQ) based electron beam resist is chosen for one of its benefits, which is better exposure to oxygen plasma, the patterned resist cures into silicon dioxide (SiO₂). These cured features in conjunction with nanoscale gold particles help in producing a high electric field through dipole generation. In this work, a detailed process flow of the fabrication of square lattice of plasmonic structures comprising of gold coated silicon dioxide pillars
Surface-enhanced Raman scattering in C. waillesii diatom frustules

Christine E. Alvarez, Robert A. Norwood, Khanh Q. Kieu, Gregory A. Cohoon, The Univ. of Arizona (United States); Olga Kropacheva, College of Optical Sciences, The Univ. of Arizona (United States)

We demonstrate surface enhanced Raman scattering (SERS) using frustules from the centric marine diatom C. Waillesii. SERS is typically observed on rough surfaces created by chemical roughening or by building a nanostructure on a flat metallic surface. Because diatoms have a nanostructured silica shell, they are good candidates for use as a SERS substrate. In particular, the frustule of C. Waillesii has three layers of increasingly fine structure with roughness on the order of 100nm in the cribrum. Samples were prepared by first cleaning the frustules of organic material using SDS and EDTA. They were rinsed and stored in ethanol before being deposited on glass slides. Each slide was then coated in Ag of thickness 10nm, 20nm, 30nm, 40nm, or 50nm. A variety of Ag coating thicknesses were used to empirically determine the point at which the diatom shell was uniformly coated, but without the 10-100 nm holes of the frustule being filled in. A monolayer of thiophenol was deposited on top of the Ag of each sample. A confocal Raman microscope with a 532 nm excitation wavelength was used to observe enhancement of the well-known thiophenol Raman spectrum. Using the confocal capabilities of the microscope, the Raman signal was maximized in the z direction at each point to correct for variation in diatom height. Different points on a diatom frustule were compared to a flat glass surface coated in the same amount of Ag and thiophenol. Raman signal enhancements on the order of 10^2-10^3 were observed.

Modulation of surface plasmon polaritons with metal and alloy nanofilms

Benjamin D. Hall, Heesoo Park, Azad Siahmakoun, Rose-Hulman Institute of Technology (United States)

Modulation of surface plasmon polaritons (SPPs) in metal thin films is simulated and experimentally demonstrated with the introduction of dielectric media at the plasmonic interface. The composite devices are analyzed as scattering matrices and finite elements arrays before the results of the two approaches are compared with empirical data. Each system was constructed in the Kretschmann configuration in which the SPP is excited via attenuated total internal reflection at the hypotenuse of a fused silica prism. Metal and alloy films are deposited onto the prisms using sputtering technique at pressures below 10^-7 Torr. Plasmonic behavior in silver and nickel (NiCr) samples between 20nm and 50nm thick is measured to control for more complex devices. Nominal metal thicknesses are verified using a profilometer, and the complex dielectric function of each sample is determined through spectroscopic ellipsometry. Reflectance data is analyzed as a function of the reflection angle at the plasmonic interface, and the angle of greatest attenuation is taken to be the plasmon angle. Data is shown for a He-Ne source and a near infrared source at 1320 nm and additional wavelengths are modelled for supplementary inquiry. Shifts in the plasmon angle are shown for both metal and alloy with the introduction of poly methyl methacrylate (PMMA) to the interface. The growth of Ag2O through an annealing process is also shown to shift the plasmonic angle for silver samples. Electro-optic modulation is simulated for a uniaxial crystal with the introduction of He-Ne Laser was employed as a light source. SPPs, generated at the edges of the block, propagate in opposite directions, which make standing wave on the surface. In the case of thin block, the light passing through the thin Au block can be interfered with the SPPs generated from the edge of the block. In this presentation, we will show that this interference and resonance peak of SPP with different width can be measured by a near-field scanning optical microscope.

Observation of resonance of Au single block with finite width by using a near-field scanning optical microscope

Hong-Gyu Ahn, Chang Hyun Park, Yonsei Univ. (Korea, Republic of); Kyong Seok Kim, Daeyeon Kim, Yonsei Univ (Korea, Republic of); Seung-Han Park, Yonsei Univ. (Korea, Republic of)

We have measured resonance patterns from Au single block with finite width by using a near-field scanning optical microscope. Gaussian beam of He-Ne Laser was employed as a light source. SPPs, generated at the edges of the block, propagate in opposite directions, which make standing wave on the surface. In the case of thin block, the light passing through the thin Au block can be interfered with the SPPs generated from the edge of the block. In this presentation, we will show that this interference and resonance peak of SPP with different width can be measured by a near-field scanning optical microscope.

Polarimetric techniques for determining morphology and optical features of high refractive index dielectric nanoparticles

Ángela I. Barreda Gomez, Juan M. Sanz, Rodrigo Alcaraz de la Osa, José M. Saiz, Fernando Moreno, Francisco González, Univ. de Cantabria (Spain)

Nanotechnology has revolutionized science in the last years causing important theoretical and practical developments. Concretely, interaction of electromagnetic radiation with High Refractive Index (HRI) dielectric Nanoparticles (NP’s) has undergone vigorous investigation, providing results in different areas like materials, optics, sensing,... Some of the most important advantages of such kind of NP’s are that light can travel through them with negligible ohmic losses, they can present electro-magnetic effects even for non-magnetic NP’s and they can also be design to guide light. For HRI dielectric NP’s whispering gallery modes are responsible for the resonances. The resonances positions depend on the nanostructures morphology, its optical properties and the refractive index of the surrounding medium. Another factor that influences the behavior of the resonances is the purity of the scatterer material.

The linear polarization degree of the scattered light at right-angle detection, PL(90º), is a polarimetric parameter that contains information about the electric or magnetic character of the NP’s resonances [1]. Also, unlike other parameters, like the extinction efficiency, PL(90º) can be easily measured.

In this work, focusing on the dipolar electric, dipolar magnetic and quadrupolar magnetic resonances of HRI dielectric spherical NPs, we show the utility of PL(90º) as an accurate tool for determining the NP’s size and the refractive index of the surrounding medium [2]. From an industrial point of view, pure materials are nonrealistic, since they can only be provided under certain conditions [3]. In this work, we also analyze the possibility of knowing the purity degree through PL(90º) measurement [4].

References:
9756-51, Session 12

Graded photonic crystal structures for single-pass all-angle light extraction from light-emitting diodes (Invited Paper)

Martin F. Schumann, Aimi Abass, Guillaume Gomard, Karlsruher Institut für Technologie (Germany); Samuel Wiesendanger, Friedrich-Schiller-Univ. Jena (Germany); Uli Lemmer, Martin Wegener, Carsten Rockstuhl, Karlsruher Institut für Technologie (Germany)

While the internal quantum efficiency of state-of-the-art light-emitting diodes (LED) can be close to 100%, their external quantum efficiency is much lower because not all the light can be coupled out from the high-index LED stack to free space. Many approaches have been discussed, but none of them has provided a complete solution. Here, we use transformation optics with Schwarz-Christoffel transformations to design single-pass omni-angle out-couplers comparable in size to the LED. The calculated graded-index distributions can, e.g., be mapped onto graded three-dimensional woodpile photonic crystals which can be fabricated by direct laser writing. The latest status will be presented.

Without any approximations, the Schwarz-Christoffel transformation leads to singular optical properties near corners. We show that these singularities can be truncated to realistically achievable refractive-indices without too much loss in performance. Furthermore, we show that practical out-coupling metastructures can be obtained by introducing geodesic truncation, while maintaining single-pass and omni-angle out-coupling. In this fashion, the maximum required refractive index can be kept below 2. The outcoupling metastructure can also be engineered to either preserve the substrate modes’ directionality or to increase the angular spread by curving the out-coupler exit surface.

9756-52, Session 12

Active disorder counteraction in photonic crystal cavity arrays

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Systems of coupled high-Q nanocavities are fascinating for their promising applications like slow-light and enhancement of light-matter interaction [1, 2]. Inevitable fabrication defects result in disorder, therefore some cavities may become detuned from the designed frequency. However, the performance can be restored if one is able to control each resonator independently. This control will counteract disorder as well as provide the route to have programmable nanophotonic integrated circuits.

In our work we present a way to independently control multiple photonic crystal cavities by local heating. Local heating of the sample induces a positive refractive index change which results in a redshift of the resonance wavelength of the cavity. Thermal tuning together with modern holography methods [3] yields a full control over resonance wavelengths of resonators. To show that control we use holography of 405 nm laser light for local heating of the surface of the sample. We predictably control the resonant behavior of several cavities in a cavity array. Our results accurately match a coupled-mode theory.


9756-53, Session 12

Visible to near-infrared narrow-band thermal emitters based on silicon-rod photonic crystals

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Nanocavities and photonic crystal films are created by using photolithography and etching processes. However, there is a limitation to the size of the cavity in this case. A new method for making photonic nanocavities is presented. Silicon rods are used as the nanostructures, which have a large bandgap. Instead of using photolithography, we design a photonic crystal structure using the Schrödinger equation.
Selective thermal emitters which can emit light at the wavelengths shorter than near-infrared regime are important for highly efficient thermo-photovoltaic (TPV) power generation systems. Here, we demonstrate visible to near-infrared narrow-band thermal emitters for silicon photovoltaic cells (bandgap energy -1.1 eV, wavelength 1.1 um) by using rod-type two-dimensional photonic crystals made of silicon. In this structure, inter-band absorption of silicon and optical resonances of photonic crystals are expected to increase the emissivity at visible to near-infrared wavelength regime. On the other hand, intrinsic carriers generated at high temperature might induce free carrier absorption at the middle- to far-infrared wavelength region, which may degrade the thermal emission selectivity. We have found theoretically that by employing the rod-type photonic crystals, the visible to near-infrared thermal emission can be enhanced while the emission in longer wavelengths can be suppressed substantially due to the reduced volume effects. We have fabricated silicon-rod photonic crystals on silicon on insulator (SOI) systems by using electron beam lithography and dry-etching techniques. The fabricated thermal emitters have been heated up to 1300 K by external heater and their thermal emission has been measured between 0.5 and 8 um. The emitter shows maximum emissivity of 0.8 at wavelength less than 1.1 um, while the emissivity at the wavelengths between 1.1 and 4 um has been suppressed below 0.05. In the wavelength longer than 4 um, thermal emission from the SiO2 layer of the SOI system has been observed. These results indicate that our thermal emitters are promising candidates of highly efficient thermo-photovoltaic power generation systems.

9756-56, Session 12

Self-assembled photonic crystals for a chemical sensing

Céline Bourdillon, Catherine Schwob, Agnès Maître, Laurent Coolen, Sarra Gam Derouich, Univ. Pierre et Marie Curie (France); Claire Mangeney, Univ. Paris 7-Denis Diderot (France)

Studies of materials at the nanometric scale allow great advances in industry and research especially since the breakthrough of nanotechnologies occurred at the end of the last century. As these innovations in nanomaterials are recent, the toxicology of materials at this scale is unknown or right known and it has become an important challenge to detect and identify nanoparticles and molecules. Thus physicists in optic realized sensors based on the measurements of light properties, like variations of the fluorescence in the case of fluorophores or nano-emitters which permit localized, sensitive and instant but not necessarily specific detections. Counter, scientists in material chemistry devised new materials with specific and chemical recognitions, for example using imprinted polymers, but these sensing methods are not easily localized and sensitive.

We developed a sensor based on the modification of the optical properties of self-assembled photonic crystals and quantum-dots coupled with the chemical properties of an imprinted polymer to obtain a specific, ultrasensitive and localized detection. Our sensor consists of an inverse opal made with a molecularly imprinted copolymer material which has the particularity to change the spectral location of its photonic band gap depending on the presence of the target molecule or nanoparticle.[1],[2] The sensing is obtained by spatially and spectrally resolved measurements of the fluorescence intensity of nanocrystals filtered by the molecularly imprinted inverse opal. Furthermore we demonstrated that the spatial information on the fluorescence transmitted through an opal is linked to the spectral properties of the nano-emitters.[3]


silicon photonic crystals. We measured reflected intensity from the crystals
we investigate three-dimensional (3D) opals and two-dimensional (2D)
transport inside real photonic crystals.
attenuates light propagation through the crystal [2]. Here, we propose a
unavoidable deviations from perfect periodicity result into scattering, which
positions of the building blocks as well as the finite size of the crystal. The
modified due to the presence of structural imperfections in size and
smaller pore - a single line defect - with two intersecting pores with smaller
the resulting point defect is predicted to show cavity resonances inside
woodpile photonic crystal by targeting certain pores to have smaller radii
reflectivity study of silicon 3D inverse woodpile photonic crystals fabricated
gap cavities, line defects and arrays of cavities. We present the first optical
reflectivity study of silicon 3D inverse woodpile photonic crystals fabricated
via a novel technique [3]. We create intentional defects inside the inverse
woodpile photonic crystal by targeting certain pores to have smaller radii
than in the bulk of the crystal. When two pores with smaller radii intersect,
the resulting point defect is predicted to show cavity resonances inside
the band gap [4]. We present optical measurements on crystals with one
smaller pore - a single line defect - with two intersecting pores with smaller
radii - a single band gap cavity - and an array of band gap cavities that are
intended as the photonic version of the Anderson tight-binding model.

Controlled point and line defects in 3D silicon inverse woodpile photonic band
gap crystals
Diana A. Grishina, Univ. Twente (Netherlands); Jorge Pérez Vizcaino, Univ. Jaume I (Spain); Oluwafemi Ojambati, Ad Lagendijk, Willem L. Vos, Univ. Twente (Netherlands)
Many efforts are devoted worldwide to control emission and propagation of
light using nanophotonic metamaterials [1,2]. Of particular interest are 3D
photonic band gap crystals in which light is forbidden to propagate in all
directions and for all polarizations. One of the major challenges is to realize
embedded defects with controllable optical properties such as 3D band
gap cavities, line defects and arrays of cavities. We present the first optical
reflectivity study of silicon 3D inverse woodpile photonic crystals fabricated
via a novel technique [3]. We create intentional defects inside the inverse
woodpile photonic crystal by targeting certain pores to have smaller radii
than in the bulk of the crystal. When two pores with smaller radii intersect,
the resulting point defect is predicted to show cavity resonances inside
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smaller pore - a single line defect - with two intersecting pores with smaller
radii - a single band gap cavity - and an array of band gap cavities that are
intended as the photonic version of the Anderson tight-binding model.

Optical correlations in 2D and 3D photonic crystals with weak and strong disorder
Oluwafemi Ojambati, Elahe Yeganehi, Allard P. Mosk, Willem L. Vos, Univ. Twente (Netherlands)
Light propagates inside an ideal infinite photonic crystal when the Bloch
condition is satisfied [1]. In real photonic crystals, light propagation is
modified due to the presence of structural imperfections in size and
positions of the building blocks as well as the finite size of the crystal. The
unavoidable deviations from perfect periodicity result into scattering, which
attenuates light propagation through the crystal [2]. Here, we propose a
new experimental method to characterize the effects of disorder on light
transport inside real photonic crystals.
We investigate three-dimensional (3D) opals and two-dimensional (2D)
silicon photonic crystals. We measured reflected intensity from the crystals
with a high numerical aperture. The statistics of the reflected intensity
differs from that of uncorrelated scattered intensity typical of statistically
homogeneous media. Thus, the reflected intensity is correlated, which
is caused by the statistically periodic nature of the crystals. We quantify
the optical correlations by measuring the position-dependent correlation
coefficient across each crystal surface. We find that the correlation
coefficient depends on the disorder in different regions within the opal
photonic crystal. In contrast, the CMOS-fabricated 2D crystal shows a very
high correlation over a large range. Our method provides a new way to
categorize the correlation length of the waves throughout the crystal,
which plays a central role in Mesoscopics and Anderson localization.
References

Compound grating structures in photonic crystals for resonant excitation of
azobenzene
Sabrina Jahns, Christine Kallweit, Christian-Albrechts-Univ. zu Kiel (Germany); Jost Adam, Univ. of Southern Denmark (Denmark); Martina Gerken, Christian-Albrechts-Univ. zu Kiel (Germany)
Photo-switchable molecules such as azobenzene are of high interest for
“smart” surfaces. Such “smart” surfaces respond to external light excitation
by changing their macroscopic properties. The absorbance of light on a
single normal path through a layer of azobenzene immobilized on a
surface is small and thus a high excitation light intensity is required. We
examine the enhancement of the local energy density using periodically
nanostructured surfaces in a high refractive index material. Such photonic
crystals support quasi-guided modes viable as resonances in the reflection
as well as in the transmission light spectrum. These guided modes have
field contributions decaying exponentially in the near field of the photonic
crystal. Azobenzene immobilized on the photonic crystal surface will
experience a significantly increased light intensity compared to
non-resonant surfaces. We performed finite-difference time-domain (FDTD)
calculations for determination of resonance positions and electric field
strengths in compound grating structures. By superimposing two single-
period gratings a photonic crystal can be designed supporting multiple
guided mode resonances suitable to switch azobenzenes between the trans
and cis isomer. To accomplish this, the central wavelength of the guided
mode resonances should be in a range of ?cis= 350 – 370 nm to initiate
transition to the cis isomer and ?trans= 420 – 450 nm generating the trans
isomer. Additionally, the impact of the periods, the duty cycle of each period
and the distance between the two superimposed periods on the electrical
field strength propagating on the surface are investigated and compared to
non-resonant surfaces.

Mechanically tunable optical response of large-area stretchable plasmonic arrays
Sage Doshay, Stanford Univ. (United States); Li Gao, Univ. of Illinois at Urbana-Champaign (United States); Yihui Zhang, Yonggang Hong, Northwestern Univ. (United States); John A. Rogers, Univ. of Illinois at Urbana-
Champaign (United States); Jonathan A. Fan, Stanford Univ. (United States)
Large-scale, dense arrays of plasmonic nanodisks on low modulus, highly
stretchable elastomeric substrates are demonstrated as a tunable optical
system. This system's optical resonances reversibly shift over a range of nearly 600 nm. At extreme levels of mechanical deformation, with strains greater than 40 and up to 107 percent, nonlinear buckling processes transform initially planar arrays into three-dimensional configurations. Analytical and finite element models are used to capture the physics of these buckling processes and the distinct modes that occur. We use finite-difference time-domain simulations to explore the optical properties of the system as a function of strain, including the quantitative effects of the nonlinear deformations on the plasmonic responses. The resulting mechanically tunable optical system has potential relevance to soft optical sensors that could be integrated with the human body or other deformable systems.

9756-62, Session 14
Reconstruction of photonic crystal geometries using a reduced basis method for nonlinear outputs
Martin Hammerschmidt, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Carlo Barth, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany) and Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Jan Pomplun, JCMwave GmbH (Germany); Sven Burger, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany) and JCMwave GmbH (Germany); Christiane Becker, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Frank Schmidt, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany) and JCMwave GmbH (Germany)

Fast solvers for Maxwell's equations are indispensable in optimization of optical properties or reconstruction of unknown parameters. Finite element Maxwell solvers like our implementation JCMsuite based on the hp-adaptive finite element method on unstructured 3D meshes allow for accurate geometrical modelling and high numerical accuracy of the electromagnetic field solutions. The computational complexity for large problems can be too high to evaluate the solution for a reasonable sampling of multiple parameters. A reduced order model however allows to compute solutions for a parameter configuration orders of magnitude faster.

We present a reduced basis method (RBM) for the time-harmonic electromagnetic scattering problem. The reduced basis is built self-adaptively and error controlled from snapshot solutions in the construction phase. Subsequently, the RBM allows to evaluate linear and nonlinear outputs of interest such as the enhancement of the electromagnetic field in narrow spatial regions in milliseconds.

We apply the RBM to compute light-scattering off two dimensional photonic crystal structures made of silicon. These can trap light or localize and enhance electromagnetic fields to narrow spatial regions. The increased field could be used for sensing applications or raise yield in upconversion solar cells. We employ the RBM to reconstruct geometrical parameters from measured data.

9756-63, Session 14
Metal-dielectric frequency-selective surface for high performance solar window coatings
Fatima Toor, Ananda C. Guneratne, The Univ. of Iowa (United States); Marina Temchenko, Madico, Inc. (United States)

We demonstrate a solar control window film consisting of metallic nanoantennas designed to reflect infrared (IR) light while allowing visible light to pass through. The film consists of a Capacitive Frequency-Selective Surface (CFSS) which acts as a band-stop filter, reflecting only light at target wavelengths. The designed CFSS when installed on windows will lower air conditioning costs by reflecting undesired wavelengths of light and thus reduce the amount of heat that enters a building. State-of-the-art commercial solar control films consist of a multilayer stack which is costly (~$15/m2 to $40/m2) to manufacture and absorbs IR radiation, causing delamination or glass breakage when attached to windows. Our solar control film consists of a nanostructured metallic layer on a polyethylene terephthalate (PET) substrate that reflects IR radiation instead of absorbing it, solving the delamination problem. The CFSS is also easy to manufacture with roll-to-roll nanoimprint lithography at a cost of <$12/m2. We design the CFSS using the COMSOL Wave Optics module to solve for electromagnetic wave propagation in optical media via the finite element method. The simulation domain is reduced to a single unit cell with periodic boundary conditions to account for the symmetries of the planar, periodic CFSS. The design is optimized using parametric sweeps around the various geometric components of the metallic nanoantenna. Our design achieves peak reflection of 80% at 1000 nm and has a broadband IR response that will allow for optimum solar control without significantly affecting the transmission of visible light.

9756-65, Session 14
Analysis of dispersion relation in three-dimensional single gyroid
Pei-Lun Jheng, Yu-Chueh Hung, National Tsing Hua Univ. (Taiwan)

Gyroid is a type of three-dimensional chiral structures and has been found in many insect species. Besides the photonic crystal properties exhibited by gyroid structures, the chirality and gyroid network morphology also provide unique opportunities for manipulating propagation of light. In this work, we present studies based on finite-difference time-domain (FDTD) method for analyzing the dispersion relation characteristics of dielectric single gyroid (SG) metamaterials. The band structures, transmission spectra, dispersion surfaces, equi-frequency contours (EFC) and circular dichroism (CD) of SG metamaterials are examined. Some interesting wave guiding characteristics, such as negative refraction and collimation, are presented and discussed. We also show how these optical properties are tailored by varying the refractive index contrast and volume fraction. These results are crucial for the design of functional devices at optical frequencies based on dielectric single gyroid metamaterials.
Regular coined metal nanosphere trimer: Simple and efficient polarization-independent SERS nanostructure

Chao Feng, Yan Zhao, Yijian Jiang, Beijing Univ. of Technology (China)

In this study, we research and analyze the surface enhanced Raman scattering (SERS) polarization of a regular gold nanosphere trimer using finite difference time domain (FDTD) simulations and group theory. The results clearly demonstrate why a regular gold nanosphere trimer shows polarization-independent SERS characteristics, as reported in previous experiments. Based on the explanation of the experimental phenomenon, we conducted many more simulations and calculations of regular gold, silver, platinum and copper nanosphere trimers under excitation wavelengths of 457 nm, 488 nm, 514.5 nm, 532 nm, 632.8 nm, 660 nm, 785 nm and 830 nm. From these results, we then predict the polarization-independent SERS characteristics and EFEM of these regular coined metal nanosphere trimers in the visible and near-infrared bands. The results demonstrate that all regular coined metal nanosphere trimers possess excellent polarization-independent SERS characteristics. Because of their perfect polarization-independent SERS performance over a 360° range, and the significantly hybridized SERS intensity of regular coined metal nanosphere trimers, gold and silver trimers in particular, regular coined metal nanosphere trimers are reliable and reproducible SERS substrates, which have the potential for conveniently and flexibly practical SERS detection without the uncertainty of polarization.
Conference 9757: High Contrast Metastructures V

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Part of Proceedings of SPIE Vol. 9757 High Contrast Metastructures V

9757-1, Session 1

Flat high-contrast metastructures (Invited Paper)

Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

No Abstract Available

9757-2, Session 1

Widened photonic functionality of asymmetric high-index contrast/photonic crystal gratings (Invited Paper)

Hai Son Nguyen, Xavier Letartre, Jean Louis Leclercq, Christian Seassal, Pierre Viktorovitch, Univ. de Lyon (France)

High index contrast/Photonic Crystal membrane resonators (HCG) are exploited to process free-space as well as wave-guided optical modes along a variety of addressing configurations and transfer functions.

In this presentation we emphasize that, within the variety of parameters usable for the design of HCGs, the transverse (vertical) symmetry properties of HCGs provide a power-full joystick for the dispersion engineering of guided mode resonances. The basic idea lies in that coupling between guided modes promoted by the grating is strongly dependent of the transverse symmetry properties of HCGs; for example coupling between guided modes of different transverse parity is prevented in transversely symmetric waveguide gratings, while it is made possible in asymmetric structures; the accessible degree of freedom for the molding of dispersion characteristics may therefore be considerably improved. The generation of optical beams with an arbitrary angle of the far field emission was reported in specifically designed HCGs, along this general approach*.

In this contribution, we concentrate on asymmetric HCGs designed to accommodate guided mode resonances with ultra-flat zero-curvature dispersion characteristics (or photons with ultra-heavy effective mass). Examples of the great potential of this family of asymmetric HCGs for new practical applications as well as for original physical studies will be presented. This will include the production of micro-lasers particularly suited for hybrid III-V / silicon heterogeneous photonic integration and the development of a platform for polaritonic devices, along CMOS compatible technological schemes. The relevance of this approach for efficient HCG thin film photovoltaic solar cells will also be pointed out.

*Pierre Viktorovitch et al, Photonic West 2014.

9757-3, Session 1

Flat free-space optical components and systems based on sub-wavelength high-contrast gratings (Invited Paper)

Andrei Faraon, California Institute of Technology (United States)

Flat optical devices based on sub-wavelength high index dielectric structures promise to revolutionize the field of free-space optics. I discuss our work on high contrast transmittarrays and reflectarrays that enable precise control of both polarization and phase with large transmission and high spatial resolution. These structures are composed of arrays of silicon nano-posts located on top of a low index substrate like silica glass or transparent polymers. Complete control of both the phase and polarization of light is achieved at the level of single silicon nano-post, which enables sampling of the optical wavefront with sub-wavelength spatial resolution. We demonstrate high numerical aperture lenses, high performance waveplates and polarizers. Devices operating simultaneously at different wavelengths are demonstrated. Ultra-thin optical elements integrated on flexible substrates are fabricated and characterized. Multiple flat optical elements are integrated in optical systems such as planar retro-reflectors and Fourier lens systems. New functionalities enabled by flat optical components and the prospects for tunable devices are discussed.

9757-4, Session 2

Guided-mode resonance nanophotonics in materially sparse architectures (Invited Paper)

Robert Magnusson, Manoj Niraula, Jae W. Yoon, Yeong H. Ko, Kyu J. Lee, The Univ. of Texas at Arlington (United States)

Interesting device concepts in nanophotonics rely on intricate resonance effects generated with nanopatterned films. As incident light couples to the film, attendant resonance effects impose diverse spectral signatures on the output light. The guided-mode resonance (GMR) concept refers to lateral quasi-guided, or leaky, waveguide modes induced in periodic layers. Whereas the fundamental GMR occurs in any diffraction regime, subwavelength architectures enable the most useful spectra. Even though these effects have been known for a long time, new attributes and application possibilities continue to appear. Here, we review the physics of GMR device operation, illustrate their design with rigorous methods, discuss fabrication processes, and present results of physical and spectral characterization. In particular, we discuss properties of wideband resonant reflectors designed with gratings in which the grating ridges are matched to an identical material thereby eliminating local reflections and phase changes. This critical interface therefore possesses zero refractive-index contrast; hence we call them “zero-contrast gratings.” We introduce a new class of reflectors and polarizers fashioned with dielectric nanowire grids that are mostly empty space. Computed results predict high reflection and attendant polarization extinction in multiple spectral regions for these sparse lattices. Experimental verification with Si nanowire grids yields a band of total reflection for one polarization state and free transmission of the orthogonal state. Finally, we present ultra-narrow bandpass filters using all-dielectric resonant gratings. We design, fabricate, and test nanostructured single-layer filters exhibiting high efficiency and sub-nanometer-wide passbands surrounded by 100-nm-wide stopbands.

9757-5, Session 2

Dielectric nanoantennas and metasurfaces for control of light at the nanoscale (Invited Paper)

Arseniy I. Kuznetsov, A*STAR - Data Storage Institute (Singapore)

Nanoantennas made of high-refractive index dielectric materials may have strongly resonant behaviour at optical frequencies. In simple spherical or disk geometries both electric and magnetic dipole resonances can be efficiently excited. This brings novel opportunities to control light at nanoscale dimensions using such resonant dielectric nanoantennas. Sub-diffractive arrays of these nanoantennas may act as metasurfaces, which have both electric and magnetic resonant response and may bring unique opportunities for the amplitude and phase manipulation. In this
presentation I will review recent progress of our team in the field of resonant dielectric nanoantennas and metasurfaces. This will include: (i) experimental demonstration of electric and magnetic dipole resonances and directional light scattering by single silicon nanoparticles, (ii) light guiding and magnetic near-field enhancement in coupled nanoantenna chains, and (iii) advanced phase and amplitude manipulation by resonant dielectric metasurfaces. In particular for the last point I will introduce ultra-thin transmissive optical elements allowing for compact 2-pi phase engineering as well as unique reflection characteristics of high-index dielectric metasurfaces with strong magnetic response associated with generalized Brewster effect.

9757-6, Session 2

**Dielectric metasurfaces on thin flexible substrates**

Seyyedeh Mahsa Kamali, Amir Arbabi, Ehsan Arbabi, Yu Horie, Andrei Faraon, California Institute of Technology (United States)

Metasurfaces are planar structures that control the wave front of light using a large number of sub-wavelength thick scatterers. Different plasmonic and dielectric based metasurface platforms have been proposed and demonstrated recently. Among those, high efficiency dielectric metasurfaces are promising candidates for replacing conventional free-space optical components like lenses, waveplates and polarizers. Their ultrathin structure makes them suitable for flexible platforms in a way that could not be achieved by conventional optical devices. Here, we demonstrate a platform for design and fabrication of dielectric metasurfaces on a flexible non-planar substrate. The method is based on fabricating the metasurface on a silicon wafer, and transferring it to a thin (~50 µm) polydimethylsiloxane (PDMS) layer as a flexible substrate. The metasurface layer is made of a periodic hexagonal lattice of amorphous silicon nano-posts with subwavelength lattice constant and thickness. As a first demonstration, a planar metasurface lens on PDMS substrate operating at the 915nm wavelength is fabricated. A diffraction limited spot size with 70% focusing efficiency is measured, showing the effectiveness of the design and the fabrication process. These results are promising for future applications of flexible dielectric metasurfaces in various fields where the flexibility of the device can be utilized. In addition, using a similar platform with flexible electronics, adds the possibility of integrating flexible photonics and electronics in the same device.

9757-7, Session 2

**High-efficiency aperiodic two-dimensional high-contrast-grating hologram**

Pengfei Qiao, Li Zhu, Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

High efficiency phase holograms are designed and implemented using aperiodic two-dimensional (2D) high-contrast-gratings (HCGs). With our design algorithm and an in-house developed rigorous coupled-wave analysis (RCWA) program for periodic 2D HCGs, the structural parameters are obtained to achieve a full 360-degree phase-tuning range of the reflected or transmitted beam, while maintaining the power efficiency above 90%. For given far-field patterns, we can generate the near-field phase distribution through an iterative process. The aperiodic HCG phase plates we design for holograms are pixelated, and the local grating parameters for each pixel to achieve desired phase alternation are extracted from our periodic HCG designs. Our aperiodic HCG holograms are simulated using the 3D finite-difference time-domain method. The simulation results confirm that the desired images are successfully reconstructed under the incidence of light with the designed wavelength. The HCG holograms are implemented on the silicon-on-insulator wafers. The grating structures are patterned using the electron-beam lithography and etched using the transformer-coupled plasma etcher. The high-contrast gratings allows us to realize low-cost, compact, flat, and integrable holograms with sub-micrometer thicknesses and 100-micrometer length-scales.

9757-8, Session 3

**Multi-mode rate-equation analysis of VCSELs with >30GHz bandwidth (Invited Paper)**

Werner H. Hofmann, Technische Univ. Berlin (Germany)

Multi-Mode Rate-Equation Analysis of VCSELs with >30GHz Bandwidth

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With the increasing bandwidth demand of optical interconnects, directly modulated VCSELs with ultimate speed ratings are needed [1]. For serial 100 Gbps solutions today’s VCSELs have to increase their high-speed performance. Here we report about our next generation devices.

The devices discussed here are an optimized version of our very successful high-speed, temperature-stable 980 nm VCSELs [2] and serve as reference-structure for high-contrast-grating high-speed VCSELs which are in fabrication. Sharing the very short half-lambda cavity and a binary bottom-mirror with 32 pairs, levels were further optimized in order to minimize internal loss. Like previously parasitics are controlled by two oxide passivation layers and a high conductivity current-spreading layers. InGaAs MQW active layers with with strain compensated GaAsP barriers were utilized for high differential gain. The 22 -pair AlInGaAs/AlInGaAs top-mirror was replaced by a 18-pair GaAs/AlInGaAs mirror for lower photon lifetime, better confinement and better heat extraction. The epi-structure was grown by IQE Europe.

A detailed small-signal analysis was performed. The VCSELs showed modulation bandwidth around and exceeding 30 GHz. The measured data was fitted to single-mode and multi-mode rate-equation based models assuming self-organized carrier reservoirs formed by spatial hole burning. The common set of figures of merit is extended consistently to explain dynamic properties caused by carrier fluctuations.

Mode control, which can ideally be performed by high-contrast-gratings, seems essential for next generation high-speed VCSEL devices.

References


9757-9, Session 3

**Hybrid III-V on Si grating as a broadband reflector and a high-Q resonator (Invited Paper)**

Il-Sug Chung, Alireza Taghizadeh, Gyeong Cheol Park, Technical Univ. of Denmark (Denmark)

We propose a new grating structure referred to as hybrid grating, which consists of an un-patterned III-V layer and a sub-wavelength grating layer. We show that the hybrid grating can be designed to be a reflector with a bandwidth broader than high contrast gratings as well as a resonator with a quality (Q) factor higher than photonic crystal cavities. Since the un-patterned III-V layer may include a gain region, ultra-compact lasers or resonant cavity detectors can be realized by using the hybrid grating. In the talk, the physics of broadband reflection process and a high-Q resonance process will be discussed. Furthermore, experimental device demonstrations will be presented.
9757-10, Session 3

**Heterogeneously-integrated InP HCG-VCSEL for flexible optoelectronics**

Li Zhu, James E. Ferrara, Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

Light manipulation on a flexible, conformable, wearable surface with the function of emission, detection and processing is the frontier for many applications, including ubiquitous environment-awareness sensors for bridge, buildings, airplanes and robots; wearable health monitoring devices for public health; active camouflage; wearable displays and visual arts for commercial products. Photonic integrated circuits (PICs) have been the workhorse of communication, displays and sensors. However, the rigidity of the devices limits their use in the soft optoelectronic applications. In order to achieve the complete optoelectronic functionality for soft PICs, components, such as emitter, transmitter and detector, have to be realized on the flexible substrate with the performance comparable to the devices on rigid substrate. Attributing to excellent performance of the silicon photonics, transmitter, such as Si waveguide, and detector, such as Ge photodetectors, can be transferred to a flexible substrate without major physics obstacles. On the other hand, the laser emitter, preferably working at silicon transparent wavelength, e.g. 1550nm, is difficult to work because of the poor thermal conductance of the flexible substrate. In this work, we fabricate the vertical cavity surface emitting laser (VCSEL) using AlGaInAs quantum well as gain and an high contrast grating (HCG) on silicon as mirror. Such a device is transferred to the polydimethylsiloxane (PDMS) substrate. The device achieves lasing at 1585nm under electrical pumping with continuous power greater than 0.8 mW. This is the first report for C-band semiconductor laser working the flexible carrier.

9757-11, Session 3

**Two-dimensional designed fabrication of subwavelength grating HCG mirror on silicon-on-insulator**

Shen-Che Huang, Kuo-Bin Hong, Tien-Chang Lu, National Chiao Tung Univ. (Taiwan); Sailing He, KTH Royal Institute of Technology (Sweden)

High contrast subwavelength gratings (HCGs) with a thickness of only a few hundred nanometers lead to large stopband reflected spectra, polarization control and light mass for fast tuning of cavity modes. Compared with the distributed Bragg reflectors (DBRs) structure, HCG is utilized the destructive interference in the in-plane direction. These gratings also can propose a polarization-independent mirror and have superior performance to that of DBRs.

In this letter, here we report the realization of designed and fabricated a novel silicon-compatible two dimensional subwavelength grating, which could improve the laser characteristics and achieve the much lower cost of the integrated optoelectronic device. The investigated actual nano-fabrication structure in details with distinct geometry-dependent designs was employed to verify the structural parameters including grating periods and filling factors by using three dimensional computer-aided software. From the optimized simulation results, the optimized structure was obtained large stopband spectra with reflectivity greater than 90%. The HCG designed mirror with a wide reflection stopband of over 200 nm via the monochromator system to record the reflectivity spectrum was fabricated on a silicon-on-insulator wafer with a 220 nm silicon layer by electron-beam lithography and inductively coupled plasma process. The experimental result was almost consistent with simulated one. We believe this achievement should have an impact on numerous photonic devices operating in the multi-telecommunication wavelength or even near-infrared region of the light emitting devices and helpful attribution to the integrated HCG VCSELs in the future.

9757-12, Session 4

**Multi-parameter optimization of monolithic high-index contrast grating reflectors** (Invited Paper)

Magdalena Marciniak, Marcin Gebski, Maciej Dems, Michal Wasiak, Tomasz G. Czyszanskowski, Lodz Univ. of Technology (Poland)

Conventional High-index Contrast Gratings consist of periodically distributed high refractive index stripes surrounded by low index media. Practically, such low/high index stack can be fabricated in several ways, however low refractive index layers are electrical insulators of poor thermal conductivities. Monolithic High-index Contrast Gratings (MHCGs) overcome those limitations since they can be implemented in any material with a real refractive index larger than 1.75 without the need of the combination of low and high refractive index materials. This, in contrary to the conventional HCGs, allows to provide more efficient current injection and better heat flow through the mirror. It has a great application potential in passive and active optoelectronic devices, but mostly it has great prospects in application to monolithically integrated phosphide and nitride-based Vertical-Cavity Surface-Emitting Lasers (VCSELs) that lack monolithically integrated materials of high refractive index contrast. Incorporation of MHCG can lead to simplification of VCSELs design, reducing the structure to the active region with carrier confinement scheme sandwiched between MHCG mirrors etched on both surfaces in post processing.

We present extensive numerical analysis of a Monolithic High-index Contrast Gratings using a three-dimensional, fully vectorial optical model. We investigate possible designs of MHCGs using multidimensional optimization of grating parameters for different refractive indices corresponding to typical phononic materials. Nonetheless the final conclusions are of much more general meaning and can be used to MHCGs realized in numerous possible materials and applications related to phase engineering.

9757-13, Session 4

**Design of athermal and tunable MEMS VCSELs with a thermally-actuated HCG mirror**

Shunya Inoue, Mansanori Nakahama, Fumio Koyama, Tokyo Institute of Technology (Japan) and Precision and Intelligence Lab. (Japan)

Athermal and widely tunable lasers are desired for ultra-high capacity access networks and optical interconnects based on WDM. The thermal wavelength shift of semiconductor lasers is caused by refractive index change and has been avoided with a TE cooler and precise temperature controller. We proposed and demonstrated an athermal and tunable VCSEL emitting at 850nm and 1550nm. In this paper, we design the thermally actuated high-contrast grating (HCG) mirror consisting of AlGaAs membrane with different compositions or semiconductor/metal hybrid structure. The thermal actuation and its impact on the temperature dependence of HCG VCSELs will be discussed.

9757-14, Session 4

**Beam engineering of VCSELs using high-contrast grating and coupled cavities** (Invited Paper)

Fumio Koyama, Tokyo Institute of Technology (Japan)

We present the beam engineering of VCSEL photonics using high-contrast grating (HCG) and/or coupled cavities. The radiation pattern from a VCSEL
can be tailored by using angular-dependent high-contrast grating and laterally coupled cavities. We demonstrate the dual beam emission from a single-mode VCSEL with an engineered angular dependent HCG. We also realize a high-speed electrical beam switching of a VCSEL with a transverse coupled cavity. Sub-gigahertz and large deflection angle (>30°) beam switching is demonstrated by employing the transverse mode switching. The proposed concept may open up the beam engineering of VCSEL photonics toward electrical high-speed beam steering function in semiconductor lasers.

9757-15, Session 4
Active tunable high contrast meta-structure Si waveguide
Lingjun Jiang, Hussein Taleb, Z. Rena Huang, Rensselaer Polytechnic Institute (United States); Weimin Zhou, U.S. Army Research Lab. (United States)

We have designed a novel Si based 1-dimensional high contrast metastructure waveguide that has slow light effect as well as phase tunability using p-n junction. The goal is to use such waveguide to design active optical devices such as high frequency modulators and tunable filters for analog RF-photonic or data communication applications.

The Si ridge waveguide has a pair of high contrast grating wings adhered to the waveguide core in the center. Grating bars at two sides of the waveguide are doped P and N-type respectively, while a p-n junction region is formed in the middle of the waveguide core. Dispersion engineering is applied for structure optimization. By carefully adjusting the grating lattice constant, filling factor and width of the central rib waveguide, a photonic band gap is observed, and the “defect line” introduces the fundamental guided mode inside the band gap. Using a voltage to bias the p-n junction, one can sweep the free carriers to change the effective index of the waveguide as well as the dispersion property of the grating.

Compared with traditional line-defect photonic crystal waveguide, this Si waveguide exhibits good slow light effect as well as smaller propagation loss. The simplicity of the structure also makes it less fabrication accuracy demanding.

This metastructure Si waveguide is ideal in the design of high frequency optical modulators since the slow light effect can reduce the modulator waveguide length, increase the modulation efficiency as well as compensate other nonlinearity factors of the modulator for analog applications.

9757-16, Session 5
Advanced photonic orbital angular momentum devices based on silicon photonics high-contrast gratings (Invited Paper)
Xinlun Cai, Sun Yat-Sen Univ. (China); Ning Zhang, Univ. of Bristol (United Kingdom); Siyuan Yu, Sun Yat-Sen Univ. (China) and Univ. of Bristol (United Kingdom)

Using a semi-analytical model that fully simulates the 3D vectorial mode coupling process in the cylindrical space with high precision and fast speed, we designed and optimised a number of devices for the emission, multiplexing and detection of orbital angular momentum (OAM) modes of light based on our silicon photonics micro-ring angular grating structure. We demonstrated single OAM mode emitters with high emission efficiency and high modal purity and multiple OAM emitters as either OAM multiplexers for optical communications or super-positional OAM state generators for quantum photonic systems. We further demonstrated the selective detection of superpositional photonic orbital and spin angular momentum states.

9757-17, Session 5
Experimental demonstration of a metasurface planar retroreflector
Amir Arbabi, Ehsan Arbabi, Yu Horie, Seyyedeh Mahsa Kamali, Andrei Faraon, California Institute of Technology (United States)

Retroreflectors reflect back optical beams along their incident directions. Two main categories of retroreflectors are commonly used in optics: corner cube and cat’s eye retroreflectors. Corner cube retroreflectors are made of three mutually perpendicular reflective surfaces which resemble the surfaces forming a corner of a cube. Cat’s eye retroreflectors are made by reflective coating half of a transparent sphere and can be considered as a combination of a convex lens and a concave mirror. In many of the applications including space optical communication and optical remote sensing, low weight retroreflectors with planar form factor are desirable. For example, low power free-space optical transceivers mounted on aircrafts have been realized in a form of a modulating retroreflector composed of a multi quantum well modulator and a corner cube retroreflector. None of the two conventional retroreflector designs provide the low weight and planar form factor required for such applications. Here we experimentally demonstrate an efficient planar metasurface retroreflector composed of two cascaded dielectric metasurfaces and a flat metallic reflector. For the operation wavelength of 850nm, the two metasurface layers are made of arrays of 600 nm tall amorphous silicon nano-posts arranged on a periodic hexagonal lattice with subwavelength lattice constant. One of the metasurfaces operates as a convex lens and the other combined with the metallic layer forms a focusing mirror. The metasurface retroreflector shows experimentally measured retroreflectivity of more than 70% close to normal incidence and half power field of view of 60 degrees.

9757-18, Session 5
Broadband flat optics with metasurfaces and applications in computational imaging
Francesco Aieta, Hewlett-Packard Labs. (United States)

Metasurfaces provide a new path for designing planar optical devices with new functionalities. Most of the demonstrations proposed so far are significantly affected by a limitation: the chromatic dispersion of their operation. As a consequence, the properties characterizing their functions such as lens focal length and beam deflection angle change as a function of the wavelength. This condition is shared by all planar optical devices, such Fresnel lenses, zone plates and so forth and while it can be an advantage for some applications, it restricts the use of flat optics to a limited space. By designing an array of low-loss dielectric resonators, we create metasurfaces with an engineered wavelength-dependent phase shift that introduces for the first time correction for the large chromatic effects typical of all flat optical components. A flat lens without chromatic aberrations and a beam deflector are demonstrated. The suppression of chromatic aberrations in metasurface-based planar photonics will find applications in lightweight collimators for displays, and chromatically-corrected imaging systems.

Computational imaging provides a new path for designing imaging systems where both the optics and the image processing are jointly adjusted simultaneously for global system optimization. The local control of amplitude, phase and polarization of light at the subwavelength scale introduces new capabilities for computational imaging not possible with conventional optics. The integration of metasurface-based devices with image processing is proposed to achieve miniaturized and compact novel sensors and imaging components.
Polarization insensitive multi-wavelength metasurface lens

Ehsan Arbabi, Amir Arbabi, Seyedeh Mahsa Kamali, Yu Horie, Andrei Faraon, California Institute of Technology (United States)

Optical metasurfaces are subwavelength thick devices, working based on diffraction of light at nanostructured surfaces. Several different metasurface devices have been demonstrated in recent years, including high efficiency lenses with large numerical apertures, polarization and phase controllers, and retroreflectors. One major drawback, however, is that they suffer from high chromatic aberrations due to their diffractive operation principle. Thus, a metasurface lens will focus optical waves with different wavelengths at different focal lengths, and will have distorted focal points at wavelengths other than the design one. For some applications, it is useful to have a metasurface that works at two different wavelengths, sometimes with a significant separation. For instance, in two photon microscopy, the lens should operate at both the pump and fluorescent photon wavelengths. Here we discuss several methods for designing metasurface lenses with moderate numerical apertures working at two different wavelengths. We present experimental results of devices operating in the near infrared and telecom, fabricated using a dielectric metasurface platform based on submicron thick amorphous silicon nano-posts, located on the vertices of a hexagonal lattice on a fused silica substrate. The devices are theoretically and experimentally shown to have a diffraction limited spot size in the focus, and have the same focal distance at the two design wavelengths. Focusing efficiencies of above 60% in one wavelength, and above 25% in the other are measured. We will compare the results of the different proposed methods, and summarize their advantages.

Planar lens with a quasi-periodic circular design

Thaibao Q. Phan, Li Zhu, Pengfei Qiao, Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

In recent years, subwavelength dielectric gratings have been engineered for use as planar focusing elements at optical communication frequencies. Pioneering designs were based on aperiodic one-dimensional gratings, which were polarization-sensitive and designed bar by bar. More recent advances eliminated polarization dependence by using two-dimensional hexagonal lattices; these can be designed algorithmically, but the inherent geometry requires the use of only one period for the hexagonal lattice. We propose a unique geometry for designing two-dimensional grating lenses: dielectric posts arrayed in concentric circles. Because it is straightforward to space concentric rings apart at varying distances, we no longer need to restrict the design to a uniform grating period. By choosing two periodicities to work with, we managed to algorithmically design a two-dimensional lens, but with the advantage that our smallest feature sizes are up to twice as large as those of lenses designed with only one period. This increases the ease of fabrication for lenses working at current wavelengths and opens up the possibility for working with shorter wavelengths. Furthermore, this concentrically arrayed grating lens can be designed using phase information calculated for a periodic hexagonal lattice, even though the two designs show very little geometric resemblance. Also, we found that the grating lens is suitable not only for focusing plane waves, but also for imaging point sources. Finally, we show that bifocal lenses can be created from diffraction gratings using our design algorithm as well.

Quantum dot cavity quantum electrodynamics with photonic crystals (Invited Paper)

Satoshi Iwamoto, Yasutomo Ota, Shun Takahashi, Kazuhiro Kurum, Yusuhiko Arakawa, The Univ. of Tokyo (Japan)

Photonic crystal (PhC) structures embedding semiconductor quantum dots (QDs) are a fascinating platform for exploring the frontier of solid-state cavity quantum electrodynamics (QED) and its applications. Here, we discuss our recent experimental progresses in QD-CQED systems using PhC structures. After discussing strong coupling effect in QD-CQED systems using a high Q HO-type PhC nancavity, we report an accurate measurement technique of QD position in PhC nanocavities, which enables us to directly investigate the effect of QD position on the QD-cavity coupling constant. Control of circularly polarized spontaneous emission from QDs by using chiral 3D PhCs will be also discussed.

A coherent polariton laser using a high-contrast grating-based microcavity (Invited Paper)

Hui Deng, Seonghoon Kim, Bo Zhang, Zhaorong Wang, Univ. of Michigan (United States); Sebastian Brodbeck, Christian Schneider, Martin Kamp, Sven Höfling, Julius-Maximilians-Univ. Würzburg (Germany)

Semiconductor polariton laser has emerged as a new light source that promises coherent emission without requiring population inversion. Polariton lasers have been widely observed in diverse material systems with thresholds many orders of magnitude than those of semiconductor photon lasers. However, intensity stability, a critical feature of a laser, remains poor. Large intensity noise persisted in polariton lasers due to complexities of 2D systems. The large intensity noise in turn limits the temporal phase coherence of a polariton laser.

Using a high-contrast grating (HCG) mirror to enforce tight confinement and single-mode lasing, we achieve the first polariton laser with Poisson intensity noise, measured by a sharp decrease of the auto-correlation function to unity above the lasing threshold. Furthermore, we show a change from Lorentzian to Gaussian linewidth of the polariton laser when the condensate interaction energy exceeds the lasing mode bandwidth. This is unique to matter-wave lasers. These coherence properties are well described by an analytical model for single-mode atom lasers that includes interactions among the particles in the lasing mode. Comparison of experiment with the model yields large interaction strength between condensed polaritons, which is important for polariton-based nonlinear device.

Design flexibility of the HCG mirror will enable further mode-engineering and optimization of the polariton laser, including better lateral confinement, polarization selectivity and dispersion engineering.
Our approach relies on controlling the optical momentum of evanescent waves as opposed to conventional photonic devices, which manipulate propagating waves. This leads to a counterintuitive confinement strategy for electromagnetic waves across the entire spectrum. Finally, based on these momentum transformations, we propose a class of practically achievable waveguides that exhibit dramatically reduced cross talk compared to any dielectric waveguide (slot, photonic crystal, or conventional).

PARADIGM SHIFT IN LIGHT CONFINEMENT STRATEGY

We introduce two distinct photonic design principles that can ideally lead to subdiffraction light confinement without metal.

A. Relaxed Total Internal Reflection


9757-24, Session 6

Integrated plasmonic refractive index sensor based on grating/metal film resonant structure

Mingze Sun, Tsinghua Univ. (China); Tianbo Sun, Univ. of California, Berkeley (United States); Youhai Liu, Tsinghua Univ. (China); Li Zhu, Univ. of California, Berkeley (United States); Fang Liu, Yidong Huang, Tsinghua Univ. (China); Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

Optical biosensors with the high sensitivity is an important tool for environment monitoring, disease diagnosis and drug development. Integrating the biosensor could reduce the size and cost and is desirable for home and outdoor use. However, the integrated structure always results in the worsening of sensitivity and narrowing of sensing range, especially for small molecule sensing.

In this work, we propose an integrated plasmonic biosensor based on the resonant structure composed of dielectric grating and metal film. With vertically incident light from the grating side, the surface plasmon polariton (SPP) mode could be excited at certain wavelength and the reflected light would vanish. Simulation results indicate that, when varying refractive index (nd) of detection layer, the energy of reflected light changes dramatically. Assuming the resolution of the power meter is 0.01dB, the sensing resolution could be 4.37e-6 RIU, which is very close to the bulk lens based SPP biosensor by monitoring the light intensity variation.

Since antibody and antigen always have the size of tens of nanometers, it is necessary to check the sensing ability of the sensor in tens of nanometers. Fixing nd and varying the thickness of detection layer, calculation result demonstrates that the reflected light energy is sensitive to the thickness change with one hundred nanometers. This attributes to the surface mode property of SPP mode. It also shows the sensing range can be extended by varying the grating period, which would help to cover a wide refractive index (biomolecule) sensing range.

9757-25, Session 7

Optomechanical applications of high-contrast gratings (Invited Paper)

John R. Lawall, Yi-Chen Shuai, Navin Lingaraju, National Institute of Standards and Technology (United States); Haitan Xu, Yale Univ. (United States); Utku Kemiktarak, Avago Technologies Ltd. (United States); Jacob M. Taylor, National Institute of Standards and Technology (United States)

High-contrast gratings (HCGs) fabricated from silicon nitride under tensile stress can realize a mechanical resonator with a very high quality factor, that is simultaneously an extremely lightweight mirror. Such an optomechanical element offers a fruitful platform for experiments in optomechanics. Our canonical platform is to use such HCGs as one mirror of a Fabry-Perot cavity, in which the optical power circulating in the cavity is correlated to the mechanical motion of the HCG. I will briefly review our early experiments with this system, in which we optically cool hundreds of mechanical modes of the HCG to cryogenic temperatures, realize a “phonon laser,” and explore the analogies between various properties of this system and familiar properties of an optical laser. In a richer experimental platform, we have used an HCG to couple two optical resonators both optically and mechanically. We have observed avoided crossings in the optical spectra, from which we are able to extract more detailed information concerning the optical loss mechanisms in HCGs, and optically-induced symmetry breaking corresponding to tailorable multiwell optomechanical potentials. Our current effort involves HCGs with a two-dimensional pattern, which are largely insensitive to polarization, provide better dissipation of heat, and have better mechanical properties. I will discuss the design of these structures, the mechanical quality factors achieved, and their performance as mechanically compliant elements in optical cavities. I will also discuss ongoing efforts to improve the mechanical quality factor of these devices, as well as operating them in a cryogenic environment.

9757-26, Session 7

Optical and mechanical design of metastructures for optomechanical VCSELS

Stephen A. Gerke, Weijian Yang, Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

MEMS-tunable vertical-cavity surface-emitting lasers with high-contrast metastructure (HCM) reflectors have recently demonstrated the first instance of optomechanical self-oscillation in an electrically pumped lasing cavity. Self-oscillation in the tuning mechanism produces broadband self-swept light at megahertz sweep rates, with substantial applications in laser ranging and imaging. In this work, we analyze the high contrast metastructure’s unique contribution in enabling active-cavity optomechanical phenomena. In addition to being an ultralight broadband reflector, a high contrast metastructure supports a variety of mechanical oscillation modes that each induce different changes on grating reflectivity and cavity length, leading to qualitatively different optomechanical oscillation phenomena. Through finite-difference time-domain optical simulations of the effects of mechanical deformation on HCM reflectivity together with finite element method simulations of HCM mechanical modes, we present designs of metastructure reflectors to selectively exhibit large laser amplitude or frequency modulation due to self-oscillation. Analysis of damping mechanisms in HCM mechanical modes confirmed by laser Doppler vibrometry (LDV) illustrate the high mechanical quality factor of HCM modes and its important role in lower self-oscillation threshold. These design insights enable improved self-swept source performance and point to new applications in radio-frequency clock generation.

9757-27, Session 7

Cavity optomechanics with 2D photonic crystal membrane reflectors

Navin Lingaraju, Yi-Chen Shuai, John R. Lawall, National Institute of Standards and Technology (United States)

To achieve high optomechanical coupling in Fabry-Perot cavities or membrane-in-the-middle optomechanical systems, devices with high reflectivity and low mass are needed. Building on our previous work with one-dimensional gratings on suspended membranes, we patterned two-dimensional photonic crystal (PhC) gratings on monolithic, suspended
membranes made from silicon nitride. Such silicon nitride-based membrane reflectors offer the potential to achieve high optomechanical coupling while also reducing thermal fluctuations in an optomechanical system owing to their high mechanical Q-factor. We performed computer simulations for the various designs and the results of our simulations tracked with actual device performance. In our experiments, we also evaluated the sensitivity of membrane reflectivity to input beam polarization. For linearly polarized light, we obtained reflectivity upwards of 99% over several nanometers in the telecom band. These membrane reflectors were used as the moving mirror in a Fabry-Perot cavity in order to probe their optical response. We were able to achieve cavities with a finesse of about 1,200. At present we are developing computer simulations to model the mechanical response of the silicon nitride membrane reflectors and will discuss measurements of their mechanical properties.

9757-28, Session 7

Progress and prospects of silicon-based design for optical phased array (Invited Paper)

Weiwei Hu, Chao Peng, Peking Univ. (China); Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

Optical phased array (OPA) has been considered as a promising technology for realizing flexible and efficient beam-steering applications that avoids mechanical moving parts. The directions and field patterns of the outgoing beam can be tuned by manipulating the phases of individual array unit. Therefore, compact, high-speed, high-efficient phase modulator array is indispensable for the OPA.

In our research, we propose to utilize high-contrast grating (HCG) as phase modulator. It is proved that HCG possesses high-Q resonances that origins from the cancellation of leaky waves. As a result, sharp resonance peaks appear on the reflection spectrum thus HCGs can be utilized as efficient phase shifters. We proposed a semi-analytical model to depict the behavior of electromagnetic field within the HCGs. The high-index contrast, which weakens the validity of the perturbation assumption that was applied in some conventional models, has been properly treated in our semi-analytical model. Thus we can perform a systematic optimization of HCG devices.

On the other hand, we theoretically and experimentally investigated the system design for silicon-based optical phased array, including the star coupler, phased array, emission elements and far-field patterns. Further, the non-uniform optical phased array which is controlled by wavelength for simplified beam steering was presented. Varied elements were discussed respectively. The far field beam steering effect was presented and was seen clearly.

9757-29, Session 8

High-contrast subwavelength grating-based smart power window (Invited Paper)

Ameen Ellickott, Mallikarjun Bhavanani, Academy of Scientific & Innovative Research (India) and CSIR Madras Complex (India); Bala Pesala, CSIR Madras Complex (India) and Academy of Scientific & Innovative Research (India)

Smart windows are employed in buildings using various technologies to block infrared radiation. Here, we propose a Smart Power Window (SPW) based on High Contrast Gratings (HCG) on a glass substrate for simultaneous energy harvesting from Near Infrared (NIR) radiation, reduction of heat load and maximizing natural lighting in the building. HCG is a class of planar optics in which grating structure has high refractive index contrast with the surroundings. NIR radiation entering the building through a window causes additional heat load to air conditioning systems. The SPW minimizes the heat load by allowing visible radiation to pass through the window and guiding NIR radiation to the edges. Silicon solar cells placed at the edge can convert the NIR radiation to electricity.

The HCG parameters (material, period, thickness and duty cycle) were optimized using rigorous coupled wave analysis and finite difference time domain simulations to maximize the guiding of light in the NIR region (700-1100 nm) to the edge of the window. TiO2 is chosen as the grating material as it has high refractive index (>2) and low material absorption in visible and NIR regions. Simulation results shows that SPW can simultaneously harvest energy (20-30 W/m2) and reduce the infrared transmission through the window by 30% thereby reducing heat load to the building.

Conventional fabrication methods such as e-beam lithography, nano-imprint lithography, etc. are expensive, time consuming and have limitations for large area fabrication. Here, SPW with a large area (>100 cm2) is fabricated using interference lithography, a fast and cost effective technique suitable for large area fabrication. The proposed SPW is suitable for Building Integrated Photovoltaic (BIPV) applications.

9757-30, Session 8

Photonic-crystal slab for terahertz-wave technology platform (Invited Paper)

Masayuki Fujita, Osaka Univ. (Japan)

Photonic crystals are analogous to solid-state crystals in manipulating photons, and are composed of a dielectric material with a periodic refractive index distribution. Particularly, high-index contrast (semiconductor/air) 2D photonic-crystal slabs are promising for practical applications owing to the strong optical confinement in simple planar structures.

We present the recent progress on a 2D photonic-crystal slab as a technology platform in terahertz-wave regions, which are located between the radio and light-wave regions (0.1–10 THz). Terahertz photonic-crystal slabs hold the potential for developing ultralow-loss and compact terahertz components and devices used in applications, including wireless communication, spectroscopic sensing and imaging.

9757-31, Session 8

Slow-light effect via Rayleigh anomaly in high contrast gratings

Kyoung-Youm Kim, Xinyuan Chong, Fanghui Ren, Alan X. Wang, Oregon State Univ. (United States)

Rayleigh Anomaly, sometimes called as Wood or Rayleigh-Wood Anomaly, indicates the phenomenon when diffracted lights are directed perpendicular to the surface normal of the grating. In this paper, we found that if the diffraction efficiency is high enough, e.g., from a high index contrast grating, Rayleigh Anomaly can slow down the group velocity of the transmitted light. And more importantly, this slow light effect can extend much further away from the grating surface than the surface plasmon polaritons (SPP) waves. This can, say, increase the interaction time between light and matter over a long path, and thus be applied to the realization of enhanced optical sensing or photo detection capabilities. However, we found that both the slow-down factor and the effective range depend on the grating size, and to take this ‘finiteness’ into account is quite troublesome. In this work, we developed a general analytical approach to investigate the slow light effect of Rayleigh Anomaly on high contrast gratings with both infinite and finite sizes. Different than numerical methods such as rigorous coupled wave analysis or finite element analysis, we only need to consider the diffracted optical power after the high contrast grating, regardless of the detailed grating parameters. Our study shows that Rayleigh Anomaly can effectively slow down the group velocities of the transmitted light over a very long effective range, but the effect will diminish as the size of the grating shrinks.
A detailed investigation of strain patterning effect on bilayer InAs/GaAs quantum dot with varying GaAs barrier thickness (Invited Paper)

Binita Tongbram, Navneet Sehara, Jashan Singhal, Debi P. Panda, Subhananda Chakrabarti, Indian Institute of Technology Bombay (India)

In this paper we discuss detailed strain effects on a bilayer InAs quantum dot with varying GaAs barrier thickness and compare with uncoupled structure and detailed structure were characterized by transmission electron microscopy, atomic force microscopy (AFM), high resolution X-Ray diffraction (HRXRD) and Raman spectroscopy to evaluate the impact of strained layer and also studied the optical properties by photoluminescence measurements. On varying the thickness of the GaAs barrier layer, the role of strain demonstrates a promising approach to tuning the quantum dot morphologies and structures and hence, optical properties. This can be easily observed from the HRXRD rocking curves which result in a shift of the zero order peak position. Both in and out plane strain decrease as the thickness is increased. Even the Raman optical phonon peaks justifies the decrease of strain on increasing the GaAs barrier thickness. Therefore, coupling dots gives high emission wavelength of 1.35-1.47µm at 300K and the dots are much more uniformly spread out. Structure with a range of 5.5nm-8.5nm GaAs barrier thickness interlayer reveals even high-quality crystallinity of the epilayers with the FWHM of 21.6arcsec for the (004) plane. Uncoupled structure responds low crystalline quality with FWHM of 109arcsec. Dislocation density decreases drastically (106/m²) with increase of strain which is an important aspect for lasers and other devices in increasing their efficiency. Activation energy also shows a positive correlation with coupling structure. From AFM results, Coupled structure shows homogeneous in dots size array (density of 1.5?10^10 /cm²). DST, India and IITBNF are acknowledged.

InAs/GaAs quantum-dot light emitters monolithically grown on Si substrate

Siming Chen, Jiang Wu, Qi Jiang, Mingchu Tang, Alwyn J. Seeds, Huiyun Liu, Univ. College London (United Kingdom); Mengya Liao, University College London (United Kingdom)

There have been extensive studies on silicon photonics in recent years, with a view to solving the data traffic jam facing traditional copper interconnectors and to realize low-cost silicon optoelectronic integrated devices utilizing the maturity of CMOS technology. Despite the rapid progress being made in silicon-based light modulation and detection technology, the realization of a silicon laser has remained an unmet challenge because silicon is an indirect band-gap semiconductor, so that the probability for radiative recombination is extremely low. One of the most promising techniques for achieving an electrically pumped Si laser is hybrid integration of III–V materials on a silicon platform, where the III–V active region acting as the optical gain medium, is either bonded or directly epitaxially grown on the silicon substrate. The latter method is preferable for large scale, low-cost, and high yield fabrication. Recently, III–V quantum dot (QD) structures have received rapidly growing attention for III–V semiconductor lasers on silicon substrates due to their unique properties, in particular less sensitivity to nonradiative recombination centres and delta-function density of states.

In this work, we demonstrate experimentally that by utilizing the combined effect of strained layer superlattice dislocation filter layers and in situ thermal cycle annealing processes, high quality GaAs films with extremely low threading dislocation density can be achieved. Based on this approach, we report a c.w. 1.310 nm wavelength InAs/GaAs QD laser directly grown on a Si substrate and delivering record laser performance under pulsed operation.

Dual-band sub-monolayer InAs quantum-dot infrared photo-detector for mid- and long-wavelength infrared detection

Yao Zhai, Univ. of Massachusetts Lowell (United States); Guiru Gu, Stonehill College (United States); Xuejun Lu, Univ. of Massachusetts Lowell (United States)

We report a dual-band InAs quantum dot infrared photodetector (QDIP) operating for mid-wave infrared (MWIR) and long-wave infrared (LWIR) regions. The InAs quantum dots were self-assembly and sub-monolayer (SML) grown on GaAs substrate by molecular beam epitaxy (MBE), separately. The QDIP was able to operate at two optical windows MWIR and LWIR bands, at both positive and negative bias voltages at 78K. The detectivity, D*, was obtained as 6.0?108 Hz¹/²/W at 5.5µm and 1.2?109 Hz¹/²/W at 9.0µm.

Structural and optical properties of GaAs quantum dots grown on GaP (100) substrate

Shabnam Dadgostar, Humboldt-Univ. zu Berlin (Germany); Alfredo Torres Perez, Oscar Martinez, Juan Jimenez, Univ. de Valladolid (Spain); Jan Schmidt Bauer, Torsten Boeck, Leibniz-Institut für Kristallzüchtung (Germany); Anna Mogilatenko, W. Ted T. Masselinke, Fariba Hatami, Humboldt-Univ. zu Berlin (Germany)

We describe growth, structural and optical properties of self-assembled GaAs/GaP quantum dots grown using GS-MBE. For structures with GaAs layer thicker than a critical 2D-3D growth transition of 1.7 ML, the 3.6% lattice mismatch in the materials system results in formation of defect-free QDs via Stranski-Krastanov growth mode. The nominal coverage of the GaAs was varied between 1.2 and 5.4 monolayers. The structural analysis of the samples using atomic-force and transmission-electron microscopy show that, with increasing coverage of GaAs the average lateral size and height of QDs changes from 17 and 0.9 nm to 34 and 2 nm, respectively. The lateral density of the QDs remains in the range of 90 dots per µm² for all samples. Depending on the growth conditions, the optical emission of the samples peaks between 1.77 and 2.07 eV. The emission spectra of all QDs samples contain two peaks, whereas the QW sample emit light at a single peak. With increasing GaAs coverage the position of both peaks moves to the lower energies and the intensity of the lower energy peak increases. The low energy peak emit light up to 300 K. We picture this behavior using an ensemble of mixed strained and partially relaxed QDs in the samples. The
lower energy peaks is due to the direct e-h recombination in the partially relaxed QDs and the higher energy due to the indirect recombination in the small and strained QDs. Our model is confirmed by the results from the QD size distribution investigation.

9758-5, Session 2
Towards 1.55 μm single-photon sources on Si substrates using GaAsSb-capped InAs quantum dots (Invited Paper)

Jonathan R. Orchard, The Univ. of Sheffield (United Kingdom); Jiang Wu, Univ. College London (United Kingdom); Chris Woodhead, Robert J. Young, Lancaster Univ. (United Kingdom); Richard Beanland, The Univ. of Warwick (United Kingdom); Huiyun Liu, Univ. College London (United Kingdom); David J. Mowbray, The Univ. of Sheffield (United Kingdom)

In recent years there has been an ever increasing interest in quantum cryptography, where the quantum nature of single photons are exploited to create secure data transmission systems. Semiconductor quantum dots (QDs) are ideal candidates for single photon sources due to their 3D carrier confinement and ease of integration with other photonic components. Currently most systems operate at wavelengths <1 μm due to improved detector performance. However, this wavelength range is undesirable for optical fibre based systems, where the absorption minimum occurs at 1.55 μm. Using InAs QDs capped with a high composition GaAsSb layer (> 20%) we have been able to achieve 77K emission as long as 1.6 μm for samples grown on both GaAs and Si substrates.

The inclusion of the high composition GaAsSb capping layer causes a transition to a type-II system resulting in complex emission behaviour. To better understand this behaviour additional samples were studied. These consist of a GaAsSb quantum well (QW) grown below the QD layer with both the Sb composition and QD-QW separation varied. In this paper we will present both power and temperature dependent photoluminescence studies of the GaAsSb capped QD samples grown on both Si and GaAs substrates and the GaAsSb QW/InAs QD samples grown on GaAs. We demonstrate 77K emission > 1.6 μm for the GaAsSb capped QD samples and a QW composition dependent power dependent emission blue shift for closely coupled GaAsSb QW/InAs QD samples. We have therefore achieved emission at 1.55 μm for a QD system grown on a Si substrate.

9758-6, Session 2
Effects of high-energy proton implantation on the luminescence properties of InAs sub-monolayer quantum dots

Sourabh Upadhyay, Arjun Mandal, Indian Institute of Technology Bombay (India); Pitamber Singh, Nagaraju B. V. Subrahmanyam, Bhabha Atomic Research Ctr. (India); Subhananda Chakrabarti, Indian Institute of Technology Bombay (India)

Sub-monolayer (SML) quantum dots (QDs) are being proposed as better alternative due to the suppression of the formation of 2D wetting layer over the more popular Stranski-Krastanaw grown QD. We report the impact of high energy protons on the optical properties of SML QDs. The SML InAs QD heterostructure was grown by SSMBE. The samples were implanted with high energy protons with varying energies between 2 - 4.5 MeV, keeping the fluence constant at 2E12 ions/cm2. Low temperature (15K) photoluminescence (PL) plot demonstrated the highest PL intensity at 2.5 MeV; beyond that a steady drop was noticed for all energies. The optimum energy of proton (2.5 MeV) could be explained as: the defects (interstitial) in the system possibly created during the heavily strained QDs growth process required some amount of energy to occupy the original lattice positions, and this requisite energy was probably provided by proton implantation. As passivation of the defects is complete, increasing the implantation energy higher than optimum value possibly led to the creation of additional defects that can trap photo-generated carriers in the systems resulting in drop in PL efficiency. All implanted samples exhibited a consistent PL peak shift from 1100 nm to -1095 nm. The integrated PL intensity for all the implanted samples were higher than the as-grown. All implanted samples exhibited rise in activation energy with respect to as-grown (238.8 meV) while highest activation energy (434 meV) was showed by 2.5 MeV sample confirming that proton irradiation improved the overall optical quality of the SML QD material. Acknowledgement: DST and Riber.

9758-7, Session 2
AC electroluminescence of doped semiconductor nanocrystals

Young-Kuk Kim, Jong-Woo Moon, Eun-Jin Lee, Korea Institute of Materials Science (Korea, Republic of)

Electroluminescent (EL) devices operation under alternating electric fields using transition metal (TM) doped ZnS semiconductor nanocrystals are demonstrated. Here, the doped NCs were prepared by conventional hot injection and subsequent thick shell formation. The EL properties of these devices were investigated along with the structural and optical properties of TM-doped ZnS NCs. The size and shape of ZnS NCs were controlled by applying various processing condition including application of alkylphosphonic acid. Microscopic and spectroscopic studies confirmed near monodispersity in size distribution; the crystal size can be controlled by alternative addition of Zn-precursors. Finally, the EL devices were constructed and checked their performance under application of sinusoidal electric fields. To minimize operation electric field and frequency, device architecture were modified and NCs with various size/shape were applied.

9758-8, Session 2
Analysing radiative and non-radiative recombination in InAs quantum dots grown on Si substrates for integrated laser applications

Jonathan R. Orchard, The Univ. of Sheffield (United Kingdom); Chris Woodhead, Lancaster Univ. (United Kingdom); Samuel Shutts, Cardiff Univ. (United Kingdom); Jiang Wu, Univ. College London (United Kingdom); Angela D. Sobiesierski, Cardiff Univ. (United Kingdom); Robert J. Young, Lancaster Univ. (United Kingdom); Richard Beanland, The Univ. of Warwick (United Kingdom); Huiyun Liu, Univ. College London (United Kingdom); Peter M. Smowton, Cardiff Univ. (United Kingdom); David J. Mowbray, The Univ. of Sheffield (United Kingdom)

Integration of optical and electronic components on the same chip is highly desirable; offering increased data transmission rates, reduced cost and improved power efficiency. However full integration is made difficult by the lack of a Si laser. There have been recent promising advances using direct epitaxial growth of III-V materials onto Si utilising quantum dots (QDs), which are less sensitive to the defects resulting from the large (4%) GaAs-Si lattice mismatch, as the active region. The introduction of strained dislocation filter layers (DFLs) above the GaAs-Si interface significantly reduces the dislocation density in the active region, the strain causing lateral movement and annihilation of the dislocations. Minimising the number of dislocations is important for improving luminescence efficiency as well as device longevity, but the magnitude of the impact of the DFLs on the luminescence remains unclear.
In this paper we study both QD test and laser structures designed to emit at 1.37 μm at 300K. Samples have differing dislocation densities; controlled via temperature steps in the growth sequence. Temperature and power dependent photoluminescence (PL) measurements were carried out in addition to time resolved PL. We observe an increase in integrated PL intensity with reducing dislocation density, as well as an increase in carrier lifetime. Reducing the dislocation density results in a fall of the threshold current by greater than a factor of three.

9758-9, Session 3

Quantum-dot optics with integrated photonic circuits (Invited Paper)

Anthony J. Bennett, Toshiba Research Europe Ltd. (United Kingdom)

One of the building blocks of quantum photonics is a source of indistinguishable single photons. Semiconductor quantum dots integrated within monolithic microcavities are a promising technology in this regard as their resonant excitation can deliver coherent single photons with high efficiency. We report the resonant excitation of a pillar microcavity containing a single quantum dot. Resonant Rayleigh Scattering from a transition in the dot creates anti-bunched light a factor of 16 beyond the time-bandwidth limit [1]. Alternatively, a pulsed laser can be used to create on-demand indistinguishable single photons with wave-packet overlap as high as 0.9. Guiding these photons by optic fibre to a Silicon-Oxynitride photonic circuit held under ambient conditions we create a two-photon NOON state, and confirm its phase super-resolving ability. In future, it will be advantageous to integrate this technology on a single platform. We report such a device [2], where the emitter is bonded to the integrated optical circuit creating a highly stable source of single photons. The inclusion of couplers and reconfigurable elements on our circuit allows us to perform a Hanbury-Brown and Twiss measurement, confirming the quantum nature of the emitted light, or to create qubits in a superposition of two paths. We will discuss the possibilities for scaling to a greater number of optical elements.


9758-10, Session 3

Surface-plasmon-enhanced photoluminescence of quantum dots based on open-ring nanostructure array

Akash Kannegulla, Ye Liu, Li-Jing Cheng, Oregon State Univ. (United States)

Enhanced photoluminescence (PL) of quantum dots (QD) in visible range using plasmonic nanostructures has potential to advance several photonic applications. The enhancement effect is, however, limited by the light coupling efficiency to the nanostructures. Here we demonstrate experimentally a new open-ring nanostructure (ORN) array engraved into a 200-nm thick silver thin film with a depth of 100 nm. Different from the traditional isolated or through-hole split-ring structures, ORN is designed to maximize light absorption and, hence, PL enhancement at tunable spectral ranges. Theoretical calculations based on FDTD method show that the absorption peak wavelengths can be adjusted by their period and dimension. A theoretical absorption of 99.5% is found at the peak wavelength of 567 nm with a broad band greater than 50 nm. The emission spectrum of CdSe/ZnS core-shell quantum dots can be chosen to match the absorption band of the ORN array for PL enhancement. The engraved silver ORN array is fabricated on a silicon substrate by depositing a 200-nm thick silver thin film followed by focus ion beam (FIB) patterning. QDs were coated on the ORN substrate through a 10-nm thick alumina dielectric spacer deposited to avoid direct contact of QDs to silver. The experimental results show the enhanced PL for the QD with emission spectrum overlapping the absorption band of ORN substrate and quantum efficiency increases from 50% to 70%. The ORN silver substrate with high absorption over broad bandwidth enables the PL enhancement and will benefit applications in biosensing, wavelength tunable filters, and imaging.

9758-11, Session 3

Brewster mode: optical monitoring of the semiconductor doping level

Maria Jose Millá Rodrigo, Thierry Taliercio, Institut d’Electronique du Sud (France); Laurent Cerutti, Fernando Gonzalez-Posada Florés, Univ. Montpellier 2 (France); Franziska B. Barho, Jean-Baptiste Rodriguez, Institut d’Electronique du Sud (France); Eric Tournié, Univ. Montpellier 2 (France); Jean-Jacques Greffet, Lab. Charles Fabry (France)

Electronics and photonics are mainly based on semiconductor technology. They use complex epitaxial semiconductor heterostructures where each layer electronic and optical properties must be accurately controlled. One essential parameter to control is their doping level, key to adapt the refractive index of some layers in quantum cascade lasers [1] and to control the plasma frequency, ωp, in plasmonic devices [2], among others.

We have recently developed a new non-destructive optical technique to monitor the doping level of a semiconductor measuring ωp using the Brewster “mode”. The experimental technique consists on reflectance measurements realized with an oblique, typically 45°, p-polarized infra-red light beam. The reflected spectra evidence a resonant dip near the plasma frequency of the thin layers. This experimental result can be explained using a model based on Fresnel coefficient in the case of transverse electromagnetic waves. The resonance dips correlates to the doping level of the epitaxial thin layers.

We will present plasma frequency measurements obtained on different semiconductors such as InAs, InAsSb, GaSb, GaAs. We will demonstrate the efficiency of the technique and the simple scientific protocol needed to obtain accurate values of the doping level of each investigated semiconductor. The potential interest of this mode for in-situ monitoring during epitaxial growth and device fabrication technology will be also discussed.


9758-12, Session 3

Low-threshold wavelength-tunable organo-metal lead halide perovskites nanolasers

Qi Hua Xiong, Qing Zhang, Jun Xing, Nanyang Technological Univ. (Singapore)

Solid-state micro/nanolasers are important building blocks for true integration of optoelectronic circuitry. Although significant progress has been made in III-V nanowire lasers with achieving near-infrared (NIR) lasing at the room-temperature, challenges remain including low quantum efficiencies and high Auger losses. Here we demonstrate a new family of planar room-temperature NIR nanolasers based on organic-inorganic perovskite CH3NH3PbX3-a (X = I, Br, CI) nanoplatelets [1, 2]. Well-defined polygonal crystalline perovskite nanoplatelets are grown on mica substrates by chemical vapour methods, which naturally forms high-Q whispering-gallery-mode cavity. Their high quantum yield and long diffusion lengths...
and naturally formed high-quality planar whispering-gallery mode cavities ensure adequate gain and efficient optical feedback for low-threshold optically pumped in-plane lasing. Further, we synthesize perovskite nanorodlets and nanowires [3] with varied bandgap from ultra-violet to near-infrared and demonstrate wide-band tunable lasing based on the structures. Our findings open up a new class of wavelength tunable nanomaterials potentially suitable for on-chip integration and flexible optoelectronic devices.

References:

9758-13, Session 3

Growth of high-quality self-catalyzed core-shell GaAsP nanowires on Si substrates

Yunyan Zhang, Univ. College London (United Kingdom); Martin Aagesen, Gasp Solar ApS (Denmark); Ana M. Sanchez, Department of Physics, University of Warwick (United Kingdom); Jiang Wu, Univ. College London (United Kingdom); Richard Beanland, Department of Physics, University of Warwick (United Kingdom); Thomas Ward, Department of Physics, University of Warwick, (United Kingdom); Dongyoung Kim, Department of Electronic and Electrical Engineering, University College London, (United Kingdom); Pamela Jurczak, Department of Electronic and Electrical Engineering, University College London (United Kingdom); Suguo Huo, London Ctr. for Nanotechnology (United Kingdom); Huiyun Liu, Univ. College London (United Kingdom)

We developed the technique for growing high-quality GaAsP NWs by using self-catalyzed growth mode. The NWs have very good diameter and length uniformity with almost defect-free zinc-blend crystal structure. The P incorporation efficiency was found to be two-times higher than that of As, which is apparently different from the thin film growth. This is because that the NW growth is controlled more by the chemical potential of As and P, while the thin film growth is governed more by the physical properties of these two elements. On the core NW, the NW shell growth, with uniform coverage along the entire NW length and the highly regular hexagonal tip, have been achieved. Those NWs show very strong room-temperature photoluminescence emission, which reveals the good core-shell quality. In the shell, a special quasi-3-fold composition symmetry phenomenon was observed for the first time in the III-V-V NWs. This symmetry was found to be related to the polarity of sidewalls. This observation and theory provide a third way to do the NW structure design, in addition to the axial and core-shell methods. The potential application of these NWs has been demonstrated by single NW solar cells with a world record efficiency exceeding 10% and water splitting devices with a wafer-scale solar-to-hydrogen conversion efficiency of 0.5%. Those results not only provide valuable information in the high-quality NW growth, but also show the perspective for achieving high-efficiency low-cost photovoltaic and light-emitter devices.

9758-14, Session 3

Violation of Bell’s inequality with a nanowire quantum dot

Klaus D. Joens, Technische Univ. Delft (Netherlands); Marijn A. M. Versteegh, Technische Univ. Delft (Netherlands) and Univ. Wien (Austria) and Austrian Academy of Sciences (Austria); Michael E. Reimer, Technische Univ. Delft (Netherlands) and Univ. of Waterloo (Canada); Lucas Schweickert, Technische Univ. Delft (Netherlands); Dan Dalacu, Philip J. Poole, National Research Council of Canada (Canada); Angelo Gulinatti, Politecnico di Milano (Italy); Andrea Giudice, Micro Photon Devices S.r.l. (Italy); Valery Zwiller, Technische Univ. Delft (Netherlands) and Royal Institute of Technology (Sweden)

We present a bright and directional polarization-entangled photon-pair source generated by a photonic nanostructure that violates Bell’s inequality. The solid-state quantum light source is an InAsP quantum dot in a tapered InP nanowire waveguide [1]. The tapering of the nanowire shell results in a Gaussian far field emission profile [2] and bright single-photon emission. We perform quantum state tomography to reconstruct the density matrix of the emitted quantum state [3]. Birefringence in the nanowire rotates the state during its propagation along the nanowire. Therefore, the measured quantum state is not the commonly observed (|HH⟩ + |VV⟩)/√2 state. We can fully compensate for the birefringence using a set of waveplates and thereby recover the initial state. We also investigate the underlying physical mechanism in the nanowire that leads to our observation of strongly entangled photon pairs. Utilizing quasi-resonant excitation at the wurtzite InP nanowire resonance reduces multi-photon emission resulting in an entanglement fidelity of F = 0.835 ± 0.004 without temporal post-selection. The performed Bell test using the Clauser-Horne-Shimony-Holt inequality reveals clear violation (S_CHSH=2) of the local hidden variable theory by 3.5 standard deviations without discarding any emitted photon-pair [4]. Our results highlight the possible application of nanowire quantum dots in source-independent quantum key distribution.


9758-15, Session 4

Enhanced absorption with quantum dots, metal nanoparticles, and 2D materials (Invited Paper)

Ergun Simsek, Bablu Mukherjee, The George Washington Univ. (United States); Asim Guchhait, Yin Thai Chan, National Univ. of Singapore (Singapore)

Mono- and a few-layer of metal dichalcogenides (TMDs) hold great promise in energy harvesting applications due to their extremely high excited absorption efficiency (~ 30%) in the lower portion of the visible range. However, their average absorption over the entire visible range is quite low (~8%). This amount can be increased by positioning them into a finite-period of multilayer Bragg stack geometry and/or combining them with metal nanoparticles or quantum dots.

In this work, we fabricate mono- and a few-layer of MoS2 and WSe2 on glass and SiO2/Si substrates. The crystalline quality and film thickness of the samples are characterized via optical microscopy, atomic force microscopy, and Raman spectroscopy. We extract the wavelength and thickness dependent refractive index of TMDs from the reflection (from non-transparent samples) and both reflection and transmission (from...
transparent-samples) spectroscopy measurements using home-built specially resolved experimental set-up.

Then, we deposit these TMD samples with gold nanoparticles and PbS quantum dots in a controlled way. We calculate their absorption spectra from spectroscopy experiments and compare the experimental results with the ones obtained numerically using the extracted wavelength dependent refractive indices of the materials. A very good agreement between the experimental and numerical results show that these atomically thin transition metal dichalcogenides indeed can be utilized in broadband ultra-efficient light absorption. The average absorbance of single units of gold nanoparticles and PbS quantum dots deposited TMD structures are -41 and -23 %, respectively; multiple units can absorb as high as 96 %.

9758-16, Session 4

Two-dimensional photonic crystal band-edge laser using colloidal quantum dots as gain material

Hojun Chang, Myungjae Lee, Minsu Kang, Kyungtaek Min, Seoul National Univ. (Korea, Republic of); Yeonsang Park, Kyung-Sang Cho, Samsung Advanced Institute of Technology (Korea, Republic of); Heonsu Jeon, Seoul National Univ. (Korea, Republic of)

Colloidal quantum dots (QDs) exhibit efficient photoluminescence with widely tunable bandgaps. Not only could such core-shell type QDs be used to replace epitaxially grown semiconductor gain materials, but also be functionalized for brand-new concepts of optical devices and applications. Here we demonstrate lasing emission from a two-dimensional (2D) photonic crystal (PC) backbone with densely packed colloidal QDs embedded within the PC films gain material. The PC slab consists of a silicon nitride (SiN; n ~ 2.01) film on silica (SiO2; n ~ 1.475) substrate, forming an asymmetric slab waveguide. Numerical analyses based on finite-difference time-domain method show that photonic band structure of a simple square lattice could have an M-point band-edge mode in the air-band. An array of air-holes is fabricated into a SiN film by e-beam lithography and reactive ion etching with various air-hole diameters. On top of the PC backbone (lattice period = 250 nm; air-hole diameter = 60 - 150 nm; slab thickness = 140 nm), colloidal QDs are spin-coated and cured, resulting in the air-holes of the PC backbone infiltrated by colloidal QDs to provide optical gain for lasing action. Completed SiN/QD 2D PC structure is then optically pumped using a sub-nanosecond 532 nm pulse laser (frequency-doubled Nd:YAG; repetition rate = 1 kHz, pulse duration ~ 400 psec.) The QD-embedded PC structure showed single band-edge mode laser operation at ~ 630 nm with emission linewidth less than 1 nm at full-width-half-maximum.

9758-22, Session 5

Plasmonically enhanced photoluminescence of nanoscale semiconductors

Gabrielle Abraham, Alejandro Tejerina, Hugh Churchill, Pooja Bajwa, Colin D. Heyes, Joseph B. Herzog, Univ. of Arkansas (United States)

Recent work has shown that plasmonic structures enhance the emitted light of nanoscale semiconductor materials, such as the photoluminescence of colloidal quantum dots (QDs) and MoS2 2D materials. This project will compare the photoluminescence of CdSe colloidal quantum dots and MoS2. A variety of studies will be performed such as photobleaching effects, how photoluminescence relates to lifetime of sample, and polarization studies. In addition, this project will further the understanding of plasmonically enhanced photoluminescence between these semiconductor nanostructures and metal nanostructures. Initial studies will drop cast colloidal metal nanoparticles onto quantum dots and MoS2, while future work will fabricate gold structures with electron beam lithography.

9758-23, Session 5

Alkali quantum dots as nanophosphors

Hal Gokturk, Ecoken (United States)

Quantum dots (QDs) developed for optical applications are mostly made of Group II-VI or III-V semiconductors like cadmium sulfide or indium phosphide. In this research QDs of Group I elements are investigated because of their bright, multi-photon emissions in vapor form. Most of the alkali elements have their primary emissions in the near infrared. When they aggregate into QDs, those emissions shift towards shorter wavelengths. To determine the size range that would make alkali QDs suitable as nanophosphors in the visible, optical emissions of QDs consisting of lithium to rubidium are investigated as a function of size. The research is carried out with quantum mechanical calculations using the Configuration Interaction method with Pople type basis sets. Lithium and sodium atoms have their primary emissions at 670 nm and 589 nm, respectively. Emission wavelengths of Li and Na QDs shorten rapidly with increasing size, reaching near UV at ~8 atoms (~0.3 nm). Potassium and rubidium atoms have their primary emissions at 767 nm and 780 nm,
have grain boundary with oxygen atoms incorporated into silicon were defects and isotopic variations. It is assumed that the nanocrystals which in bonding variation for Si and O atoms, types of dipoles for different point and LO modes are varied in their energy positions because of wide spread amorphous silicon Raman spectra around and 520 cm\(^{-1}\) for crystalline TO and point defects. The Si-O dipoles play the most significant role because the external field, and migration the atom of impurities, such as hydrogen, field causes the changes in the electric dipoles' orientations to compensate means of Raman spectroscopy technique. The applied external electric field and detected by using the laser films by applied external electrical spectroscopy

Resonant tunneling diodes (RTDs) provide high speed current oscillation which is applicable to THz generation when coupled to a suitably designed antenna. For this purpose, the InGaAs/AlAs/InP materials have been used as this system offers high electron mobility, suitable band-offsets, and low resistance contacts. However for high current density operation (~MA/cm\(^{-2}\)) the epitaxial structure is challenging to characterize using conventional techniques as it consists of a single, very thin AlAs/InGaAs QW. Here, we present a detailed low temperature photoluminescence spectroscopic study of high current density RTDs and test structures that allow the non-destructive mapping of a range of critical parameters for the device. For test structures we show how the doping level may be mapped using the Moss-Burstein shift, and describe how this may also be measured in the real device. For the full device structure, we show how emission from the QW may be identified, and detail how the emission changes with differing indium composition and well widths. We show that by studying nominally identical, un-doped structures, a type II QW emission is observed, and explain the origin of the type I emission in doped devices. This observation opens the way for a new characterization scheme where a “dummy” RTD active element is incorporated below the real RTD structure. This structure allows significantly greater control in the epitaxial process. Latest results from such devices is presented.

Magneto-optic evaluation of antiferromagnetic [alpha]-Fe2O3 nanoparticles coated on a quartz substrate

Srinath Balasubramanian, Tennessee Technological Univ. (United States); Rajendra P. Panmand, Ctr. for Materials for Electronics Technology (India); Ganapathy Kumar, Satish M. Mahajan, Tennessee Technological Univ. (United States); Bharat B. Kale, Ctr. for Materials for Electronics Technology (India)

Magneto-optic Kerr Effect (MOKE) evaluation of antiferromagnetic hematite (\(~\gamma\)-Fe2O3) nanoparticles coated on quartz is reported. Concentrations of the hematite nanoparticles in the coats, varied from 8.6% to 21.5%, exhibiting a linear increase in film thickness changing from a net-like morphology to a crystalline morphology. Hysteresis was analyzed by measuring the Kerr rotation at applied magnetic fields. Asymmetric magnetization reversals were observed in the measured hysteresis loops with the ascending/descending branch of the hysteresis occurring on the same side. A non-uniform reversal with fluctuations in Kerr rotation angles and an open ended hysteresis loop, characterized the lower concentration samples. This observed asymmetry in magnetization reversal is attributed to the angle between the antiferromagnetic easy axis and the applied magnetic field. With increased nanoparticle concentrations, an improvement in the MO response was observed, characterized by the magnetization reversal occurring via coherent rotation for ascending/descending branches of the hysteresis loop. The hysteresis loops were shifted from the origin indicating a possible exchange bias in the system. The changes in the MO behavior, for the samples with higher concentrations, is attributed to the strong exchange

respectively. Emission wavelengths of K and Rb QDs reach blue at a size of ~20 atoms (~1.5 nm). These results indicate that QDs made of K or Rb are more favorable to generate a broad range of colors from red to blue. QDs described above can be made by wet chemistry using alkali elements covalently bonded to organic molecules, such as butyl lithium. Core-shell type of QDs can be also designed using for example an alkali QD in a carbon based shell.

9758-24, Session 5

Characterisation of high current density resonant tunneling diodes for THz emission using photoluminescence spectroscopy

Kristof J. P. Jacobs, The Univ. of Sheffield (United Kingdom); Razvan Baba, Univ. of Glasgow (United Kingdom); Ben J. Stevens, The Univ. of Sheffield (United Kingdom); Toshikazu Mukai, Dai Ohnishi, ROHM Co., Ltd. (Japan); Richard A. Hogg, Univ. of Glasgow (United Kingdom)

We studied the microcrystalline and nanocrystalline silicon thin films by means of Raman spectroscopy technique. The applied external electric field causes the changes in the electric dipoles' orientations to compensate the external field, and migration the atom of impurities, such as hydrogen, and point defects. The Si-O dipoles play the most significant role because of electron affinity for oxygen. Phonon eigen-frequencies 480 cm\(^{-1}\) for amorphous silicon Raman spectra around and 520 cm\(^{-1}\) for crystalline TO and LO modes are varied in their energy positions because of wide spread in bonding variation for Si and O atoms, types of dipoles for different point defects and isotopic variations. It is assumed that the nanocrystals which have grain boundary with oxygen atoms incorporated into silicon were destroyed in their crystal structure by Si-O dipoles reorientations caused by applied field. The initial crystal orientation was (111). The incorporated oxygen atoms are adsorbed in determined places. Their position results the appearance of numerous dangling bonds which are multiplied by the electric field and create the deep cracks in crystals. The crystal order is damaged along the axis that is perpendicular to (111). It is supposed that the microcrystal is a fractal structure on 2D plane.

9758-26, Poster Session

Structural characteristics of Au-GaAs nanostructures for increased plasmonic optical enhancement

Grant P. Abbey, Univ. of Arkansas (United States) and Mississippi State Univ. (United States); Ahmad I. Nusir, Omar Manasreh, Joseph B. Herzog, Univ. of Arkansas (United States)

This research has been performed to improve upon optical qualities exhibited by metallic-semiconductor nanostructures in terms of their ability to excite electrons and generate current through the fabricated device. Plasmonic interactions become very influential at this scale, and can play an important role in the generation of photocurrent throughout the semiconductor. When the device is fabricated to promote the coupling of these radiated electromagnetic fields, a very substantial optical enhancement becomes evident. A GaAs substrate with an array of Au nanowires attached to the surface is studied to determine structural qualities that promote this enhancement. Using computational electromagnetic modeling and analysis, the effect of the Ti adhesion layer and various structural qualities are analyzed to improve photocurrent generation. Emphasis is placed on the amount of enhancement that is occurring in the semiconductor layer of the model. The photocurrent is then calculated mathematically and generalized for optimization of the device.

9758-25, Poster Session

Crystalline phase destruction in silicon films by applied external electrical field and detected by using the laser spectroscopy

Dmitry E. Milovzorov, Ryazan State Radio Engineering Univ. (Russian Federation)

Magneto-optic evaluation of antiferromagnetic [\(\gamma\)]-Fe2O3 nanoparticles coated on a quartz substrate

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9758-27, Poster Session

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Interactions and change in the nanoparticle morphology. Sensitivity studies on the samples showed an increased magneto-optic sensitivity for samples of higher concentration. This high sensitivity of the samples could be exploited in magneto-optic and optical sensors.

9758-28, Poster Session
**Short-wavelength infrared InAs nanowire photodetector on Si**

Jae Cheol Shin, Chanho Choi, Minhyeok Jo, Jong goo Jeon, Ji Yeong Hwang, Donghwan Kim, Byeong min Ahn, Yeungnam Univ. (Korea, Republic of)

Integrating III-V semiconductors on silicon (Si) can lead to the compact optical integrated circuits with complementary metal-oxide-semiconductor (CMOS) technology. For instance, high speed transmitter chips or semiconductor infrared (IR) imaging sensors has been processed via a hybrid bonding of the III-V devices on the CMOS based readout integrated circuit. The bonding process, however, requires high production costs and limits size reduction of the device. Instead, direct epitaxy of III-V semiconductors on Si substrate provides low-cost production with a large-scale integration. Note that one dimensional (1D) crystal growth allows an epitaxial integration of III-V on Si despite large lattice mismatch. In this presentation, we demonstrate the Si-based short-wavelength infrared (SWIR, 1.4 – 3 μm) photodetector employing catalyst-free growth of InAs nanowire array. The average height of the InAs nanowires grown on Si reach to ~50 μm with a number density of approximately 5 × 107 cm−2. The InAs nanowire array absorbs ~95% of incident light over the entire SWIR band. The photoconductive-type photodetector exhibits a peak detectivity of 1.86 × 107 cmHz1/2/W at 77 K at 1.4 μm at 77 K and operates at a temperature as high as 230 K. The wafer-scale production of the SWIR InAs nanowire photodetector on Si platform is promising for future low-cost optical sensors.

9758-29, Poster Session
**Effect of varying capping composition and number of strain-coupled stacks on In0.5Ga0.5As quantum dot infrared photodetectors**

Debi Prasad Panda, Saikalash Shetty, Akshay Balgarkashi, Hemant J. Ghadi, Navneet Sehara, Subhananda Chakrabarti, Indian Institute of Technology Bombay (India)

In this paper, we have reported the optical and electrical properties of strain coupled multi-stack quantum dot infrared photodetectors (QDIPs) of In0.5Ga0.5As dots with different capping composition. Bilayer, trilayer, pentalayer and heptalayer coupled QDIPs are grown by solid source molecular beam epitaxy with one set of samples containing conventional GaAs capping (12nm) and second set containing a combinatorial capping of In0.15Ga0.85As (3nm) and GaAs (9nm) layers with same total thickness. The entire set of strain coupled QDs shows a red shift in ground state photoluminescence peak in comparison to the uncoupled structures with higher redshift in the combinational capped structures than the corresponding GaAs capped structures due to the reduction in In interdiffusion from In0.5Ga0.5As dots in the former ones resulting in larger dot size. Full width half maximum values (FWHM) of In0.15Ga0.85As/GaAs capped QDs are lower showing uniform distribution of dot size compared to the corresponding GaAs capped QDs. Trilayer sample with In0.3Ga0.7As/GaAs capping shows best results in terms of peak emission wavelength of 1177nm, FWHM of 15.67nm and activation energy of 339meV compared to all the structures. Trilayer sample seems to be the optimum stacking having the best confinement resulting lower dark current density of 6.5E-8 A/cm2 measured at 100K. The sample also shows a multicolor response at ~4.89μm and at ~7.08μm in the mid infrared range. Further optimization of the spacer thickness and dot layer deposition can improve the response towards long infrared range.

9758-30, Poster Session
**Photoluminescence blinking and spectral diffusion of single CdSe/ZnS nanocrystals: charge fluctuation effects**

Hiroto Ibuki, Toshiyuki Iihara, Yoshihiko Kanemitsu, Kyoto Univ. (Japan)

Single nanocrystal (NC) spectroscopy revealed that photoluminescence (PL) blinking and spectral diffusion (SD) of NCs are caused by ionization of NCs and/or local charge fluctuations in and around the NCs. However, the detailed mechanisms of the charge fluctuation and the relation between intermediate charged-exciton states and SD remain unclear. Deep understanding of PL blinking and SD is useful to realize single photon sources without PL intensity and PL energy fluctuations and to develop unique NC-based devices. In this work, we measured the PL intensity, spectrum, and lifetime of single CdSe/ZnS NCs and discuss the SD in NCs showing charged-exciton states. Charged-exciton emission was clearly observed at the lower energy side of neutral-exciton emission, exhibiting SD. We found that the neutral-exciton emission often exhibits large redshifts before and after the appearance of the charged-exciton emission. This indicates that the appearance and disappearance of charged excitons cause large changes in the electric field. We also found that the redshift of the charged-exciton emission is smaller than that of the neutral-exciton emission. This indicates that the polarizability of the charged excitons is smaller than that of the neutral excitons. Clear correlations between the PL energy and linewidth were observed for both neutral- and charged-exciton emission. Based on the PL energy shifts the mean value and standard deviation of electric field around the NCs were estimated to be ~150 and ~80 kV/cm, respectively. These values are almost equivalent to an electric field generated by one or two electron charges around NCs.

9758-31, Poster Session
**Growth strategy to achieve mono-modal quantum-dot size distribution in InAs/GaAs multi stack coupled heterostructures**

Aijaz Ahmad, Debi Prasad Panda, Saikalash Shetty, Akshay Balgarkashi, Subhananda Chakrabarti, Indian Institute of Technology Bombay (India)

In multi-stack structures, the strain field existing in the seed layer induces the nucleation of subsequent dots on the pre-existing dots, and as the InAs quantum dot (QD) coverage is fixed we eventually get dissimilar overgrowth percentage between subsequent layers. Therefore such structures are prompt to defects and dislocations and also produce multimodal distribution of dots. In this paper, a detailed investigation has been done on the growth strategy of strain-coupled multi-stack InAs/GaAs heterostructures, to achieve mono-modal distribution of InAs QDs. The heterostructures discussed in this paper have been grown with fixed seed layer coverage of 2.5 monolayer (ML) InAs in order to maintain constant overgrowth percentage between the subsequent QD layers. The subsequent QD layers coverage has been varied from 2.5ML to 2.1ML and the GaAs spacer thickness in between them varied from 10nm to 12nm. Power dependent photoluminescence (PL) spectra at 18K revealed the transition from multi-modal to mono-modal as the growth parameters varied. We have also optimized the spacer thickness between the seed layer and immediate dot layer to 6.5nm, by keeping other parameters constant. It results in a red shift in PL emission peak and lowers the full width half maximum by 12nm, which seems to be improvement in dot size and homogeneity. The highest activation energy has been obtained from the
optimized structure, which attributes to a better QD confinement and hence lowers dark current value. An enhancement in the optical properties may happen by further optimization.

9758-32, Poster Session

**Diffusion impact on thermal stability in self-assembled bilayer InAs/GaAs quantum dots (QDs)**

Binita Tongbram, Navneet Sehara, Jashan Singhal, Debabrata Das, Debi Prasad Panda, Subhananda Chakrabarti, Indian Institute of Technology Bombay (India)

The thermal stability of InAs/GaAs bilayer quantum dots structure has been investigated by photoluminescence (PL) measurements. The fabricated structure on thermal annealing PL shows no shift in peaks up to 650°C indicating a robustness till a certain temperature making it a suitable candidate for vertical cavity surface emitting lasers (VCSELs) and feedback lasers where ideally a fixed wavelength is required. Integrated Photoluminescence gave a high activation energy in the range of 200 meV for the ground state PL peak for all the coupled structures. Above 650°C there is a blue-shift in the PL peak. And at a very high temperature the dots start to diffuse into InAs wetting layer hence decreasing the quality of the crystal.

The stability in the PL for temperatures below 650°C can be accounted by strain energy as it works against the interdiffusion of QD and the seed layer till a certain temperature hence it compensates for the temperature effect but after 650°C diffusion term becomes too strong and we observe a blue-shift in the peak. This can be justified theoretically by modifications in the Arrhenius diffusion equation. Due to this interdiffusion of In/Ga adatom the dominance of the peak and the intensity of PL peak also changes as the QD composition changes. Coupling the dots also leads to high activation energy which in-turn generates a stronger carrier confinement. But as the temperature increase, a sharp decrease in activation energy observed which weaken the carrier confinement potential because of interdiffusion between dot and seed layer. DST, India and IITBNF are acknowledged.

9758-33, Poster Session

**Interaction of evanescent field superposition on nanoparticles**

María C. Blázquez Villalobos, Jesús Manuel Muñoz Pacheco, Erwin A Martí Panameño, Benemérita Univ. Autónoma de Puebla (Mexico)

Nowadays the importance of nanophotonics has grown significantly, thanks to the positive impact in different fields of the sciences, as well as in industrial applications. For example, one area where nanophotonics techniques are indispensable is handling nanoparticles with the help of evanescent optical near field excitations. In literature can be found a large number of papers in such a subject. However, many publications and reports are based on the use of simple mathematical models, or only supported by numerical calculations. In this work, we focus our attention into the theoretical fundaments of evanescent near-field generation. The physical system under study consists of a circular nanoaperture, located in a perfectly conducting crystal. There is a blue-shift in the PL peak. And at a very high temperature the dots start to diffuse into InAs wetting layer hence decreasing the quality of the crystal.

The stability in the PL for temperatures below 650°C can be accounted by strain energy as it works against the interdiffusion of QD and the seed layer till a certain temperature hence it compensates for the temperature effect but after 650°C diffusion term becomes too strong and we observe a blue-shift in the peak. This can be justified theoretically by modifications in the Arrhenius diffusion equation. Due to this interdiffusion of In/Ga adatom the dominance of the peak and the intensity of PL peak also changes as the QD composition changes. Coupling the dots also leads to high activation energy which in-turn generates a stronger carrier confinement. But as the temperature increase, a sharp decrease in activation energy observed which weaken the carrier confinement potential because of interdiffusion between dot and seed layer. DST, India and IITBNF are acknowledged.

9758-35, Poster Session

**Fabrication of distributed-Bragg-reflector cavity with InAs quantum dots grown on InP(311)B substrate for improvement of photon echo generation efficiency**

Hoshihiko Kanazawa, Yoshitaka Sato, Keio Univ. (Japan); Kouichi Akahane, National Institute of Information and Communications Technology (Japan); Junko Ishi-Hayase, Keio Univ. (Japan)

Photon echo (PE) in conjunction with InAs quantum dots (QDs) is a promising technique to realize broadband quantum interface in the telecommunication wavelength range. Our group recently succeeded in demonstrating the coherent transfer of ultraweak optical pulse with 1-THz bandwidth at 1.33 m using PE technique in highly-stacked InAs QDs on InP (311)B substrate. However, low PE generation efficiency (0.01 %) remains a severe obstacle. In this work, we fabricate and characterize distributed-Bragg-reflector (DBR) cavity containing highly-stacked InAs QDs to improve PE generation efficiency.

The fabricated sample consists of InAs QD multilayers and SiO2/TiO2 DBR cavity. The over 100 layers of InAs QDs were grown on InP(311)B substrate by using molecular beam epitaxy to tune the emission wavelength of InAs QDs to telecommunication wavelengths. However, the large lattice mismatch between InP substrate and GaAs/AInAs DBR makes difficult to successively grow GaAs/AInAs multilayer and InAs QD layers by using molecular beam epitaxy. Therefore, in this work, we sputtered SiO2/TiO2 multilayer on the both side of the QD layers. To fabricate SiO2/TiO2 multilayer, InP(311)B substrate was removed by mechanical polishing and wet etching after the QD growth. We characterized the fundamental optical properties and PE generation efficiency of the fabricated sample by numerical calculations and experimental measurements. As a result, we demonstrate the improvement of the PE generation efficiency by fabricating DBR cavity.

9758-36, Poster Session

**Local trapping and recombination of charge carriers in heterostructures with Ge nanoclusters**

Anastasia A. Mykytiuk, Sergiy V. Kondratenko, National Taras Shevchenko Univ. of Kyiv (Ukraine)

In nanosize semiconductor heterostructures quantum size effects can result in changes of the electron spectrum. In our sample Ge was deposited on boron doped p-Si(100) substrate with temperature of 600 degrees centigrade. For in-plane photoc conductivity studies ohmic contacts were formed by annealing of Au at 370 degrees centigrade into the planar surface normal to the epitaxial layers. Transient in-plane photocurrent of the Ge-Si heterostructure with Ge nanoclusters on p-Si (100) upon exposing with different photon energies at 120 K were studied. When only nanoclusters were excited we observed a comparably fast relaxation. When the temperature drops to 120 K the long-term relaxation of the photocurrent is observed.

Using the Kelvin probe method we recorded the fluctuations of the electrostatic potential in the Si-Ge heterostructures with Ge nanoclusters. It was shown that Ge nanoclusters can accumulate positive charge, which affects the contact-potential difference (CPD) within the nanosilicon by varying it by 5 to 10 mV depending on the size of the nanocluster. The CPD increases with the increasing of the nanocluster diameter. The recombination efficiency of the electron-hole pairs involving quantum confinement states in nanosilicon is higher in comparison with the rate of recombination of the carriers photogenerated in Si substrate. It was found that when we have selective photoexcitation, recombination of electron-hole pairs in SiGe nanoclusters is defined by spatial separation of nonequilibrium electron-hole pairs.
charge carriers, when the holes are captured in the valence band states of SiGe nanoislands and electrons are in silicon environment.

9758-37, Poster Session

**Optical and electrical properties of plasmonic metal nanostructures at percolation threshold obtained by laser annealing**

Igor Gladskikh, Anton A. Starovoytov, Artur Ayvazyan, ITMO Univ. (Russian Federation)

The nonlinear behavior of electrical properties, such as the resistance switching effect, is of great interest for producing resistive memory devices. The resistance switching effect was observed in metal oxides, organic materials, and materials containing metal nanoparticles. In previous studies we found that the thin metal films at the percolation threshold have similar properties. These films were produced by physical vapor deposition in vacuum chamber of conductive silver film and subsequent thermal annealing up to a sharp increase of the resistance of this film.

In this work silver films at the percolation threshold were obtained by laser annealing. Conductive granular silver film with a thickness of 10 nm was irradiated by 532 nm pulsed laser with the energy density up to 50 mJ/cm² and duration for 10 ns. During laser annealing a nonlinear increase of the resistance over time and a sharp step of the resistance after 60 minutes of irradiation with repetition rate of 5 Hz were observed.

I-V characteristic of the film was similar to films produced by thermal annealing. The film switches from the high resistance state (1*10¹¹ Ohm) to the low resistance state (2*10³ Ohm) at the threshold voltage of 2-3 volts. On the other hand the optical properties of the films are changed differently. Laser radiation selectively heats the particles with a plasmon frequency close to the laser wavelength. This leads to spectral hole burning at 552 nm in the extinction spectra.

9758-38, Poster Session

**Coincident donor decay and acceptor rise in “visible” FRET between multicolor QD**

Wenping Yin, Namhun Kim, Dasom Kim, Hee Won Shin, Heeyeop Chae, Tae Kyu Ahn, Sungkyunkwan Univ. (Korea, Republic of)

Quantum Dots (QDs) have been extensively used as light absorbers in photovoltaics and fluorescent labelings, as well as light emitters in optoelectronics. The former generally requires unobstructed resonance energy transfer (FRET) between different sizes of QDs, whereas the latter typically demands suppressing FRET, especially in tunable high-resolution white and flexible QDs Light-Emitting Diode (QLED). All those above, rely on how we understand the principle, therein. Although there are some general and sweeping studies about FRET of QDs using average lifetime theory before, few of them have well-defined each components separately, let alone the real transfer time. Here, we fabricated multicolor Green-Red (GR) and Blue-Red (BR) bilayer stacked QDs using electrospray deposition, singly. Along with steady state and time-resolved photoluminescence (TRPL), FRET transfer rates were achieved as about 1.55E9 and 1.75E9 for GR-stack and BR-stack, respectively. For the first time, we got directly evidences of FRET from the coincident rise signal of acceptor under room temperature and zero extra magnetic field. Meanwhile, mixture state of homologous stack samples were measured under the same condition, getting similar transfer rate but consistent qualitative higher description of FRET efficiency (63.58% for GR-mix and 81.10% for BR-mix), which are clear indications for the geographical effect. We further inferred that most of the FRET occurred between dipole forbidden “dark” state of QDs (QD-07), what can be essential guide for optimum performance both of photoluminescent (PL) and electroluminescent (EL) devices under low temperature and high magnetic field.
9759-1, Session 1

Active 3D DNA plasmonics (Invited Paper)
Na Liu, Max-Planck-Institut für Intelligente Systeme (Germany)

We utilize structural DNA technology to achieve intelligent plasmonic nanomachines with engineered optical response and active functionalities. Plasmonic metal particles are assembled at specific locations on an active 3D DNA origami template with nanometer scale accuracy. The plasmonic system constitutes a well-defined 3D configuration with unique optical response. Due to the intrinsic programmability and excellent functionalities of DNA, the plasmonic nanomachine can respond to external stimulus upon recognition of biochemical events or stimulated movements of the DNA template. Any conformational changes of the plasmonic nanomachine will lead to the near-field interaction changes of the metal particles in the 3D assembly and therefore give rise to immediate optical signal changes in the spectrum, providing an active optical response to external stimulus. Due to the native biocompatibility of DNA, this will enable a new generation of 3D plasmon rulers.

9759-2, Session 1

Observation of topological edge states in plasmonic waveguide arrays (Invited Paper)
Stefan Linden, Felix Bleckmann, Andrea Alberti, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany)

Coupled arrays of optical waveguides can show interesting dynamics that resemble quantum mechanical condensed matter phenomena. Mapping the time-dependent probability distribution of an electronic wave packet to the spatial light intensity distribution in the waveguide array allows to directly visualize the quantum mechanical evolution in a coherent, yet classical wave environment. This approach has been used to demonstrate discrete diffraction, Bloch oscillations, Zener tunneling, and Anderson localization in dielectric waveguide arrays. Here, we use arrays of evanescently coupled dielectric-loaded surface plasmon polariton waveguides (DLSPPPWs) to implement the Su-Schrieffer-Heeger (SSH) model, i.e., the prototypical system of a 1D topological insulator, in a plasmonic system. The waveguide arrays were fabricated by negative-tone grey-scale electron beam lithography, whereby alternating strong and weak bonds were realized by choosing two different separations between neighboring plasmonic waveguides. The evolution of surface plasmon polaritons in the arrays was monitored by leakage radiation microscopy. Excitation of a single waveguide in the interior of the array resulted in discrete diffraction. In contrast, we observed a localized topological edge state if we excited the array at the boundary between two different domains. The experimental findings are in agreement with numerical calculations based on the coupled mode theory.

9759-3, Session 1

Tuning chiroptical response in chiral metamaterials (Invited Paper)
Vivian E. Ferry, Univ. of Minnesota, Twin Cities (United States)

Nanoscale chiral plasmonic systems formed from the assembly of achiral plasmonic nanostructures exhibit strong chiroptical responses, and find application in circular polarizers, plasmon rulers, and in nonlinear optics. In contrast to their molecular counterparts, chiral metamaterials can be manipulated systematically to tune the chiroptical response. This talk will discuss the optical properties of chiral metamaterials in analogy to chiral molecules. The first portion of my talk will discuss plasmonic nanoparticles arranged in a pyramid and assembled with DNA in solution. The system is designed such that each pair of nanoparticles within the tetrahedron is attached by one double-strand of DNA, and targeted interactions with specific sequences along these strands change the distance between the nanoparticles. The symmetry of the tetrahedron is designed so that one targeted interaction inverts the sign of the chiroptical response. The second part of my talk will discuss a different strategy to switching the sign of the CD spectrum, focusing on plasmon hybridization. Here multilayer electron beam lithography is used to pattern coupled L-shaped resonators. Under illumination with circularly polarized light, two modes are excited, and the spacing is controlled such that one mode is predominantly excited by right-handed circularly polarized light and the other by left handed circularly polarized light. Controlled displacements of the resonators tune the energies of the hybridized modes, eventually reversing their energetic ordering, which reverses the sign of the chiroptical response. This finding is important for plasmon ruler designs where the optical response encodes information about nanoscale structural manipulations.

9759-4, Session 1

Two-dimensional silver nanodot array fabricated using nanoporous alumina for a chemical sensor platform of localized surface plasmon resonance
Mi Jung, Tae-Ryong Kim, Myung-Gi Ji, Chung-Ang Univ. (Korea, Republic of); Seok Lee, Deokha Woo, Korea Institute of Science and Technology (Korea, Republic of); Young-Wan Choi, Chung-Ang Univ. (Korea, Republic of)

The noble metal nanostructure has attracted significant attention because of their potential applications as sensitive sensor platform blocks for biological and chemical sensing. The unique optical property of the metal nanostructure is originated from surface plasmon being the collective oscillation of electrons stimulated by the incident photon illuminated on that. Localized surface plasmon resonance (LSPR) is a resonance of surface plasmon confined in metal structure with sub wavelength size at a specific wavelength. The resonance frequency wavelength depends on the dielectric environment and the composition, size, and shape of the metal nanostructure, the intensity of which is greatly enhanced near the surface. The LSPR spectra is highly sensitive to the local environment of the metal surface. Accordingly, the minute amounts of chemicals on the metal nanostructure can be measured through extremely small wavelength shifts from the spectra. Therefore, the fabrication of metal nanostructure is the key issue for applications of LSPR sensor.

In this study, we report the fabrication of Ag nanodots array on ITO glass via the nanoporous alumina mask and the utilization as a platform for LSPR sensor application. Well-ordered Ag nanodot array with 60 nm diameter in periodic pattern of 105 nm was fabricated using a nanoporous alumina with through-holes as an evaporation mask. As an example of the chemical sensor, the wavelength-shift of the LSPR by varying the concentrations of Methylene Blue adsorbed on Ag nanodot array were examined by ultraviolet-visible spectroscopy. These results show Ag nanodot array is useful as a LSPR sensor platform.
Patterning techniques beyond milling like masking or functionalization with continuous waveguides or antenna on highly topographic samples. Small feature sizes even in large plasmonic arrays, complex 3D structures, are discussed here. Ion beam, including ion species like gold or silicon being key materials in the processes. Moreover we investigated and optimized milling approaches for feature sizes repeated over large areas and within automated long-term as high precision sample positioning. These system benefits enable small pattern (write field) stitching and for truly continuous patterning based on instrumentation.

Recently, we have extended the FIB technology beyond gallium towards the ion beam, which has been enabled in particular by dedicated instrumentation. Here we report on photonic and plasmonic devices that could print any custom-input color images using inkjet-printed silver film. The color properties of the nanostructures are also investigated, especially the plasmonic structures functioning with high resolution of 100,000 dots per inch (Kumar et al., Nature Nanotechnology, 7: 557, 2012). Despite the progress in this research field, there is still lacking an efficient strategy to print large-scale color images using structural pixels, because the structural pixels require nanoscale patterning techniques and the fabrication cost increases too drastically with increasing image size. To address this challenge, we present a scalable technique that could print any custom-input color images using nanostucture pixels in very high throughput and at a reasonable cost. The core component of the presented technique is a special nanostuctured substrate containing arrays of prefabricated nanostructures that display red, green and blue primary colors. The substrates are replicated from a stamp using high throughput nanoimprint into a large quantity. Rapid and low-cost nanoscale patterning technique is applied onto the substrate to selectively activate the primary pixels according to the input color image. Two different microscale patterning methods are presented: 1) solvent-free optical lithography and 2) drop-on-demand inkjet printing. The results show that structural color images can be printed with a resolution better than 1000:→300 dots per inch. The color properties of the nanostructures are also investigated, especially the plasmonic structures functioning with inkjet-printed silver film.

Large area and high accuracy FIB nanofabrication for photonic and plasmonic devices (Invited Paper)

Sven Bauerdick, Achim Nadzeyka, Raith GmbH (Germany); Andre Linden, Joel Fridmann, Raith America, Inc. (United States)

Photonic and plasmonic devices are one of today’s challenges in R&D nanofabrication. They require highest accuracy in resolution, feature placement or pitch and cover large areas of 100 μm up to mm’s. Focused Ion Beam (FIB) systems are widely used for sample preparation and also basic patterning, since FIB shows unique benefits like direct, resistless and 3D patterning based on a range of techniques. Here we report on photonic or plasmonic devices like antenna, waveguides or resonant arrays created by FIB nanofabrication, which has been enabled in particular by dedicated instrumentation.

We have improved the FIB instrumentation specifically for high resolution, low drifts in beam current and position, accurate pattern placement as well as high precision sample positioning. These system benefits enable small feature sizes repeated over large areas and within automated long-term processes. Moreover we investigated and optimized milling approaches for pattern (write field) stitching and for truly continuous patterning based on precise stage movement while simultaneously cutting with the ion beam. Finally, we have extended the FIB technology beyond gallium towards the delivery of multiple ion species selectable into a nanometer-scale focused ion beam, including ion species like gold or silicon being key materials in the area discussed here.

As a result we will show the advanced capabilities by various applications: Small feature sizes even in large plasmonic arrays, complex 3D structures, continuous waveguides or antenna on highly topographic samples. Patterning techniques beyond milling like masking or functionalization with different ion beams will be discussed as well.

Ultrafast third-harmonic spectroscopy of single nanoantennas fabricated using helium-ion beam lithography (Invited Paper)

Martin Silies, Heiko Kollmann, Martin Esmann, Simon F. Becker, Carl von Ossietzky Univ. Oldenburg (Germany); Xianji Piao, Seoul National Univ. (Korea, Republic of); Guido Boesker, Lars-Oliver Kautschor, Carl Zeiss Microscopy GmbH (Germany); Chuong Huynh, Carl Zeiss Microscopy, LLC (Germany); Henning Vieker, Andre Beyer, Armin Götzhäuser, Univ. Bielefeld (Germany); Namkyoung Park, Seoul National Univ. (Korea, Republic of); Christoph Lienau, Carl von Ossietzky Univ. Oldenburg (Germany)

Metallic nanoantennas are able to localize far-field electromagnetic waves in volumes of a fraction of their wavelength [1,2]. Standard tools for fabricating bow-tie and rod structures are Electron Beam Lithography or Ga-based Focused Ion Beam (FIB) Milling. The restricted accuracy of these techniques with sub-20 nm feature sizes however results in a limited electric field localization and a limited optical polarization contrast.

Here, we combine Ga- and He-ion based lithography (HIL) for the fabrication of Au bow-tie and rod antennas with gap sizes of less than 6 nm combined with a high aspect ratio. Using polarization-sensitive Third-Harmonic (TH) micro-spectroscopy with 10-fs time resolution, we compare the nonlinear optical properties of single HIL-antennas with sub-6-nm gaps with those produced by standard Ga-based FIB. We find a pronounced enhancement of the total TH intensity of more than three in comparison to Ga-FIB antennas and a highly improved polarization contrast of the TH intensity of 250:1 for the HIL antennas [3].

These findings, combined with Finite-Element Method calculations demonstrate, that by using HIL, a field enhancement of more than 100 in the few-nanometer gap is possible. This makes He-ion beam lithography a highly attractive and promising new tool for the fabrication of plasmonic nanoantennas with few-nanometer feature sizes.


Nanoscale engineering of resonant open cavities using ion beam milled templates

Jason M. Smith, Aurélien A. P. Trichet, Philip R. Dolan, David M. Coles, Lucas Flatten, Sam Johnson, Anais Gouesmel, Claire Alice Hebert, Robin Patel, Claire Vallance, Dean James, Univ. of Oxford (United Kingdom)

Open microcavities have emerged in recent years as flexible tools for quantum optics and engineered light matter coupling. By constructing a Fabry Perot resonator with concave mirrors on the micrometre scale, highly resonant optical modes can be generated with volumes of order 1x10 cubic wavelengths, along with facile tunability and efficient external coupling. Here we will describe our latest advances in open cavity fabrication using focused ion beam milled templates on which high reflectivity mirrors can be deposited providing measured finesse up to 50,000. A high degree of control over the mode shape can be achieved using this method. By carefully controlling the ion beam milling parameters it is possible to average out redeposition of milled material and produce surfaces that deviate by less than 2 nm rms from a prescribed surface. This degree of control provides opportunities for engineering optical modes both to suit
different applications and to accommodate different mirror deposition morphologies. We will describe the optimization process and its application to novel cavities including those with concave mirrors with radius of curvature down to 1.5 micrometres, and the realization of coupled cavities with controlled mode overlap. We will further describe some of the application of these open cavity devices, to particle sensing, chip-scale tuneable dye lasers, single photon sources and spin-photon interfaces using diamond colour centres.

9759-9, Session 2

Investigation and optimization of Rowland ghosts in high efficiency spectrometer gratings fabricated by e-beam lithography

Martin Heusinger, Friedrich-Schiller-Univ. Jena (Germany); Michael Banasch, Vistec Electron Beam GmbH (Germany); Uwe D. Zeitner, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Thomas Flügel-Paul, Fraunhofer Institute for Applied Optics and Prec. Engineering (Germany)

Optical gratings are a key component in almost all high performance optical spectrometers. Electron beam lithography has been shown to be a versatile method which allows fabricating micro-optical devices like spectrometer gratings with a very high resolution and accuracy. When fabricating large area gratings a special writing strategy is necessary to address all regions of the grating by the electron beam. Hence several subareas are sub-sequentially exposed and stitched together leading to the final full size grating. Due to this stitching approach the subareas induce secondary periodic structures that are prone to generate spurious secondary stray light peaks in the order of magnitude of \(<10^{-4}\) compared to the useful diffraction order.

In order to further reduce these spurious diffraction ghosts a 3-step-iteration was performed to optimize the e-beam writing process. Here we will report about different ways to improve the optical performance of a binary spectrometer grating fabricated with e-beam lithography. One way to reduce the impact of alignment errors is the technique of “multi-pass-exposure”. Here the sample is exposed multiple times with an accordingly shifted and dose-reduced subarea in each pass. As a second way the direct improvement of the stitching accuracy during the writing process via special calibration parameters is investigated. And as a third way we try to break the strong periodicity of the subareas by introducing random-sized subareas.

The achieved results show that specific calibration parameters of the e-beam writer have a strong influence on the strength of stray light peaks and that their recalibration combined with an adapted writing regime reduces the peaks significantly.

9759-11, Session 3

Controlled guidance of light through a flexible optical waveguide sheet

Chloë Nicholson-Smith, George K. Knopf, The Univ. of Western Ontario (Canada); Evgueni Bordatchev, National Research Council Canada (Canada)

Mechanically flexible large area polymer optical waveguide sheets can be designed to act as either light concentrators or diffusers based on the geometry and spatial distribution of micro-optical features patterned on the active surfaces. The impact of design parameters on the performance of these non-rigid light guiding structures are discussed, and the optimization of the size, shape, orientation and position of the micro-optical features for maximum efficiency are investigated using Zemax OpticStudio software. To illustrate the concept of controlled light guidance and distribution, a flexible polydimethylsiloxane (PDMS) waveguide sheet that performs both controlled light collection (concentrator) and targeted illumination (diffuser) is introduced. In this application the incident light is collected over the large center area of the sheet and then transmitted to the border regions where it is emitted. Photo-sensors, photovoltaic cells or illumination windows may be located at these light diffusing regions. The collector consists of microlens located on the sheet surface area that receives incident light and prism cavities embedded on the opposite face to redirect the light rays to the edges. The diffuser region along the border of the sheet consists of densely packed protruding and recessed microfeatures that direct scattered light out of the sheet. To simplify the analysis, the geometry of the individual micro-features are assumed to be fixed and do not change as the sheet conforms to the shape of the underlying freeform surface. The efficiencies of the collector and illuminating regions of the hybrid polymer collector-diffuser waveguide sheet are discussed.
Polymer strip-loaded waveguides on ALD-TiO2 films
Leila Ahmadi, Ville Kontturi, Janne Laukkkanen, Markku Kuitinen, Jyrki Saarinen, Seppo Honkanen, Matthieu Roussey, Univ. of Eastern Finland (Finland)

We have used the strip-loaded waveguide concept to guide light in a TiO2 film with the help of polymer strips on the film. We introduce a new process of fabrication of the TiO2 film strip-loaded waveguides formed by combining several low cost fabrication techniques: nickel electroplating, nano-imprinting, Atomic Layer Deposition (ALD), and nano-lamination. We present the detailed fabrication technique of the polymer strips (n=1.6), which enable light guiding in an amorphous TiO2 film fabricated by ALD (n=2.27 at λ=1550 nm). A rib waveguide is first fabricated in a polymer by thermal or UV imprinting of either polycarbonate films or polycarbonate film substrates carrying a hybrid homemade polymer with matched refractive index. The device is then flipped upside down and laminated on a 200 nm-thick TiO2 film. This high index film is the guiding layer. In order to prove the great potential of this novel fabrication process for waveguides, we realized ring resonators with different radii. This gives us access to the propagation losses, bend loss and the effective index of the propagating mode. The first experimental results are in good agreement with the theoretical predictions, showing an effective index of 1.61, a quality factor of 1790 and an estimation of the propagation losses around 18 dB/cm. We believe that our process is compatible with high throughput, mass production techniques such as roll-to-roll. The advantage of this technique is its flexibility concerning the guiding layer material, and its potential to create simultaneously optical waveguides and some fluidic channels for sensing devices.

Fabrication of low-loss ridge waveguides in z-cut lithium niobate by combination of ion implantation and UV picosecond laser micromachining
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Ridge waveguides in ferroelectric materials like LiNbO3 attended great interest for highly efficient integrated optical devices, for instance electro-optic modulators and ring resonators. The main challenges are the realization of high index barrier towards the substrate and the processing of smooth ridges for minimized scattering losses. For fabricating ridges a variety of techniques, like chemical and wet etching as well as optical grade dicing, have been investigated in detail. Laser micromachining offers a versatile and flexible processing technology, but up to now only a limited side wall roughness has been achieved by this technique. Hence, we report on laser micromachining of smooth ridges for low-loss optical waveguides in LiNbO3.

The ridges with a top width of 7 μm were fabricated in z-cut LiNbO3 by a combination of UV picosecond micromachining and thermal annealing. The laser processing parameters show a strong influence on the achievable sidewall roughness of the ridges and were systematically investigated and optimized. Finally, the surface quality is further improved by an optimized thermal post-processing. The roughness of the ridges were analysed with confocal microscopy and the propagation losses were measured at an optical characterization wavelength of 632.8 nm by using the end-fire coupling method. In these investigations the index barrier was formed by multi-energy low dose oxygen ion implantation technology in a depth of 2.7 μm.

With optimized laser processing parameters and thermal post-processing a scattering loss as low as 0.1 dB/cm has been demonstrated.

Packaging and micro-structuring for enabling multi-functional fiber-cladding photonics and lab-in-fiber
Moez Haque, Stephen Ho, Erden Ertorer, Kevin A. J. Joseph, Jianzhao Li, Peter R. Herman, Univ. of Toronto (Canada)

Ultrafast laser material processing has enabled the realization of a vast range of structures, processes, and devices by exploiting the various types of glass modification: ablation, micro-explosions, and density / refractive index changes. We will first present recent milestones on 3D optical circuits (9.55 dB/cm) and microfluidic networks (22 nm rms surface roughness) written in single mode optical fibers (SMFs) by femtosecond laser irradiation and selective chemical etching (FLICE), where optical taps (directional and X-couplers) couple light out of the SMF core waveguide and into the fiber cladding to laser-formed optical circuits that may probe FLICE-formed optical resonators for multi-functional lab-in-fiber (LIF) sensing applications. Next, phase-shifted Bragg grating waveguides were formed in the core waveguide of SMFs by dynamic modulation of an acousto-optic-modulator for position-synchronized laser firing, leading to π-phase-shifted resonances with 10 dB contrast and 10 pm linewidth. Two new types of optical resonator sensors were fabricated by FLICE: (1) optical resonator arrays (ORAs) that stack open Fabry Perot interferometers for the previously unexplored benefits of open dielectric stacks, and (2) wavefront splitting interferometers (WSIs) that detect the coherent interference of two wavefronts after being equally split by a single buried resonator and collected into a single mode waveguide. Both ORAs and WSIs present a desirable compact sensor as possible with Fabry Perots, but with the additional benefits of a stronger visibility contrast and higher sensitivity to external parameters as expected with Mach-Zehnder Interferometers. New modes of fiber assembly and packaging are presented: (1) optical fiber arrays were laser welded to fused silica wafers and (2) packaged into through holes precisely formed by helical laser scanning and FLICE. Such high finesse optical elements and laser processing and packaging methods open a new realm of optofluiddic sensing and integrated optical circuit concepts that may find importance in chemical and biological sensors, telecom sensing networks, biomedical probes, low-cost health care products, and OEM manufacturing.

Integrated nanophotonics in bulk single-crystal diamond substrates
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Single-crystal diamond is an attractive nanophotonics platform, due in part to its wide transparency window and vast inventory of luminescent defects. Integration of such color centers with monolithic diamond nanophotonic networks would ultimately enable scalable quantum information architectures and sensitive nanoscale magnetometry. While integrated nanophotonics are typically realized through scalable planar fabrication, whereby the device layer is a thin film optically isolated from a supporting substrate of a different material, high quality single-crystal diamond thin film heterolayer structures do not exist. To address this, we recently demonstrated an ‘angled-etching’ nanofabrication method for realizing suspended nanostructures in bulk single-crystal diamond. Angled-etching employs anisotropic oxygen-based plasma etching at an oblique angle to the substrate surface, resulting in suspended structures with triangular cross-sections. Using this approach, we demonstrated high Q-factor (>105) optical nanocavities fabricated in bulk single-crystal diamond, operating over a wide wavelength range (visible to telecom). Beyond isolated photonic devices, we have further developed free-standing angled-etched
waveguides which efficiently route photons between diamond optical nanocavities, while maintaining physical support through attachment to the bulk substrate. A high efficiency fiber-optical interface with aforementioned on-chip diamond nanophotonic networks, achieving > 95% power coupling, is also demonstrated, including techniques to robustly pigtail single-mode fibers with diamond waveguide couplers. This packaged technology will enable deployment in vacuum, cryogenic, or even liquid/biological environments. With these newly developed structures, bulk single-crystal diamond is now a viable integrated nanophotonics platform, servicing a range of applications, from non-linear optics and chemical sensing, to quantum science and cavity optomechanics.

9759-15, Session 4

Holographic fabrication of 3D photonic crystal templates with 4, 5, and 6-fold rotational symmetry using a single beam and single exposure

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A method of fabricating large-volume 3D photonic crystal and quasicrystal templates using holographic lithography is presented. Fabrication is accomplished using a single-beam and single exposure by a reflective optical element (ROE). The ROE is 3D printed support structure which holds reflecting surfaces composed of silicon or gallium arsenide. Large-volume 3D photonic crystal and quasicrystal templates with 4-fold, 5-fold, and 6-fold symmetry were fabricated using ROEs and found to be in good agreement with simulation. The ROE, being a compact and inexpensive alternative to diffractive optical elements and top-cut prisms, facilitates the large-scale integration of holographically fabricated photonic structures into on-chip applications.

9759-16, Session 4

Single-step etch mask for 3D monolithic nanostructures

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Current nanofabrication by etching is usually limited to planar structures as they are defined by a planar mask. Realizing three-dimensional (3D) nanostructures requires technologies beyond planar masks [1]. We present a method to fabricate a 3D mask that allows to etch 3D monolithic nanostructures using only CMOS-compatible processes [2]. The mask is written in a hard-mask layer on two adjacent inclined surfaces of a Si wafer using focused ion beam lithography (FIB). The mask pattern consists of two 2D patterns, each intended for a different inclined surface, and by design in perfect mutual alignment. After the mask pattern is defined, the etching of deep pores in two oblique directions yields a three-dimensional structure in silicon. We demonstrate 3D mask fabrication for 3D diamond-like photonic band gap crystals in silicon that reveal a broad stop gap in optical reflectivity measurements. The 2D patterns for the different surfaces can be completely independent while still in perfect mutual alignment. Indeed, we observe an alignment accuracy of better than 3.0 nm between the mask patterns on the inclined surfaces. We demonstrate realisation of the photonic version of the Anderson tight-binding model, a 3D array of band gap cavities. We demonstrate how 3D nanostructures with different Bravais lattices can be realised.


9759-17, Session 4

Photonic crystal fiber long-period grating sensors with nanocoatings for ammonia gas detection

Shiue Zheng, Harbin Institute of Technology (China)

Long-period gratings (LPGs) in photonic crystal fiber (PCF) offer excellent prospects for many diverse sensing applications. In this work, we present a nano-film coated PCF-LPG ammonia sensor that has been developed with high sensitivity and selectivity for applications of nondestructive detection in structural health monitoring. Two types of nano-films are coated in the grating region by electrostatic self-assembly (ESA) deposition process. The primary bi-layer coatings of polyylylamime hydrochloride/ polyacrylic acid increase the sensitivity to refractive index change of the surrounding environment. The secondary bi-layer coatings of Zirconia/Poly-sodium 4-styrenesulfonate are for selectivity purpose, in this case to absorb ammonia molecules only. Those two coatings significantly modify the cladding mode distribution of PCF-LPG and enhance the evanescent wave interaction with the external environment, leading to a highly sensitive and selective ammonia corrosion sensor. The integrated sensor has potential in a variety of applications, especially for nano-liter scale measurement in situ. The proposed sensor is high sensitive to ammonia with negligible cross-sensitivity to moisture, methanol or acetone. It can also be further designed as multi-channel sensor system to monitor the concentration distribution for structural health conditions and safety through in situ measurements. Meanwhile, a numerical analysis of light power overlap of cladding modes with core mode has been investigated. The design to maximize the overlap can be established based on the PCF structure and the dependence of cladding modes.

9759-18, Session 4

Stacking of polymer nano-gratings by electron beam writing to form 3-level diffractive optical elements for 3D holographic lithography

Leon Yuan, Peter R. Herman, Univ. of Toronto (Canada)

Multilevel nanophotonic structure is a major goal in creating advanced optical functionalities such as found in photonic crystals and metamaterials. Here, we seek to control the diffraction and interference of light with multilevel diffractive optical elements (DOEs) that are tailored for precise phase control amongst multiple diffracting beams. The objective is holographic patterning of photonic crystal templates in photos resist that can provide 3D photonic band gaps (PBGs) in the optical domain when inverted in high index materials. This requires small grating periods (600 nm), low axial-to-lateral period ratio (c/a ~1.4), and 1/2 phase shifts on orthogonal diffraction axes, placing high demands on the DOE design to generate the optimal 3D diamond-like symmetry in its holographic pattern. To meet this criterion, two-layered phase gratings have been formed in transparent dielectric resist (350 nm thick ma-N resist) in two-processing steps by electron beam lithography. The polymeric resist is highly insulating and challenging to image by SEM. In order to verify the nanostructure formation, a reversible soft-coating method (aquASAVE) has been developed that enables step-by-step SEM inspection of each grating layer. A thin SiO2 layer was further used to isolate the grating layers and followed with multiple spin-coating steps to planarize the final resist coating layer. This method provided a three-level phase mask with 600 nm x- and y-axis periodicity, first order beam efficiency of up to 3.5% for 800 nm wavelength light, and appropriate 1/2 phase shift such that diamond-like 3D nanostructure could be fabricated in SU-8 photosist. This 3D structure is anticipated to provide an 8% complete PBG upon Silicon inversion. Hence, the present method is promising in creating more advanced diffractive optical components based on multi-layered dielectric nanograting masks, with benefits of phase control that is not possible with traditional binary (single layer) phase masks.
9759-19, Session 5

Innovative plasmonic active TopUp substrate for surface enhanced Raman spectroscopy

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The low Raman scattering intensities can be increased to almost single molecule detection limit by utilizing the plasmonic properties of metallic nanostructures. Beside colloidal nanoparticles, SERS substrates fabricated by wet-chemical bottom up techniques, e.g. enzymatically generated silver nanoparticles (EGNP) [1], or lithographic top down techniques, e.g. silver nano squares [2], are commonly used.

Here we report on the production and application of an innovative TopUp SERS substrate by combining top down and bottom up fabrication techniques. A template structure made by electron beam lithography is combined with a wet chemical bottom up procedure. The so prepared plasmonic active structure shows a self-organized growth of sharp silver needles occurring in a well-ordered array, defined by the template structure. Therefore the benefit of top down techniques like e.g. highly ordered structures, easy tunability, reproducibility and long shelf storage are combined with the benefit of bottom up structures like e.g. easy preparation, self-organization and fast assembly. In doing so both the drawbacks of bottom up (e.g. low reproducibility, changing quality) and top down methods (e.g. slow preparation times, costly manufacturing) are overcome at the same time. The successful preparation and characterization of the TopUp SERS substrate as well as their application to detect trace amounts of antibiotics (like e.g. sulfamethoxazole) in water is presented within this contribution.


9759-20, Session 5

Texturing using metal oxide nano-structures for high efficient light extraction and absorption

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Multiple light scattering and modulating light penetrating path using nanostructure is well known method to increase light extraction and absorption in active layer. Theoretically, it could reach as much as Yablonovitch limit defined as $\pi n^2/2 \sin^2(\theta)$, where $\theta$ is incidence angle of light. However, until now, the methods to control surface nanostructure are quite inefficient for large area (more than several tens of inches) fabrication and expensive process such as nanostructured active layer growth (Si nanowire solar cells, etc), nano-imprint or anodic aluminum oxide template, and e-beam lithography. In this work, we have developed self-assembled metal-oxide nanostructure based on isotropic properties between crystal orientations. First, we have successfully grown nano-facet of rock-salt ionic materials such as MgO, CaO, and NiO. The rock-salt nano-facet has (111) orientation which has repeated stacking of cation and anion layers. Due to strong polarity of this (111) orientation, it should be enclosed by neutral charge plane such as (100), resulting in self-assembled nano-facet (nano-tetrahedron). Second, we also have grown self-assembled indium-tin-oxide (ITO) nano-branches. By using high-density electron beam irradiation, we can continuously supply tin-doped indium metal-catalyst, resulting in multiple nucleation for vapor-liquid-solid process. These multiple nucleation can happen on (100) side wall plane of ITO nanorods, finally, nano-branch structure can be formed. Those nano-structures have been applied several opto-electronic devices such as Alq3-based organic light emitting diodes (LEDs), GaN-based LEDs, and P3HT-PCBM based organic photovoltaics, resulting in successful increase of device performance.

9759-22, Session 5

Azimuth orientation method of a photonic crystal fiber based on side image

Zhe Chen, Yunhan Luo, Jieyuan Tang, Jun Zhang, Jinan Univ. (China)

A nondestructive method to determine the azimuth angle orientation of a photonic crystal fiber has developed. An incoherent light is used to illuminate the photonic crystal fiber and its side image is recorded. A characteristic value was defined by using the maximum intensity of the image to characterize the azimuth angle orientation. A ray tracing simulation was performed to confirm the unique relationship between the characteristic value and the azimuth angle. The method was employed to determine the azimuth angle for three types of photonic crystal fibers, and achieved accuracy better than 0.50°. The method offers merits in nondestructive and contamination-free measurement. It is expected to greatly benefit the manipulation of photonic crystal fibers and device fabrication.

9759-23, Session 6

Size scaling with light patterned dielectrophoresis in an optoelectronic tweezers device

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We report the experimental measurement of the relationship between the size of particles being moved by optically patterned dielectrophoresis in and Optoelectronic Tweezers (OET) device and the force that they experience. The OET device turns an optical pattern into a pattern of electrical fields through the selective illumination of a photoconductive material. In this work we use a data projector to create the structured illumination which gives a relatively flat optical profile with steep optical gradients and hence steep electrical gradients at the edges of the light patterns created. For a small particle in a constant electrical gradient it would be expected that the force due to dielectrophoresis would scale with the cube of the particle’s radius whereas the forces needed to move it against the viscous fluid scale with the radius squared so that there would be a linear increase with how fast a particle could be moved with its radius. As the particles in an OET device are often larger than the area over which the electrical gradients are produced it is not obvious how their forces scale with size. In this paper we compare results from physical experiments with those from Finite Element Method (FEM) simulations and show that there are regimes where the size relationship with force is well described by a linear fit and regimes where it is not. We show that the magnitude of the force is dependent on the light pattern used and that with larger particles and optimized light patterns velocities of over 1mms⁻¹ can be achieved.
High-throughput depth-resolved parallel laser machining based on temporal focusing

Dapeng Zhang, Chenglin Gu, Shih-Chi Chen, The Chinese Univ. of Hong Kong (Hong Kong, China)

In this paper, we will present a parallel depth-resolved laser fabrication technique for micro- and nano-patterning based on temporal focusing. Femtosecond laser amplifier in combination with a digital micromirror device, which simultaneously serves as a programmable mask and a diffraction grating, are used to create arbitrary 2-D patterns on silicon and metal substrates. In the optical system, the spectrum of a femtosecond laser pulse is first spatially dispersed by the DMD, a lens then collimates these beams, and lastly the objective lens recombines the beams to the focal region, where a thin light sheet is formed for micro-machining. Temporal focusing only occurs at the focal region because the different frequency components only spatially overlap within the focal region of the objective lens; thus the pulse width is the shortest only at the focal plane, enabling depth discrimination. Experimental results show direct patterning of silicon of 80 μm with 500 nm resolution within 5 – 10 ultrashort pulses. Depth control capability is theoretically and experimentally proved. For example, a 4-μm deep hole was laser machined on silicon with a flat and relatively smooth bottom of RMS roughness ~ 60 nm. This new method substantially improves the throughput of ultrafast laser machining, enabling direct area patterning without compromising the resolution. The patterning resolution and speed may be further improved by using lasers of shorter wavelengths, e.g. 400nm and 266nm, or higher repetition rates.

Fabrication of waveguide spatial light modulators via femtosecond laser micromachining

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We have previously introduced an anisotropic leaky-mode modulator as a waveguide-based, acousto-optic solution for spatial light modulation in holographic video display systems. Waveguide fabrication for these and similar surface acoustic wave devices relies on proton exchange of a lithium niobate substrate, which involves the immersion of the substrate in an acid melt. While simple and effective, waveguide depth and index profiles resulting from proton exchange are often non-uniform over the device length or inconsistent between waveguides fabricated at different times using the same melt and annealing parameters. In contrast to proton exchange, direct writing of waveguides has the appeal of simplifying fabrication (as these methods are inherently maskless) and potential of fine and consistent control over waveguide depth and index profiles. In this paper, we explore femtosecond laser micromachining as an alternative to proton exchange in the fabrication of waveguides for anisotropic leaky-mode modulators.

Assembling silver nanowires using optoelectronic tweezers

Shuaifong Zhang, Steven L. Neale, Jonathan M. Cooper, Univ. of Glasgow (United Kingdom)

Optoelectronic tweezers (OET) has proven to be an effective micromanipulation technology for cell separation, cell sorting and control of cell interactions. Apart from being useful for cell biology experiments, the capability of moving small objects accurately also makes OET an attractive technology for other micromanipulation applications. In particular, OET has the potential to be used for efficiently and accurately assembling small optoelectronic/electronic components into circuits. This approach could produce a step change in the size of the smallest components that are routinely assembled; down from the current smallest standard component size of 400×200 μm (0402 metric) to components a few microns across and even nanostructured components. In this work, we have demonstrated the use of OET to manipulate conductive silver nanowires into different patterns. The silver nanowires (typical diameter: 60 nm; typical length: 10 μm) were suspended in a 10 mS/m solution and manipulated by direct writing of the assembly. This proof-of-concept demonstration was also made to prove the feasibility of using OET to manipulate silver nanowires to form a 150-μm-wide conductive path between two isolated electrodes. It can be seen that the resistance between two electrodes was effectively brought down to around 700 Ω after the silver nanowires were assembled and the solution evaporated. Future work in this area will focus on increasing the conductivity of these tracks, encapsulating the assembled silver nanowires to prevent silver oxidation and provide mechanical protection, which can be achieved via 3D printing and inkjet printing technology.

Large-area fabrication of nanoscale features by R2R-UV nanoimprint lithography (Invited Paper)

Dieter Nees, Ursula Palfinger, Stephan Ruttkoff, Maria Belegatis, Volker Schmidt, Christian Sommer, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria)

The structure resolution of mass printing processes such as fhemographic printing, gravure printing, screen printing or offset printing is typically found in the range of 100μm. Contrary, R2R-UV-Nanoimprint Lithography (R2R-UV-NIL) is capable of patterning down to the sub-μm and even nanoscale regime with production-fit throughput thus paving the way for high-resolution patterning on large-area flexible substrates. This talk will raise your awareness that substantial effort has to be taken in order to realize the vision of producing square-meters of complex nanostructures utilizable for functionalized surfaces in optical, electrical and sensor devices. Critical topics cover the development of an appropriate imprint resist system, the fabrication of flexible polymer stamps, the surface treatment of the imprint tools and the definition of design rules for high yield high-throughput nanopatterning. Applications ranging from biomimetic surfaces, over metallic nanopatterns to microfluidics and light management structures - all realized on m2-areas - will be presented.

Fabrication of large area flexible PDMS waveguide sheets

Robert Green, George K. Knopf, The Univ. of Western Ontario (Canada); Evgueni Bordatchev, National Research Council Canada (Canada)

Mechanically flexible large area polydimethylsiloxane (PDMS) waveguide sheets are fabricated using soft-lithography techniques based on replica molding. These non-rigid optical waveguide sheets can be designed to act as either light collectors (concentrators) or illuminators (diffusers) based on the position and geometry of micro-optical features embedded in the sheet or imprinted on its surface. The active surface area of the waveguide sheet can range from less than a sq. cm to several sq. m. The performance of the large area waveguide is a function of the location and geometry of micro-optical structures, thickness and shape of the flexible waveguide.
core and cladding material (i.e., refractive indices), and the wavelength of the incident light source. The refractive index of the optically transparent PDMS sheet can be controlled during fabrication by modifying the ratio of base to curing agent, adjusting the curing temperature or time, and applying deep ultra-violet irradiation. In this manner both the core and cladding layers can be molded separately and bonded together to maintain desired total internal reflection. The proposed soft lithography technique utilizes precision machined polymethylmethacrylate (PMMA) molds with negative patterned PDMS inserts that transfer the desired micro-optical features onto the molded waveguide. PDMS is used for micro-feature transfer because the material’s elastic properties enable damage-free part demolding. The fabrication of several monolithic and multiple reflective-indexed patterned waveguides are described and evaluated in terms of light transmission efficiency.

9759-29, Session 7
Soft mold-based nanomanufacturing process for fabricating photonic devices on nonplanar substrates
Jianwei Chen, Shih-Chi Chen, The Chinese Univ. of Hong Kong (Hong Kong, China)

Patterning micro- and nano-scale optical elements on nonplanar substrates has been technically challenging and prohibitively expensive via conventional processes. A low-cost, high-precision fabrication process is thus highly desired and can have significant impact on manufacturing that leads to wider applications. In this paper, we present a scalable multi-modality soft mold-based process that enables high-resolution patterning of 2-D and 3-D, micro- and nano-structures on non-planar substrates. In this process, a flexible elastomer stamp, i.e., PDMS, is used as a mold to perform various contact printing processes, including microcontact printing, UV molding, and hot embossing, on substrates of arbitrary curvatures. The printing process is optimized through the development of an automated vacuum imprinting system that allows non-clean room operation as well as precise control of all process parameters, e.g., pressure, temperature and time. To demonstrate the precision, uniformity, and scalability, various optical components of relatively large sizes (10 – 100 mm), including microlens array and concave optical gratings, are fabricated via the different modalities of the vacuum imprinting system. Surface profiles and optical properties of the fabricated components are also characterized quantitatively, e.g., RMS ~ /30 for a micro-lens, and proved to be comparable with high cost conventional precision processes such as laser lithographic fabrication.

9759-30, Session 7
Tunable Fabry-Pérot interferometer with subwavelength grating reflectors for MWIR microspectrometers
Marco Meinig, Steffen Kurth, Fraunhofer-Institut für Elektronische Nanosysteme (Germany); Mario Seifert, Karla Hiller, Julia Wecker, Technische Univ. Chemnitz (Germany); Martin Ebermann, Norbert Neumann, InfraTec GmbH (Germany); Thomas Gessner, Fraunhofer-Institut für Elektronische Nanosysteme (Germany) and Technische Univ. Chemnitz (Germany)

This report presents recent advances in the design and fabrication of a tunable Fabry-Pérot interferometer (FPI) with subwavelength grating reflectors, as well as measurement results and applications. The FPI is designed as wavelength selecting element for highly miniaturized MWIR spectrometers. Many technical gases, e.g., hydrocarbons have specific absorption bands between 3 µm and 4 µm wavelength. The optical resonator of the FPI is built between two highly reflecting mirrors. The mirrors are integrated in a supporting MEMS structure with one electrostatically movable and one fixed mirror carrier. The FPI is fabricated in a bulk micromachining batch process on wafer level from two silicon substrates. The substrates are bonded together with an intermediate SU-8 layer. The reflectors are made of aluminum subwavelength gratings, structured on a thin LP silicon nitride membrane by nano-imprint lithography. The subwavelength structures build a metasurface with high reflectivity and low absorption in a defined spectral range. Simulations and optimization of the design were done with a 3D EM frequency domain solver. Comparison of simulation results and measurements of fabricated reflectors and FPIs are in very good agreement. The FPIs are used in the 4th or 5th interference order and can be tuned from 3.7 µm to 31 µm electrically. The measured maximum transmittance is between 55 % and 80 % and the measured FWHM is lower than 60 nm. The new subwavelength grating reflectors can be fabricated in a MEMS batch process more cost-efficient than previously used reflectors of dielectric layer stacks.

9759-31, Session 7
Fabrication of high-aspect-ratio wire-grid polarizers by displacement Talbot lithography
Harun H. Solak, Christian Dais, Francis Clube, Li Wang, Eulitha AG (Switzerland)

Metallic wire-grid polarizers (WGPs) are attracting interest for use in LCD displays because of the potential benefits including improved energy efficiency, reduced display thickness and lower cost. For good performance, they should be made of Al lines with a period below 150 nm and height greater than 100 nm, the fabrication of which presents challenges for conventional lithographic techniques. Here we demonstrate the fabrication of WGPs by Displacement Talbot Lithography (DTL) which is well suited for volume production.

DTL is an innovative photolithographic technique in which a periodic pattern is transferred from a mask to a substrate in a manner similar to proximity printing except that the separation between the mask and substrate is varied during exposure. This technique offers the major advantage of enabling patterns with sub-wavelength period to be printed uniformly onto non-flat substrates.

In this work, fused silica wafers coated with a 250 nm-thick Al film and photoresist were exposed using the DTL technique at near-UV wavelength to obtain 250 nm-period gratings of area 30x30mm2 in photoresist. The developed structures were etched into the underlying Al film using an RIE process. The TM transmission and contrast of the resulting WGPs at a wavelength of 635nm were measured to be 78% and 2200 respectively, which are close to predictions from numerical simulations.

Our results demonstrate the unique potential of DTL for fabrication of large-area polarizers. Extension of the technique to the DUV region, which has recently been demonstrated, allows the fabrication of higher performance polarizers with periods below 150nm.

9759-32, Session 8
Photonics walking up a human hair (Invited Paper)
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In the microbial kingdom, it is harder to walk than swim. While <1 micron moving plankton species were found in water, the smallest terrestrial walking creatures are somewhat bigger than 100 microns (the thickness of human hair). We show that it is possible to make an artificial walker that
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9759-35, Session 8

**Beam-bending in spatially variant photonic crystals at telecommunications wavelengths**

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This work reports the fabrication of micron-scale spatially variant photonic crystals (SVPCs) and their use for steering light beams through turns with bending radius Rbend on the order of ten times the optical wavelength ?0. Devices based on conventional photonic crystals, metamaterials, plasmonics and transformation optics have all been explored for controlling light beams and steering them through tight turns. These devices offer promise for photonic interconnects, but they are based on exotic materials, including metals, that make them impractically lossy or difficult to fabricate. Waveguides can also be used to steer light using total internal reflection; however, Rbend of a waveguide must be hundreds of times ?0 to guide light efficiently, which limits their use in optical circuits. SVPCs are spatially variant 3D lattices which can be created in transparent, low-refractive-index media and used to control the propagation of light through the self-collimation effect. SVPCs were fabricated by multi-photon lithography using the commercially available photo-polymer IP-DIP. The SVPCs were structurally and optically characterized and found to be capable of bending light having ?0 = 1.55 µm through a 90-degree turn with Rbend = 10 µm. Curved waveguides with Rbend = 15 µm and 35 µm were also fabricated using IP-DIP and optically characterized. The SVPCs were able to steer the light beams through tighter turns than either waveguide and with higher efficiency.

9759-36, Session 8

**Realization of photonic quantum simulators with direct laser writing**

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As the propagation distance z in the paraxial Helmholtz equation corresponds to time in the Schrödinger equation one can simulate quantum-optical effects by looking at the propagation of light in evanescently coupled waveguides. This way pure systems without defects and with tunable hopping between lattice sites at arbitrary time-steps (z-steps) can be examined:

- Implementations include lossy plasmonic systems [1], photoinduced waveguides in nonlinear crystals [2] and femtosecond laser written waveguides in fused silica [3]. While the latter has the advantage that arbitrary 3D structures can be fabricated, the contrast in refractive index is very small (~10^-4) and necessary length scales are huge (propagation lengths of cm).

- We present a new technique of manufacturing low-loss easily tunable 3D waveguide structures on micrometer length scales: A hollow waveguide array is fabricated via 3D laser lithography in a negative tone photoresist. The sample is infiltrated with a higher index material, creating waveguides

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9759-33, Session 8

**Complex micro-optics fabricated by femtosecond 3D direct laser writing (Invited Paper)**

Harald Giessen, Univ. Stuttgart (Germany)

We present complex micro-optics fabricated by femtosecond 3D direct laser writing. We fabricate optical free-form lenses directly onto single mode fiber tips and achieve near-perfect centration and alignment. We measure the beam propagation of a variety of free-form surfaces such as spheres, aspheres, astigmatic lenses which deliberately introduce astigmatism, as well as diffractive structures. Flat-top intensity distributions as well as deliberately designed donuts have been achieved. When using more complex manufacturing methods, multi-lens micro-objectives can be fabricated with near-perfect alignment onto single- and multi-mode fibers, as well as on transparent surfaces or directly onto CCD chips. MTF measurements compare the manufactured systems and demonstrate their extremely high performance when compared with their designed parameters. Both illumination as well as imaging is possible. We will show the limits and challenges of this new field for the future. Remote imaging and microscopy is possible when using multi-core single-mode fibers. These complex micro-optical high-performance microscopy systems can be inserted into the finest syringe needles.

This work was carried out in collaboration with Timo Gissibl, Simon Thiele, and Alois Herkommer (both from ITO, Stuttgart). Support from ERC, BW Stiftung, BMBF, DFG, and AvH is acknowledged.

9759-34, Session 8

**Study of 3D printing method for GRIN micro-optics devices**

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Gradient index materials have been studied more than several decades, although the theoretical design and analysis of GRIN lenses have been well documented for some years. However, the progresses in Two-Photon Absorption photochemistry in the past decade have promoted the idea of making lenses by layer-on-layer in 3D structure. The applications of 3D printing of optical lenses in GRIN materials seem to be more feasible then ever. This paper studies the UV polymerization of acrylic and epoxy based materials in refractive index versus degree of curing. And, optics simulations show promising future of 3D printing in GRIN lens prototyping and manufacture.
of about 1 micrometer in diameter. By choosing appropriate infiltration materials the coupling constant between waveguides can be tuned. We use soft-baked SU8, corresponding to a refractive index contrast of 0.05 and coupling lengths of about 50 micrometers.

For straight waveguides arranged on a honeycomb-lattice the bulk modes and static edge modes are observed. Using helical waveguides as in [3], a Floquet topological insulator with chiral edge modes can be realized. Experimental results are compared to numerical simulations and evaluated quantitatively.


9759-38, Session 9

Hybrid integration approaches for functional nanophotonic circuits (Invited Paper)
Wolfram Pernice, Westfälische Wilhelms-Univ. Münster (Germany)

Nanophotonic circuits allow for realizing complex optical functionality with compact footprint and high reproducibility. Often such circuits are fabricated from passive materials which prevent active capability, such as light generation, detection or on-chip tunability. Because predominantly planar structuring approaches are used for manufacturing nanophotonic components, access to the important third dimension is generally limited. Here I will present hybrid approaches to overcome these limitations by using additive manufacturing and 3D laser lithography. This way control of both the polarization state within a waveguide mode and free-form geometry can be controlled after planar lithography. In order to implement nanoscale light sources we combine passive substrates with carbon nanotube emitters. Their emission profile is tailored using nanophotonic cavities and on-chip filter elements. Using electrophoresis deposition such devices can be realized on a wafer-scale, compatible with scalable nanofabrication of circuit elements. To further achieve active tunability, we employ phase-change materials co-integrated with planar devices after nanostructuring. These components are in particular of interest because they provide stark contrast in their optical properties upon phase transition from the amorphous to crystalline state. Because the phase state is preserved after switching they allow for nonvolatile device operation. By combining such a suite of hybrid integration techniques a rich toolbox for extending the capability of traditional integrated optical devices can be compiled for applications in optical signal processing, on-chip sensing and metrology.

9759-39, Session 9

STED lithography for applications in biology
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It was proposed already in the early reports of STED microscopy that the confined excitation volume can be applied to spatially control chemical reactions on the nanometer scale [1]. Recently, this prediction has been experimentally realized in the field of optical nanolithography [2, 3]. Nanoscale structures written with some acrylate compositions show good biocompatibility and allow for bio-functionalization with proteins, down to the single protein level [4, 5]. The ability to place individual proteins into nano-confined spaces plays a growing role in bioscience, from basic studies in biology to the development of nanoscopic sensors. Other compositions of acrylates, specifically those containing polyethylene glycol, are protein repellent. This allows us to write two-component structures, where non-adhesive scaffolds are written in three dimensions and later on, protein adhesive nanoscale regions are added for targeted protein attachment. While such two-component acrylate structures already allow for many applications in physiological and medical research, it would be even more appealing, if proteins and other biomolecules could be attached covalently. We will also address routes in this direction.

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9759-40, Session 9

3D SLM-based STED-lithography
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3D direct laser writing (DLW) is a commonly used technology for the fabrication of almost arbitrarily complex polymer structures in a single processing step [1]. As the achievable resolution in standard DLW is diffraction limited, several proposals using superresolution technology have been presented in recent years [2]. One of the most promising is stimulated emission depletion (STED) inspired lithography. Here, using especially shaped phase masks, a second laser beam suppresses the polymerization reaction via stimulated emission. Alignment of the two beams and phase mask design are technologically challenging. Using spatial light modulators (SLMs) for the writing as well as the depletion laser beam allows for (i) automatically aligning the setup, (ii) correcting aberrations present in the setup, and (iii) varying the phase masks used for the depletion laser to find optimal conditions. We compare the standard doughnut- and bottlebeam-modes realized with the SLMs to theoretical expectations. In writing experiments we observe a reduction of the lateral polymerization linewidth of 50% for the doughnut- mode. The bottlebeam-mode results in a reduction of the axial feature size by 56%. Furthermore, we use a numerical algorithm [3] to calculate corresponding phase- and amplitude-patterns for alternative mode patterns: We compare the writing performance of so called lateral and axial multifoci-modes with the results achieved for doughnut and bottlebeam phase masks. Experimentally, the multifoci-modes show at least comparable performance while being conceptually much simpler to realize. The performance of our approach is demonstrated with photonic woodpile crystals as benchmark structures.

Multi-photon lithography of 3D micro-structures in As2S3 and Ge5(As2Se3)95 chalcogenide glasses

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This work reports a detailed study of the processing and photo-patterning of two chalcogenide glasses (ChGs) ? arsenic trisulfide (As2S3) and a new composition of germanium-doped arsenic triselenide Ge5(As2Se3)95 ? as well as their use for creating functional optical structures. ChGs are materials with excellent infrared (IR) transparency, large index of refraction, low cost of thermal expansion, and low change in refractive index with temperature. These features make them well suited for a wide range of commercial and industrial applications including detectors, sensors, photonics, and acousto-optics. Photo-patternable films of As2S3 and Ge5(As2Se3)95 were prepared by thermally depositing the ChGs onto silicon substrates. For some As2S3 samples, an anti-reflection layer of arsenic triselenium (As2Se3) was first added to mitigate the effects of standing-wave interference during laser patterning. The Ch films were photo-patterned by multi-photon lithography (MPL) and then chemically etched to remove the unexposed material, leaving free-standing structures that were negative-tone replicas of the photo-pattern in networked-solid ChG. The chemical composition and refractive index of the unexposed and photo-exposed materials were examined using Raman spectroscopy and near-IR ellipsometry. Nano-structured arrays were photo-patterned and the resulting nano-structure morphology and chemical composition were characterized and correlated with the film compositions, conditions of thermal deposition, patterned irradiation, and etch processing. Photo-patterned Ge5(As2Se3)95 was found to more resistant than As2S3 toward degradation by formation of surface oxides.

Fabrication of metamaterial-based infrared perfect absorber structures using direct laser write lithography

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Recently, perfect absorbers of electromagnetic radiation exploiting properties of electromagnetic metamaterials have attracted significant attention. However, so far, most perfect absorber architectures have been implemented for microwave or terahertz spectral ranges, where the required unit cell size is relatively large and practical fabrication is easier. Fabrication of similar structures for shorter, optical wavelengths, such as infra-red (IR), near-infrared (NIR), or visible wavelengths requires one to downscale the unit cell size, and is therefore hindered by the lack of suitable micro-/nano-fabrication techniques, especially when 3D architectures are considered. Here we report design, fabrication and optical characteristics of chiral plate perfect absorber for IR spectral range. The absorber architecture consists of single-turn metallic helices periodically arranged on a metallic plane. Such architecture produces resonant electromagnetic coupling leading to nearly perfect extinction of incident waves within a single, sub-wavelength layer of the absorber. Active wavelength of the absorber is unable by design. The structures were designed and optimized using finite-element electromagnetic simulations, and fabricated using femtosecond direct laser write (DLW) technique in a dielectric photoresist followed by subsequent metallisation by gold. Characterisation of the samples by IR reflection spectroscopy has revealed a resonant absorption band centred at the 7.6µm wavelength with peak absorptivity in excess of 90%, in accordance to theoretical predictions. In the future, similar metamaterials may be applied for harvesting of IR radiation and thermal detection enhancement. Owing to the constant advancement of the DLW lithography technique and increase of its spatial resolution, further downscaling of the unit cell and tuning of the perfect absorption resonance towards NIR spectral range can be expected.

3D direct laser writing of metal structures for novel optical applications (Invited Paper)

Michael G. Moebius, SeungYeon Kang, Kevin Vora, Philip A. Muñoz, Yang Li, Guoliang Deng, Eric Mazur, Harvard School of Engineering and Applied Sciences (United States)

Fabrication of 3D optical devices on the nano- and micro-scale is limited by time-consuming and expensive layer-by-layer fabrication relying on lithographic techniques, which also restricts the complexity of patterns and shapes in the z-direction. We have developed a 3D direct laser writing technique for metal structures which allows us to overcome these challenges. We present recent advances with this fabrication technique, including fabrication and testing of multi-layer diffraction optical elements that will enable novel, complex optical devices. We fabricated samples by focusing <100-fs laser pulses with 80 MHz repetition rate centered at 780 nm into a thick polymer film doped with silver nitrate. Multi-photon absorption initiates reduction of metal ions and formation of silver structures at the focal point. Laser exposure parameters control the shape and size of fabricated features. We achieve <100 nm features and 500 nm resolution for structures spanning several millimeters. By fabricating structures within a polymer matrix, we can produce connected and disconnected metal structures with arbitrary shape. We have demonstrated fabrication of 3D gratings, pinholes, and diffractive lenses and tested their operation at visible wavelengths. These devices have potential in beam steering and shaping, dispersion compensation when paired with bulk optics, and in-situ imaging for lab-on-a-chip applications. Current and future efforts are focused on optimizing fabrication techniques and measuring the electrical properties of fabricated structures. This information will allow precise design of metamaterials and, potentially, 3D electrical circuits on the nano-scale.

Femtosecond laser direct-write of lab-in-fiber sensors through polymer-coated optical fiber

Kevin A. J. Joseph, Moez Haque, Stewart J. Aitchison, Peter R. Herman, Univ. of Toronto (Canada)

Lab-on-chip (LOC) technology, the miniaturization and integration of multiple biological and chemical processes onto a single chip, has been a hallmark of nanotechnology research for over thirty-five years. While it has led to an array of promising applications, deploying and monitoring LOC can be challenging over vast, expansive systems such as municipal water supplies, and in tightly confined and sinuous spaces such as human blood vessels. Silica fiber is a ubiquitous optical platform which has already been deployed over billions of kilometers worldwide. Translating LOC technology to fiber allows for devices which can take advantage of the fiber’s low loss, robustness, and flexibility, and that can be seamlessly integrated into existing fiber-optic networks or confined environments. Lab-in-fiber (LIF) technology is made possible through femtosecond-pulse driven nonlinear modifications that provide highly localized refractive
index change and volume nanogratings. In this way, femtosecond-laser direct writing enables highly flexible, rapidly prototypeable 3D optical waveguides to form and efficiently connect with the pre-existing core waveguide to provide fiber-cladding photonics. Additionally, differential chemical etching of the nanograting tracks provides new means to form optical resonators, microfluidic channels and MEMS structures that can be further integrated with the 3D optical circuits to open a broad base of new in-fiber Microsystems for optofluidic analysis, biomedical catheters, and Telecommunication applications.

A limitation to these LIF approaches thus far is the increased processing time and reduced fiber strength resulting from stripping the fiber’s protective polymer buffer jacket prior to laser-processing. In this paper, we extend the 3D structuring of optical fiber to femtosecond-laser writing through the urethane-acrylate buffer coating of Corning SMF-28 fibers. Immersion lens focusing removed astigmatism and spherical aberration to enable undistorted and damage free writing of optofluidic components in both the fiber core waveguide and cladding. LIF devices are presented together with the processing parameters for minimizing machining damage in the polymer jacket.

9759-46, Poster Session

Novel fabrication technique of hybrid structure lens array for 3D images

Junsik Lee, Junoh Kim, CheolJoong Kim, DooSeub Shin, Gyohyun Koo, YongHyub Won, KAIST (Korea, Republic of)

Tunable liquid lens arrays can produce three dimensional images using electrowetting principle that alters surface tensions by applying voltage. This method has advantages of fast response time and low power consumption. However, it is challenging to fabricate a high fill factor liquid lens array and operate three dimensional images which demand high diopter. This study describes a hybrid structure lens array which has not only a liquid lens array but a solid lens array. A concave-shape lens array is unavoidable when using only the liquid lens array and some voltages are needed to make the lens flat. By placing the solid lens array on the liquid lens array, initial diopter can be positive. To fabricate the hybrid structure lens array, a conventional lithographic process in semiconductor manufacturing was needed. A negative photo-resist SU-8 was used as solid and liquid master molds. PDMS and UV adhesive replica molding are done sequentially. Two immiscible liquids, DI water and dodecane, are injected in the fabricated chamber, followed by sealing. The fabricated structure has a 10 x 10 pattern of cylindrical shaped circle array and the aperture size of each lens is 500um. The thickness of the overall hybrid structure is about 1.5mm. Hybrid structure lens arrays have many advantages. Solid lens arrays have almost 100% fill factor and allow high efficiency. Diopter can be increased by more than 800 and negative diopter can be shifted to the positive region. This experiment showed several properties of the hybrid structure and demonstrated its superiority.

9759-47, Poster Session

Slanted liquid microlens array by using diffuser

DooSeub Shin, Junoh Kim, CheolJoong Kim, JunSik Lee, Gyohyun Koo, YongHyub Won, KAIST (Korea, Republic of)

Liquid lens is promising alternatives for solid lens. Conventional solid lens have fixed focal length. Movements of solid lens are required when adjusting the focus. Liquid lens, unlike the solid lens, do not need to move lens back and forth. Various curvature of liquid lens is feasible with the applied voltage between electrode and conductive liquid. Liquid microlens array, in this context, achieve its focus by forming the same shape of curvature of each liquid lens. The differences of the focal length enhances a sense of depth. Application of liquid microlens array is in 3D imaging and displays. Ordinary liquid microlens has vertical side walls. The shape of it, however, has several weaknesses such as a low value of diopter and a difficulty in evaporating electrode. This paper aim to describe a slanted liquid microlens with the diffuser. Our research shows that an effect of diffused Ultraviolet(UV) light leads to a slanted microlens with high value of diopter and well-filled electrode. Negative PR was put on the substrate and patterned mask was laid on the negative PR. The next step is to exposure UV light which passes through the diffuser. The state of diffused UV light into the negative PR can be observed. The diffuser causes UV light to spread slightly not straightly. This research shows a result of a slanted liquid microlens having side walls with an angle of 70 degrees. In order to acquire a high value of Fill Factor, it also presents matching values for refractive indices of the two media, oil and chamber.

9759-48, Poster Session

Nanoimprint of large-area optical gratings on a conventional photoresist using a teflon-coated nanoimprint mold

Aju S. Jugessur, Anthony Zhang, Yiman Lyu, The Univ. of Iowa (United States)

Nanoimprint Lithography is a promising high-throughput technology for the fabrication of optical structures at the nanoscale, over large areas in the centimeter range [1] compared to the conventional technique such as Electron-Beam Lithography [2]. However, there are limitations of the transfer resist or mask that can be used in the nanoimprint process. The commercially available nanoimprint resists are costly, proprietary and tool specific. In addition, the nanoimprint resist is not compatible with photo- or electron-beam lithography processes – key methods to define critical pattern layers. Previous work demonstrated tearing of the conventional resist (AZ1500 series) during the pattern transfer as a result of the resist sticking to the mold even at high imprint pressures [3, 4]. In this work, the photo-resist AZ181 (1-Methoxy-2-propanol acetate) diluted with PGMEA (propylene glycol monomethyl ether acetate) has been investigated as a viable nanoimprint resist with a silicon mold coated with Teflon AF 1600 as a low-surface energy coating. Preliminary results show that teflon-coated silicon mold imprint on the photo-resist provides considerable improvement on pattern transfer compared to molds without the coating (Figure 1). The results are comparable with the commercial nanoimprint resist, such as Nanonex NRX 1025 (Figure 2). The process development of the teflon coating and the optimization of nanoimprint process parameters will be presented. To our knowledge, the nanoimprint process developed in this work using a common photoresist coupled with teflon-coated mold is novel and critical for the cost-effective and high-throughput fabrication of nanostructures, in particular, optical gratings over large areas.


9759-49, Poster Session

Fabrication of liquid-filled square lens array with hemispherical partition walls

Gyohyun Koo, Junoh Kim, Cheoljoong Kim, DooSeub Shin, JunSik Lee, Yong Hyub Won, KAIST (Korea, Republic of)

Liquid-filled square lens array has been developed for an alternative to solid lens array because of its merit of variable focus length. In addition, the square lens array has advantage with high fill factor compared to liquid circular lens array which is another alternative. However, one of the
main limitations of conventional square lens array is the aberration. In this paper, aberration-free liquid square lens array is proposed. The partition walls of the proposed square lens array is fabricated into hemispherical shape to reduce the aberration, and then additional vertical walls is set up on the hemispherical structures to unify the height of partition walls. UV lithography techniques are used to fabricate this structure, and diffuser which has angle of 80 degree is used in this process. Photosist is exposed to scattered ultraviolet rays which pass through the diffuser, and hemispherical lens-shaped structures of photosist remains after development process. Supplementary vertical partition walls are obtained by additional photosist patterning process on the structure. In this structure, the interface between oil and water comes into contact with the surface of the hemispherical walls, and the refractive index of oil and the walls are equally matched to maximize the part which acts as a lens in the chamber. The proposed liquid square lens array can provide us with aberration-free 3D images with high fill factor.

9759-50, Poster Session

WGP structures patterned by Lloyd's mirror laser interference lithography system integrate into MEMS physical sensor device

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This abstract presents a novelty design concept of the Wire-Grid Polarized structure applied to physical sensor device. Regarding the histories of WGP, several studies have focused on the optical polarize application and characteristic. However, it never used on MEMS sensor development. Therefore, in this research, WGP device will be designed and manufactured as the main operation technique of MEMS physical sensors, such as accelerometer or pressure sensor.

WGP is composed of numerous nano-scale one-dimensional metallic grating which patterned on MEMS structures, such as cantilever beam, and the structure pitch must be less than half of the light source wavelength. WGP device will separates the incident light with two polarizations: the P-polarization (TP) perpendicular to the gratings will be transmitted and the S-polarization (RS) parallel to the gratings will be reflected. In addition, the optical performance of WGP was evaluated using the basic parameters of TP and extinction ratio. When physical force effect on this device, it makes the MEMS structure rotate with a few angle and get the different TP value by photodetector. For this reason, the TP values can be transferred to the homologous physical force as the sensing signal.

This research used the optical characteristic simulation software (G-Solver) to demonstrate the sensor’s design feasibility and structure parameters. Moreover, laser interference lithography (LIL) approach will be used to pattern the one-dimension periodic structures on silicon substrate at one-time exposure process. After complete the device fabrication, this research setup the optical measurement system to proof the design concept and simulation results.

This abstract provides the first trial by adapting the sub-wavelength nano-grating in the MEMS physical sensors, however, more details will be presented in the full paper.

9759-51, Poster Session

Lens array fabrication method with volume expansion property of PDMS

Wonjae Jang, Junoh Kim, Yonghyub Won, Yousung Bang, Muyoung Lee, Jooho Lee, KAIST (Korea, Republic of)

Conventionally, PDMS lens array is fabricated by replica molding. In this paper, we describe simple method for fabricating micro-lens array with expanding property of PDMS. The PDMS substrate is prepared by spin coating on cleaned glass. After spin coating, PDMS substrate is treated with O2 plasma to promote adhesion between PDMS substrate and photosist pattern on it. Negative photosist az-2070 and AZ MIF 300 developer is used for patterning on PDMS. General photolithography process is used to patterning. Then patterned PDMS substrate is dipped to 1-bromododecane bath. During this process, patterned photosist work as a barrier and prevent blocked PDMS substrate from reaction with 1-bromododecane. Unblocked part of PDMS directly react with 1-bromododecane and it will result in expanded PDMS volume. The amount of expansion of PDMS is depends on absorbed 1-Bromododecane volume, dipping time and ratio of block to open area. The focal length of lens array is controlled by those parameters. The volume expansion factor. The proposed liquid square lens array can provide us with aberration-free 3D images with high fill factor.

9759-52, Poster Session

Fabrication of plasmonic crystals using programmable nanoreplica molding process

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The ability to fabricate periodic nanostructures has a great impact on the development of plasmonic and photonic crystal devices. We report a programmable nanoreplica molding process that can trim the geometry of periodic nanostructures for the fabrication of desired devices. This versatile fabrication method is based on the nanoreplica molding approach with a stretched elastomeric mold. During a replication, a uniaxial in-plane stress is applied to the mold and alter the periodic nanostructure carried on the mold. Direction and magnitude of the strain regulate grating parameters, including lattice constant and arrangement.

The process offers a convenient means to fabricate a variety of grating-based nanophotonic devices. For example, using the mold with a 2D periodic pattern (square lattice and period = 300 nm), we demonstrated plasmonic crystal devices that exhibited different surface plasmon resonances (SPR) in a range of 110 nm. Spectral positon of the SPR mode was determined by the stress applied to the mold during the replication. In addition, by stretching the mold along the diagonal direction of the square lattice, triangular lattice structures were obtained. Photonic crystal (PC) slabs with square, rectangular and triangular lattice structures were fabricated and characterized. We will present photonic band diagrams of these PC slabs and compare them with simulation results. Furthermore, under a constant stress, the local strain can be managed by varying the thickness of the PDMS mold. This unique capability enables us to program a PDMS mold, and thus fabricate devices containing complex periodic structures, such as a chirped grating.

9759-53, Poster Session

Rate controlled metal assisted chemical etching to fabricate vertical and uniform Si nanowires

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MacEtching (metal assisted chemical etching) is a simple, low-cost and anisotropic etching method to make Si NWs (silicon nanowires). In this
method, smaller surface area is damaged compared to dry etching process. The Si NWs manufactured by MacEtching, however, increased the wall surface roughness due to immersion in the solution resulting from excess hole diffusion from the metal layers. In this research, we controlled the oxidant and oxide removal acid ratio in MacEtching solution to increase the etching speed underneath noble metal layer. Using this method, we produced the Si NWs at a faster rate having good uniformity.

References


9759-55, Poster Session

Surface-enhanced Raman spectroscopy substrate fabricated via nanomasking technique for biological sensor applications

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The nanomasking fabrication technique has been shown to be capable of producing many sub-10 nm gaps between metallic structures over a wafer-scale area. This provides the opportunity to utilize the technique in spectroscopy signal enhancement applications. Here we describe a device designed via nanomasking that holds potential as a surface enhanced Raman spectroscopy (SERS) substrate for biosensing or other applications. The high density of plasmonic hotspot nanogaps improves the feasibility of these types of patterns for signal enhancement, as it provides ease of use and increased speed of sample deposition for taking spectrum. The ability to fabricate these patterns with high repeatability at mass production scale is another benefit of nanomasking-fabricated spectroscopy substrates. This work demonstrates tests of fabricated devices for use in a custom Raman spectroscopy system as a potential source of signal enhancement. Also, theoretical enhancement results are calculated for comparison via computational electromagnetic studies.

9759-56, Poster Session

Optical and magneto-optical properties in Fe-doped silica glasses irradiated with oscillator-only femtosecond laser

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Transparent glass materials containing magnetic and magneto-optical crystalline nanoparticles have increasingly receiving attention due to potential applications in high-density recording devices, highly efficient optical isolators, and magneto-photonic crystals, and so on. For example, one externally controllable material property that can be exploited to make switchable active devices is the magneto-optic effect, also known as Faraday effect, which is measured through the Verdet constant. On the other side, femtosecond (fs) laser micromachining of transparent materials has many potential applications in integrated optics, owing to precise deposition of a large amount of energy into the volume of samples, prompting to a direct three-dimensional (3D) processing method. However, studies on space-selective modification of magnetic materials by oscillator-only femtosecond-laser irradiation have been rarely reported. In this work, we report the fabrication of waveguides inside iron-doped silica glasses (x Fe2O3 + 705/02 + 20Na2O + 10CaO, mol%) using an extended-cavity femtosecond laser irradiation (50-fs, 800-nm, 5.1 MHz). The beam was focused under the sample surface through microscope objectives. We demonstrated the waveguides functionality by measuring the near-field intensity distribution at the waveguide output and their efficiency. The Verdet constant was also measured in the waveguiding coupling setup. Optical, magnetic, and magneto-optical properties have been investigated for different doped concentration samples. We observed no need of subsequent annealing for the magnetic nanoparticles precipitation. We also reported u-Raman spectroscopy measurements, showing differences on the irradiated and non-irradiated regions of the sample.

9759-57, Poster Session

Diffusive multi-scale spheres based on composite polymer systems

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Novel fabrication pathways have been recently developed for the production of structured, functionalized polymeric micro- and nano-spheres, realized through a thermally-induced fluid instability within multilayered fibers. Unique to this methodology are the wide scope of compatible materials and additives available, the scalability of the process to industrial levels, and the narrow dispersion in particle sizes produced. Applications for these polymeric spheres span a variety of fields including biomedical diagnostics, drug delivery, imaging, paints and coatings, and cosmetics. In this work, we demonstrate the fabrication of heterogeneous composite microspheres containing a cyclic olefin polymer (COP) matrix integrated with a random distribution of nanoparticles such that there is a large refractive index contrast uniformly distributed throughout the microsphere. The nanoparticles used in the composite were selected for their performance as white pigments in that their size (~0.3 μm), transparency, and high refractive index (~2.4) are optimal for broadband scattering in the visible spectrum. These composite spheres, upon irradiation, should produce speckle patterns indicative of multiple scattering due to the interaction between the nanoparticles. This behavior is demonstrated by tightly focusing a 632-nm-wavelength laser beam onto a composite microsphere and imaging the scattered field using transmission microscopy. It is readily observed from the speckle pattern that the multiply-scattered waves exiting the microsphere vary randomly in amplitude and phase, thus exhibiting behavior beyond the known Mie scattering typical of a homogenous microsphere.

9759-59, Poster Session

Phase photon sieve inscribed on an optical fiber tip by focused ion beam milling

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Diffractive optical lenses play an important role in micro and nano imaging projection, especially Fresnel zone plates (FZP) for their versatility and compatibility with the integration on an optical system due to their planar nature. The photon sieve (PS) has been demonstrated to have an improved diffractive efficiency over the FZP and the monolithically integration of these elements on fiber optic systems is evidently beneficial presenting itself as self-aligned light source-lens system, which suppresses the need for expensive lenses and complex setups. The fabrication of a phase photon sieve on an optical fiber tip is reported. The 3D diffractive pattern was transferred to the fiber tip by focused ion beam (FIB) milling. As an alternative to the conventional metallization prior to FIB milling a dip-coating technique was used to ensure the conductivity.
of the fiber tip, resorting to the conductive polymer PEDOT:PSS. A study of the influence of four fundamental parameters on the PS focal performance was conducted, namely, variations of the etch depth, individual PS feature distribution, radii and number of sieve orders. The near field scans of the intensity profile along the optical axis under fiber illumination of a tunable laser in the infrared are shown, where we have analyzed the focusing properties of the fabricated phase photonic sieves.

9759-60, Poster Session

**Designed local fill fraction in photonic crystal templates using a spatial light modulator**

Jeffrey R. Lutkenhaus, David George, David Lowell, Usha Philipose, Hualiang Zhang, Yuankun Lin, Univ. of North Texas (United States)

We report the fabrication of designed defects and regions in photonic crystal templates with differing fill fractions using a spatial light modulator. Phase patterns with local variance of diffraction efficiency are created using phase tiles from other phase patterns with known diffraction efficiencies. Both six-fold and four-fold symmetric phase patterns are used to generate six and four beams, respectively, with locally specified phases. Fourier transform simulations of designed phase patterns are used to guide the filtering process and also give insight into the interference pattern in the 4f plane. Photonic crystal templates are fabricated using exposure of photoresist to the interference patterns generated from the phase patterns with local diffraction efficiency variance displayed on a spatial light modulator. It is shown that local control of fill fraction is achievable using this method.

9759-61, Poster Session

**Fabrication of period-gradient gratings by laser interference lithography**

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Lithography techniques for sub-micron pattern generations are very important. In particular, laser interference lithography (LIL) is a powerful method as it allows generating periodic sub-micrometer patterns over large area at high throughput, therefore at low cost. The LIL is however capable of generating periodic patterns only. In order to make it more versatile, we have developed a modified LIL technique that enables the generation of chirped grating patterns, in which the grating period varies progressively within a single grating pattern, yet the virtues of the LIL technique, such as large-area processing and high throughput, being preserved. Our LIL system has a Lloyd mirror configuration with the sample orientation perpendicular to the reflection mirror. By a simple replacement of the flat reflection mirror with a cylindrical concave mirror, we have been able to vary the grating period within a pattern as one of the incidence beam angles now changes progressively. With a particular cylindrical mirror whose radius of curvature and focal length are 1150.0 mm and 575.0 mm, respectively, we have achieved the incidence angle variation of about 8-degrees across a 1 cm long sample, which is translated into about 40 nm in grating period when the central grating period is 600 nm. The developed technique for period-chirped gratings should find many useful applications such as tunable lasers and variable color filters.

9759-62, Poster Session

**Direct write grayscale lithography as a fabrication technology for deep micro-optical freeform surfaces**

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We present a novel direct write grayscale lithography system for the fabrication of micro-optical freeform surfaces, micro-lenses, diffusors and diffractive optics on planar and curved substrates. The exposure principle uses a LCoS micro-display which is illuminated by a 405nm UV High Power LED, which can be controlled in power and exposure time. A fast micro-image and substrate positioning and an online data preparation are used to minimize stitching effects within large exposure areas. This offers an accurate and high dynamic control of the dosage, which is realized by a combination of pixel-wise exposure intensity regulation within the micro image in and a variable exposure dose. The exposure concept allows a high structure depth of >100µm and a spatial resolution below 1µm as well as the possibility of very steep edges in the profiles of (>80°). The patterning speed of up to 100cm²/h to makes the concept suitable for large scale applications. In the publication we outline the benefit of this technology for the fabrication of micro-aspHERE-arrays as we demonstrate a superior low surface deviation below 0.2% RMS of the surface sag, which makes the fabricated optics also suitable for imaging and metrology applications.
A micro-fabricated water-immersible scanning mirror with a small form factor for handheld ultrasound and photo-acoustic microscopy

Song Xu, Chih-Hsien Huang, Jun Zou, Texas A&M Univ. (United States)

Micro scanning mirrors that can operate reliably under water is useful in both ultrasound and photoacoustic microscopy, where fast scanning of focused high-frequency ultrasound beams is needed for pixel-by-pixel data acquisition. This paper reports the development of a new microfabricated water-immersible scanning mirror with a small form factor. It consists of an optically and acoustically reflective mirror plate, which is supported on two flexible polymer hinges and driven by an integrated electromagnetic microactuator. Different from conventional MEMS-based scanning mirrors, it has a much larger mirror plate (7 mm x 5 mm) to provide high numerical aperture for ultrasound beam steering. This is important to ensure good acoustic sensitivity especially when the ultrasound signals are weak. The low stiffness and high fracture strain of the polymer hinges can reduce driving force and avoid shock damage due to turbulence especially for a larger mirror plate. Electromagnetic actuation does not need high voltage or electro-heating, and therefore is suitable in a liquid environment. The scanning mirror can achieve one-axis scanning of ±12.1° at a resonant frequency of 250 Hz in air and 210 Hz in water, respectively. By optimizing the design and enhancing the fabrication with high-precision optical 3D printing, the overall size of the scanning mirror module is less than 7 mm x 7 mm x 5 mm. The small form factor, large scanning angle, and high resonant frequency of the water-immersible scanning mirror make it suitable for building compact handheld probes for high-speed and wide-field ultrasound and photoacoustic microscopy.

A two-axis water-immersible MEMS scanning mirror for scanning optical and acoustic microscopy

Song Xu, Chih-Hsien Huang, Jun Zou, Texas A&M Univ. (United States)

Fast multi-axis scanning is useful for not only optical but also acoustic microscopic imaging. Although they have been used for optical scanning, the application of (MEMS) scanning mirrors in acoustic microscopy is still very limited due to their small mirror plate size, and more importantly inability to operate in liquids (as ultrasound coupling media). This paper reports a new microfabricated two-axis water-immersible scanning mirror for optical and acoustic microscopy. It has an optically and acoustically reflective mirror plate (6 mm x 4 mm) to provide high numerical aperture for ultrasound beam steering. To achieve reliable underwater scanning, flexible polymer torsion hinges fabricated by laser micromachining were used to support the mirror plate. Two electromagnetic microactuators were constructed to drive the silicon mirror plate around a fast axis and a slow axis. The fast axis has a resonant frequency of 320 Hz in air and 250 Hz in water, which is more than 10 times higher than that of slow axis (24 Hz in air and 15 Hz in water). The large difference in the two resonant frequencies facilitates the formation of raster scanning pattern commonly used in scanning microscopy. Under a 100 mA driving current, the scanning angles of the fast axis reached ±9.5° in air and ±5° in water at the resonant frequencies, respectively. The feasibility of using the two-axis water-immersible scanning mirror in scanning acoustic microscopy was also demonstrated to enable fast scanning of focused optical and high-frequency ultrasonic beams.

Wearable and augmented reality displays using MEMS and SLMs (Invited Paper)

Hakan Urey, Erdem Ulusoy, SeyedMahdi M. K. KazempourRadi, Deniz Mengu, Selim Olcer, Sven T. Holmstrom, Koç Univ. (Turkey)

In this talk, we present the various types of 3D displays, head-mounted projection displays and wearable displays developed in our group using MEMS scanners, compact RGB laser light sources, and spatial light modulators. Polarization and coherence properties of lasers have been exploited for stereoscopic, auto-stereoscopic, and super-stereoscopic 3D architectures. Head-mounted projectors are used with retroreflective screens and microlens array based transparent screens to demonstrate new augmented reality applications. We also developed novel near-to-eye holographic projection displays using spatial light modulators. We showed that speckle-free holographic virtual images can be reconstructed at the eye using novel algorithms.

3D micro/nano manufacturing of spatial light modulators for highly compact spectroscopy systems

Sascha P. Heussler, National Univ. of Singapore (Singapore); Herbert O. Moser, Karlsruher Institut für Technologie (Germany); Alok Pathak, Daniel Schmidt, National Univ. of Singapore (Singapore); Eric Tang, A*STAR Institute of Materials Research and Engineering (Singapore); Emma Sparrow, The Univ. of Manchester (United Kingdom); Shuvan Prashant Turaga, Jianfeng Wu, Mark Breese, National Univ. of Singapore (Singapore)

Conventional micro/nano manufacturing technology relies on 2D lithography and/or subsequent micro-machining processes such as DRIE to produce what is regarded as quasi- 3D structures. These processes led to numerous micro and nano-scale systems and with it a plethora of novel sensors used in everyday life. Multi-resist layer approaches help to shape the third dimension in greater detail at the cost of process complexity. In recent years, real three-dimensional processing on the basis of multi-photon, stereo, or gray scale lithography has unraveled the machining of the third dimension in a much greater detail. Here, we present a precise 3D manufacturing technology on the basis of gray scale x-ray lithography that is capable of producing spatial phase shifting arrays used in extremely compact interferometers for visible spectroscopy. The process allows shaping the third dimension of a polymeric substrate material at sub-wavelength accuracy by precisely depositing a defined dose profile during irradiation. Subsequent development results in precisely machined 3D microstructures with a depth resolution in the order of 100 nm. For its use in a Fourier transform interferometer the required precision of the manufactured phase shifting array is dictated by the Shannon Sampling Theorem demanding a phase shift sampling of at least half the wavelength of the light being analyzed. We present initial results of manufactured phase shifting arrays allowing detection down to 380 nm wavelength at a spectral resolution of about 3 nm.
9760-5, Session 3

**MEMS-mirror based trajectory resolution and precision enabled by two different piezoresistive sensor technologies (Invited Paper)**

Jan Graßmann, André Dreyhaupt, Christian Drabe, Richard Schroedter, Jörg Kamenz, Andreas Herrmann, Thilo Sandner, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

This paper presents two new piezoresistive position sensors for resonant and quasistatic micro scanning mirrors. The sensor principle is the same but once based on a doped pn-junction into an n-doped single crystal silicon substrate material and secondly based on a structured polysilicon layer that is embedded into the device layer and isolated by an silicon dioxide. The technology process flow including the extension of design space compared to the former approach is shown and the two sensor types are compared according to their characteristics like sensitivity, SNR (signal to noise ratio), light and temperature dependence as well as reliability results. Different connection schemes of a wheatstone bridge are also compared, because due to design limitations it is not possible in general to use a full wheatstone bridge. The polysilicon sensor shows very low respectively no light dependence but lower sensitivity than the single crystal silicon sensor that shows results up to 43 mV/V°. The possible as well as measured position resolution of the two sensor types in respect to parasitic effects, mirror eigenfrequencies and therefore dependence on the anchoring stiffness are presented. Based on these new piezoresistive sensors a controlled feedback loop for quasistatic mirrors was implemented and the achieved trajectory precision measured and described in this paper.

9760-6, Session 3

**MEMS scanner integrating a position control system**

Sebastien Lani, Yves-Julien Regamey, Dara Z. Bayat, Emmanuel Onillon, Ctr. Suisse d’Electronique et de Microtechnique SA (Switzerland)

An integrated position sensor with control system for a dual-axis electromagnetic tilting mirror is presented. The MEMS scanner system is constituted by a silicon flexible membrane integrating piezoresistive (PZR) sensors on which a mirror with an adequate reflective coating and a magnet is attached on each side. The parts are mounted on a planar coils deposited on a ceramic substrate to achieve electromagnetic actuation. The basic performances of the system are a mirror size of 7mm, a tilt of +/-150mrad mechanically with an accuracy <35μrad and a first resonant frequency at 180Hz. The calibration of the PZR sensors is achieved by recording the position with an external optical sensor and the output signal of the PZR is recorded with a dedicated electronics. A polynomial fitting is applied to further determine the position in function of the PZR sensors output signal. The control of the system is realized with a state-space controller method at a rate of 20kHz. A scanning speed of 3 to 30 rad/s was achieved for a noise level of respectively 200 to 1900μrad without system compensation of non-linearity and temperature.

9760-7, Session 3

**Modelling of biaxial gimbal-less MEMS scanning mirrors**

Thomas von Wantoch, Frank Senger, Shanshan Gu-Stoppel, Christian Mallas, Ulrich Hofmann, Fraunhofer-Institut für Siliziumtechnologie (Germany); Thomas Meurer, Christian-Albrechts-Univ. zu Kiel (Germany); Wolfgang Benecke, Fraunhofer-Institut für Siliziumtechnologie (Germany)

One- and two-dimensional MEMS scanning mirrors for resonant or quasi-stationary beam deflection are primarily known as tiny micromirror devices with aperture sizes up to a few Millimeters and usually address low power applications in high volume markets, e.g. laser beam scanning picoprojectors or gesture recognition systems. In contrast, recently reported volume-packaged MEMS Scanner feature mirror diameters up to 20 mm and integrated high-reflectivity dielectric coatings. These mirrors enable MEMS-based scanning for applications that require large apertures due to optical constraints like 3D sensing or microscopy as well as for high power laser applications like laser phosphor displays, automotive lighting and displays, 3D printing and general laser material processing.

This work presents modeling, control design and experimental characterization of gimbal-less MEMS mirrors with large aperture size. As an example a resonant biaxial Quadpod scanner with 7 mm mirror diameter and four integrated PZT (lead zirconate titanate) actuators is analyzed. The FEM (finite-element-method) model developed and computed in Comsol is used for calculating the eigenmodes of the mirror as well as for extracting a high order (n > 10000) state space representation of the mirror dynamics with actuation voltages as system inputs and scanner displacement as system output. By applying model order reduction techniques using MatLab to the former approach is shown and the two sensor types are compared according to their characteristics like sensitivity, SNR (signal to noise ratio), light and temperature dependence as well as reliability results. Different connection schemes of a wheatstone bridge are also compared, because due to design limitations it is not possible in general to use a full wheatstone bridge. The polysilicon sensor shows very low respectively no light dependence but lower sensitivity than the single crystal silicon sensor that shows results up to 43 mV/V°. The possible as well as measured position resolution of the two sensor types in respect to parasitic effects, mirror eigenfrequencies and therefore dependence on the anchoring stiffness are presented. Based on these new piezoresistive sensors a controlled feedback loop for quasistatic mirrors was implemented and the achieved trajectory precision measured and described in this paper.

9760-8, Session 3

**Real-time control for micro mirrors with quasistatic comb drives**

Richard Schroedter, Thilo Sandner, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); Klaus Janschek, TU Dresden (Germany)

This paper presents the application of a real-time control for the quasistatic axis of electrostatic micro mirrors. In comparison to resonantly driven mirrors, the quasistatic comb drive allows arbitrary motion profiles with frequencies up to its eigenfrequency. A current mirror setup at Fraunhofer IPMS is manufactured with a staggered vertical comb (SVC) drive and equipped with an integrated piezo-resistive deflection sensor, which can potentially be used as position feedback sensor. The control design is accomplished with a nonlinear mechatronic system model and the preliminary parameter characterization and evaluation. In previous papers [1,2] we have shown that jerk-limited trajectories, calculated offline, provide a suitable method for parametric trajectory design, taking into account physical limitations given by the electrostatic comb and thus decreasing the dynamic requirements. Open-loop control shows in general unfavorable residual eigenfrequency oscillations leading to considerable deviations for desired triangle trajectories, especially for subharmonic trajectory frequencies of the mirror’s eigenfrequency [3]. With the real-time control, implemented on a dSPACE system using an optical feedback, we can significantly reduce these errors and stabilize the mirror motion against external disturbances. In this contribution we compare different linear and nonlinear closed-loop control strategies as well as two observer variants for state estimation. Finally, we evaluate the simulative and experimental results in terms of accuracy in the steady state and their feasibility for a low-cost realization.

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9760-10, Session 4
MOEMS fabrication using integrated
optical fiber (Invited Paper)
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Jantzen, Peter A. Cooper, James C. Gates, Peter G. R.
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Integrated Optical Fiber (IOF) is a hybrid platform that combines optical
fiber with integrated optics. Unlike alternative approaches that tend to
use binding materials such as glass frit, epoxy or glues, IOF is fabricated
using Flame Hydrolysis Deposition (FHD) and consolidated at temperatures
above 1100°C. The result is a completely different structural composition
that consists of an optical guiding planar layer, which forms a miscible
alloy around an optical fiber. The doped silica has low optical loss and the
alloy that it forms is mechanically robust. This means that IOF is distinct
from other approaches, as it both optically and mechanically connects the
previously individual components of fiber and planar in one hybridized
unit. This work shall report the fabrication and performance of MOEMS
components based upon the IOF platform. The key advantage of using
IOF for MOEMS include a reduced coupling loss as the fiber can seamlessly
be brought on-and-off the chip; mechanical robustness of interconnects
as no glue or epoxy is used and tolerances in harsh environments such as
industrial solvents and elevated temperatures (>1000°C). Physical sensor
demonstrators shall be reported that can distinguish pressure, temperature
and flow and fabrication methodologies described including FHD
compositions to tailor inherent stresses and refractive index; precision layer-
up prior to deposition and compatibility with planar cleanroom process such as
lithography, etching and thin-layer deposition shall be described.

9760-11, Session 4
Physical and geometrical optics simulation
approaches for MOEMS and hybrid optical
systems
Daniel Asoubar, LightTrans International UG (Germany);
Frank Wyrowski, Friedrich-Schiller-Univ. Jena (Germany);
Christian Hellmann, Wyrowski Photonics UG (Germany);
Hagen Schweitzer, Michael Kuhn, LightTrans International
UG (Germany)

In the recent decades the progress in fabrication technologies enabled
the miniaturization and functional integration of optical systems, ended
up with MOEMS and hybrid optical systems. Irrespective of this evolution,
most optical simulation and design concepts are still based on a classical
ray tracing approach, which do not included wave optical phenomena.
However wave optical effects like diffraction, interference, coherence and
polarization, are most essential for the exact modeling of MOEMS and
hybrid optical systems. Thus in this work alternative simulation concepts
are introduced, in which we combine physical- and geometrical-optics based
arguments to solve Maxwell’s equations fast. Simulation results of several
important MOEMS and hybrid optical systems are shown to demonstrate the
flexibility and performance of the discussed modeling concepts.

9760-12, Session 4
Synchronization dynamics of a 2D
hybrid photonic-crystal nano-electro-
optomechanical oscillator
Avishek Chowdhury, Inah Yeo, Viktor Tsvirkun, Ctr.
National de la Recherche Scientifique (France); Fabrice Raineri, Ctr.
National de la Recherche Scientifique (France) and Univ.
Paris 7-Denis Diderot (France); Grégoire Beaudoin, Isabelle
Sagnes, Rama Raj, Isabelle Robert-Philip, Ctr. National
de la Recherche Scientifique (France); Rémy Braye, Ctr.
National de la Recherche Scientifique (France) and Univ.
Paris 7-Denis Diderot (France)

We investigate the non-linear mechanical dynamics of a nano-
ophtomic with a suspended membrane pierced
by a photonic crystal. By applying to the mirror an electrostatic force
induced by interdigitated electrodes integrated below the membrane, we
evidence the full synchronization dynamics of our hybrid nano-electro-
ophtomic system and demonstrate not only the frequency/phase
locking regions but also the constant phase shift of the oscillator on the
onset of principal harmonic and subharmonic excitation regimes. Bi-phase
synchronous regimes for multiple orders of synchronization are observed.
Combined to the scalability of the nano-electrooptomechanical platform,
the observation and control of the synchronization dynamics may pave the
way to synchronized oscillator networks subjected to collective dynamics,
implementing cluster states addressable optically and electrostatically.

9760-13, Session 4
On-board misalignment compensation
using a deformable mirror for large
aperture telescopes
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 can be
achieved by a lightweight sensor system. For conventional systems, 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 the misalignments, such as lenses or mirrors, using
deformable mirror by feedback control using observed images. In remote
sensing, it is difficult to use a reference point source unless the satellite
tools its attitude toward a star. We propose the control algorithm of the
deformable mirror for the extended scene such as earth observation. Our
laboratory experiment showed that misalignment of the optical element was
compensated using deformable mirror by optimizing an image metric value.

9760-14, Session 4
Mechanically flexible waveguide arrays for
optical chip-to-chip coupling
Tjitte-Jelte Peters, Marcel Tichem, Technische Univ. Delft
(Netherlands)

This paper reports on the fabrication of mechanically flexible photonic
waveguide structures in the TriPileX material platform (i.e. a Si3N4 core
within a SiO2 cladding). These waveguide structures are part of an
alignment concept, which aims to achieve submicrometer alignment of
the waveguides of two photonic integrated circuits (PICs). The concept
consists of two steps: moderate alignment through chip-to-chip positioning
and bonding, followed by high precision alignment by on-chip positioning of mechanically flexible waveguide structures. This paper presents the fabrication of suspended TriPleX waveguide arrays and proves their suitability for the alignment concept.

The realized flexible waveguide structures consist of parallel cantilevered waveguide beams and a crossbar connecting their free ends. The compressive mean stress in the SiO2 introduces the risk of fracturing during the fabrication of suspended TriPleX structures. Depending on the designed shape of the waveguide structure, the expansion of the Si1.5ym thick TriPleX stack causes stress concentrations during the release, leading to fracturing. We demonstrate a fabrication method for the reliable release of flexible TriPleX structures. The realized suspended structures have a natural out-of-plane deflection due to mean and gradient stresses. The profiles of the waveguide beams have two components: a negative slope at the base of the cantilever (between -0.5° and -0.6°) and a concave upward deflection with a constant radius of curvature (between 250nm and 500nm). The characterization of suspended TriPleX waveguide structures provides design guidelines for both the implementation of the alignment concept and the use of suspended TriPleX waveguides in general.

9760-15, Session 4
Mechanically-tunable photonic crystal split-beam nanocavity
Tong Lin, Guangya Zhou, Fook Siong Chau, Yongchao Zou, National Univ. of Singapore (Singapore); Jie Deng, Institute of Materials Research and Engineering, A*STAR (Singapore)

Photonic crystal split-beam nanocavities are used as ultra-sensitive optomechanical transducers but their efficacy is degraded due to their relatively low optical quality factors. We proposed and experimentally demonstrated a new type of one-dimensional photonic crystal split-beam nanocavity that is optimized for ultra-high optical quality factors. The design is based on the combination of the deterministic method and hill-climbing algorithm. This split-beam nanocavity is made up of two mechanically uncoupled cantilever beams with Bragg mirrors patterned onto it and separated by a 75 nm air gap. Experimental results show that the quality factor of the second-order TE mode can be as high as 1.99?10^4. Additionally one beam of the device is actuated in the lateral direction with the aid of a NEMS actuator and the quality factor is found to be maintained for lateral offsets of up to 64 nm.

9760-16, Session 4
Narrowband MEMS thermal emitters for IR applications
Ross P. Stanley, Branislav D. Timotijevic, Rolf Eckert, Andrea L. Dunbar, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

With nanophotonics we play with light at the wavelength scale while with MEMS we fabricate silicon microsystems to manipulate light. The two meet at infrared wavelengths where wavelength scale structuring matches with MEMS fabrication technology.

Despite the wide diversity of available infrared light sources, there is no equivalent in the infrared of a light emitting device (LED), i.e. an intense light source having a limited spectral linewidth, a good directionality that is easy to manufacture and inexpensive. Here we show that the combination of plasmonics and MEMS leads to novel thermal emitters with controllable linewidth and directionality.

The device is consists of a silicon nitride (SiN) membrane resting on a silicon support. The membrane is perforated with periodic holes and partly metalized. The role of a metal layer is twofold: first, to provide access to electrodes which will be used to heat up the membrane through the Joule heating and second, to tailor the behaviour of plasmons which in turn govern the thermal emission of the MEMS devices. Microfabrication follows relatively simple process flow. Standard UV photolithography, sputtering of the metal and back KOH etching are used to fabricate suspended micron hole arrays in metalized ultra-thin (<500nm) SiN membranes. An FTIR is used to optically characterize these plasmonic emitters by measuring their spectral and angular emission as well as their duty rate. We contrast these emitters with other thermal currently on the market and discuss the reasons for the improvements seen and the challenges in further improving thermal emitters.

9760-18, Session 5
Tunable MEMS Fabry-Pérot filters for infrared microspectrometers: a review (Invited Paper)
Martin Ebermann, Norbert Neumann, InfraTec GmbH (Germany); Karla Hiller, Mario Seifert, Technische Univ. Chemnitz (Germany); Marco Meinig, Steffen Kurth, Fraunhofer-Institut für Elektronische Nanosysteme (Germany)

Infrared spectroscopy is a powerful analysis method, because many substances can be distinguished reliably by their unique absorption spectra. Conventional infrared spectrometers are complex and expensive instruments with limited portability because of their size and power consumption. Application fields including medical diagnostics and detection of hazardous substances require small, robust and transportable spectrometers, which are considerably less costly than existing products. Therefore microspectrometer technologies are rapidly emerging and many research groups all over the world spend effort on this.

For visible and the near-infrared wavelengths diverse solutions based on gratings and detector arrays were established. However, for the mid-wave and long-wave infrared (3…12 m) they have not been successful for two reasons: limited optical throughput and costly array detectors. Fourier type spectrometers (e.g. Michelson interferometers) on the other hand are very difficult to implement in MEMS technology due to their complex optical setup. In contrast, micromachined Fabry-Pérot (FP) interferometers as tunable micromachined filters (µFP filters) seem to be the best solution in terms of miniaturization and optical throughput.

The present paper is a review of µFP filters for spectroscopic use, in particular for infrared wavelengths. Different approaches from several research groups are compared including surface micromachined filters with free standing reflector membranes (e.g. VTT, Denmark, Yokogawa, University of Western Australia) as well as bulk micromachined filters constructed of bonded wafers (e.g. Axsun Technologies, InfraTec, Teledyne Scientific). Optical performance parameters like wavelength tuning range, spectral resolution and aperture size as well as complexity of fabrication and costs are discussed.

9760-19, Session 5
VIS Fabry-Pérot-interferometer with (LH)4 PE-SiO2/PE-Si3N4 reflectors on freestanding LP-Si3N4 membranes for surface enhanced Raman spectroscopy
Christian Helke, Technische Univ. Chemnitz (Germany); Marco Meinig, Fraunhofer-Institut für Elektronische Nanosysteme (Germany); Mario Seifert, Jan Seiler, Karla Hiller, Technische Univ. Chemnitz (Germany); Steffen Kurth, Thomas Gessner, Fraunhofer-Institut für Elektronische

Conference 9760: MOEMS and Miniaturized Systems XV
Deeply-etched micromirror with vertical slit and metallic coating enabling transmission-type optical MEMS filters

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Optical filters are basic building blocks for many applications in optical telecommunications, biomedical optics, atomic and chemical analysis, where the application of the MEMS technology allows system miniaturization and low-cost production. MEMS filters with out-of-plane optical axis, with respect to the substrate, are formed using high-quality dielectric coating of the wafer top surface, which results in high optical performance but with the expense of difficulty and cost in optical assembly with other optical components. On the other hand, MEMS filters with in-plane optical axis enable the monolithic integration of the whole optical system on-chip. However, achieving dielectric coating on vertically etched surface is challenging and, therefore, Bragg silicon/air layers are usually etched to achieve the filter, where the dimensions are limited by the control of the deep etching process. In this work we report a novel optical MEMS deeply-etched mirror with metallic coating and vertical slot, where the later allows reflection and transmission by the micromirror. Thanks to the SOI technology, the release of the micromirror and its attachment to an electrostatic actuator is possible; and the microsystem is fabricated using deep reactive ion etching technology. The spectrometer is successfully used in measuring the absorption spectra of methylene chloride, quartz glass and polystyrene film. The presented solution provides a low cost method for producing miniaturized spectrometers in the near-/mid-infrared.

Novel Fourier transform infrared spectrometer architecture based on cascaded Fabry-Perot interferometers

Yomna Eiltagouery, Ain Shams Univ. (Egypt); Yasser M. Sabry, Diaa A. Khalil, Ain Shams Univ. (Egypt) and Si-Ware Systems (Egypt)

Miniaturized MEMS spectrometers are gaining wide attention due to their wide spectrum potential applications. Conventional Fourier Transform (FT) spectrometers are based on scanning Michelson interferometer, where the precise alignment of the micro-sized beam splitter and the mirrors is difficult. An additional challenge for deeply-etched silicon structures is the need for anti-reflective coating on one of the beam splitter surfaces. It is also possible to build a FT spectrometer using low reflectivity Fabry Perot (FP) interferometer however, in this case, when the input is a white light source, it is quite difficult to measure the most important part of the interferogram located near the zero optical path difference. In this work, we present a novel architecture for Fourier transform spectrometers based on cascaded low-finesse FP interferometers. One of the interferometers has fixed path length while the second is a scanning interferometer output to a PbSe photoconductive detector. The spectral range of the presented spectrometer is 1200-4800 nm, where the upper value is limited by the used detector. The recorded signal-to-noise ratio is 25 dB at the wavelength of 3350 nm. The spectrometer is successfully used in measuring the absorption spectra of methylene chloride, quartz glass and polystyrene film. The presented solution provides a low cost method for producing miniaturized spectrometers in the near-/mid-infrared.
simple MEMS process flow without metallization or dielectric coating of the vertical optical surface. The fabricated compact structure is measured with both a laser source with narrow spectrum at 1550 nm and a wide spectrum source composed of an SLED and the ASE of a semiconductor optical amplifier source. The obtained results validate the concept of the new configuration.

9760-23, Session 5

MOEMS FPI sensors for NIR: MIR microspectrometer applications

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Optical MEMS-based microspectrometers enable small, mass producible sensors with potential for application in novel products based on identification of spectral fingerprints. In recent years, Fabry-Perot interferometer (FPI) technology has been demonstrated in various novel microspectrometer applications ranging from mobile gas sensing to medical- and environmental monitoring applications. This presentation focuses on the near- and mid- infrared (NIR-MIR) wavelength range MEMS devices, targeted for automotive and multi-gas sensing applications. MEMS FPI platform for NIR-range consist of LPCVD (low-pressure chemical vapour) deposited polySi-SiN7/4-thin film Bragg reflectors, with the air gap formed by sacrificial SiO2 etching in HF vapour. Characterization results for the devices for ? = 1.5 – 2.0 range are presented, with FWHM of 15 nm at the optimization wavelength of 1750 nm. Comparison is made to the lower-NIR devices, in which the substrate below the optical aperture is removed by inductively coupled plasma (ICP) resulting in a structure with free lower mirror. We also present the characterization results of a new MEMS chip prototype for ? = 2.6 – 3.6 ?m, which utilizes silicon and air in within the Bragg reflector structure to provide a high contrast for improved resolution. Results show a very narrow transmission peak width with FWHM = 18 nm in comparison to previous structure with conventional CVD-thin film materials (FWHM = 50 nm). The improved resolution and the extended operation region shows potential to enable simultaneous sensing of CO2 and hydrocarbons.

9760-24, Session 6

Ultra-slim 2D- and depth-imaging camera modules for mobile imaging (Invited Paper)

Andreas Brückner, Alexander Oberdörster, Jens Dunkel, Andreas Reimann, Frank C. Wippermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

With billions of shipped devices each year the mobile imaging market is the biggest existing market for optical imaging technologies in the world. During the last decade, the role of camera modules in cell- and smartphone products tremendously increased so that they became one of the key differentiators for the buyer’s choice. It is not surprising that this led to a rising number of innovations in digital imaging, however, mostly found in the CMOS image sensor hard- and image processing software. Disruptive optical solutions like array cameras or light field imaging techniques are hardly found. Though conventional camera optics have a huge problem – the z-height of the lens stack causing the camera module to stick out of a nicely slim designed product. We propose a multi aperture imaging system which captures different portions of the field of view (FOV) within separated optical channels on a single CMOS image sensor chip. The different partial images are joined digitally to reconstruct an image of the full FOV. The segmentation partly decouples the tradeoff between focal length and size of the FOV. The advantage is twofold: The z-height of a camera module can be decreased by up to 50% and the optics setup is easier to manufacture. The realization of such multi aperture objectives is feasible with adapted micro-fabrication techniques such as diamond milling, step and repeat micro-imprinting and UV-molding. Alignment and assembly are partially carried out on wafer-level. The optical design, technological realization and test of such a multi aperture system are discussed for the example of a 2mm-thin camera module with HD resolution. Along with the video imaging performance we demonstrate software refocussing and the ability to acquire depth maps within a single camera module.

9760-25, Session 6

Micro Fabry-Perot cavities for self-calibrating accelerometers

Thomas W. LeBrun, National Institute of Standards and Technology (United States)

We describe the application of micro Fabry-Perot cavities to develop self-calibrating accelerometers designed to surpass the performance of the best calibration systems available. Two fabrication processes have been used: glass micromachining and traditional semiconductor fabrication in silicon, leading to two device families. Glass micromachining leads to high-mass flexure-based devices that measure acceleration in the plane of the substrate, while Si-based fabrication leads to out-of-plane sensing using more ideally constrained proof masses with lower guiding errors. We compare the performance of the devices as optical resonators, mechanical resonators, and accelerometers. We also evaluate the performance of self-calibration and the prospects for achieving an acceleration sensitivity limited by the thermal motion of the mechanical resonator. Readout schemes emerge as a challenging part of the problem, as traditional cavity locking techniques have difficulty following the length excursions of micro cavities with high free spectral range. We compare readout approaches and discuss preliminary tests of readout using low-cost frequency combs, as well as other applications of the cavities to precision measurement and sensing.

9760-26, Session 6

Study on sputtered a-Si:H for micro optical diffusion sensor using laser-induced dielectrophoresis

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In this study, a MEMS sensing device, which is applicable to point-of-care testing (POCT), is developed by integrating an optical manipulation and detection technique. The diffusion coefficient is a parameter, which is sensitive to the size, the construction and the interaction of the sample, thus, the measurement of the diffusion coefficient of the bio-sample, such as proteins, is useful for the clinical diagnosis to detect interactions and conformational changes with high sensitivity. Several diffusion sensing methods have been developed, however, the technique applicable to POCT is not established because of the difficulties due to the requirement of the measurement in a short time and a small sensing device. In this study, in order to realize a high-speed detection (ms - s) with small sample volume (~ ?l) and small apparatus (tens of cm) without particular preparations, micro optical diffusion sensor utilizing laser-induced dielectrophoresis (LIDEP), which is a manipulation technique based on optoelectronic tweezers, is developed. The microscale concentration distribution is formed in the microchannel by LIDEP and plays a role of the transient diffraction grating, then, the diffusion phenomenon is optically observed. For these techniques, a photoconductive layer is essential, and a hydrogenated amorphous silicon (a-Si:H) deposited by a plasma-enhanced chemical vapor deposition is generally utilized as the layer. In this study, the a-Si:H is deposited using a plain reactive RF magnetron sputtering method under several conditions, while changing the source gas compositions. The sensing device is
has been designed, fabricated and tested: by tailoring the MMA. We could spectrum could be tailored thanks to a 2D micromirror array. A mock-up in Earth Observation, we propose an innovative reconfigurable instrument, telescope during next year. spectrograph demonstrator called BATMAN, to be placed on 3.6m TNG mask for astronomical object selection. We are developing a MMA-based tools for space and ground-based telescopes for the study of the formation and evolution of galaxies. This technique requires a programmable slit for previously reported PZT resonant micromirrors, which is based on embedded capacitive position sensors. The driving ASIC (application specific integrated circuit) takes advantages of low driving voltages offered by the PZT actuation and the well-established low-power concepts for capacitive closed-loop circuits. For closed-loop operation and the detection of the mirror-plate position two capacitances are embedded below the mirror-plate constituting differential position sensors. The vertical construction of the micromirror and the electronic applies a low-cost technology with great reliability and minimizes the footprint of the system. By applying a biasing voltage to the polysilicon substrate of the micromirror, the obtained position signal of the mirror-plate is scalable and the detecting precision is considerably enhanced. Moreover, the requirements for the subsequent interface-electronic are relaxed due to large signal amplitudes up to 1.5 V and high SNR up to 84 dB. These signals are obtained already at a small mechanical scan angle of the micromirror of 2°, so that the capacitive signals at the micromirror’s total scan angle can enable a high resolution of 14 bit. The total power consumption of the closed-loop system, including the driving ASIC and the micromirror, is 0.86 mW, which is the lowest reported value in literature. Therefore, this system combining the micromirror and the controlling-electronic are appropriate for applications requiring low-power consumption and small dimensions. Measurement results of the closed-loop driven micromirror system are presented, demonstrating its competitiveness due to the great reliability, high precision and low-power consumption.

Large arrays of micro-mirrors in future space instruments for universe and Earth observation (Invited Paper)

Frédéric Zamkotsian, Patrick Lanzoni, Lab. d’Astrophysique de Marseille (France)

In future space missions for Universe and Earth Observation, scientific return could be optimized using MOEMS devices. Large micromirror arrays (MMA) are used for designing new generation of instruments. Mock-ups have been designed and built for both applications and they show very promising results.

In Universe Observation, multi-object spectrographs (MOS) are powerful tools for space and ground-based telescopes for the study of the formation and evolution of galaxies. This technique requires a programmable slit mask for astronomical object selection. We are developing a MMA-based spectrograph demonstrator called BATMAN, to be placed on 3.6m TNG telescope during next year.

In Earth Observation, we propose an innovative reconfigurable instrument, a programmable wide-field spectrograph where both the FOV and the spectrum could be tailored thanks to a 2D micromirror array. A mock-up has been designed, fabricated and tested by tailoring the MMA. We could modify successfully each pixel of the input image: it is possible to remove bright objects or, for each spatial pixel, modify the spectral signature.

In parallel with new instrument concepts and demonstrator developments, we are currently engaged in a European development of micro-mirror arrays exhibiting remarkable performances in terms of surface quality as well as ability to work at cryogenic temperatures. MMA with 100 x 200 µm2 single-crystal silicon micromirrors were successfully designed, fabricated and tested down to 162 K. In order to fill large focal planes (mosaicing of several chips), we are currently developing large micromirror arrays integrated with their electronics.

Novel multi-aperture approach for miniaturized imaging systems

Frank C. Wippermann, Andreas Brückner, Alexander Oberdörster, Andreas Reimann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The vast majority of cameras and imaging sensors relies on the identical single aperture optics principle with the human eye as natural antetype. Multi-aperture approaches – in natural systems so called compound eyes and in technology oftentimes referred to as array cameras – have advantages in terms of miniaturization, simplicity of the optics and additional features such as depth information and refocusing enabled by the computational manipulation of the system’s raw image data. The proposed imaging principle is based on multitude of imaging channels transmitting different parts of the entire field of view. Adapted image processing algorithms are employed for the generation of the overall image by the stitching of the images of the different channels. The restriction of the individual channel’s field of view leads to a less complex optical system targeting reduced fabrication cost. Due to a novel, linear morphology of the array camera setup, depth mapping with improved resolution can be achieved.

We introduce the novel concept for miniaturized array cameras with several mega pixel resolution targeting high volume applications in mobile, environmental, medical and automotive imaging with improved depth mapping and explain design and fabrication aspects.

Two-fluid variable focus micro-lens with a large deflection polymer actuator

Florenta A. Costache, Boscij Pawlik, Christian Schirrmann, Kirstin Bornhorst, Andreas Rieck, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

This paper presents the design and fabrication of a compact micro-lens with a focal length that is variable in a wide range consisting of two microfluidic chambers filled with fluids, bonded together and sealed in between by a deformable elastomeric membrane. The shape and curvature of the lens membrane is controlled via the hydraulic pressure exerted by a liquid pumped against it with an electromechanically driven actuator. A ring-shaped bending actuator based on the relaxor ferroelectric PVDF-TrFE-CFE terpolymer, which exhibits very high electrostrictive strain, ensures a large and homogeneous deformation of the lens membrane. Liquids of different refractive indices and low membrane permeability were inserted in the chambers to optimize the focal length change and the lens membrane deformation stability to the effect of gravity.

This lens concept is the result of multiple domains 2D / 3D FEM simulations, which were employed to understand the electromechanical behavior of the bending actuator and optimize the lens design. In the simulation, the actuator stack geometry and the electrode material were adjusted to improve upon the actuator deflection.

A fabrication process flow included: layer-by-layer processing of the actuator stack; micro-machining of microfluidic chambers on silicon and
glass wafers; device assembly including actuator and lens membrane bonding and structuring, wafer direct bonding, liquid filling and sealing. The 3 mm aperture micro-lens enables focal length changes up to 10 dpt – corresponding to actuator deflections of about 100 µm – for moderate driving voltages and can be designed either in a plano-convex or plano-concave configuration.

9760-31, Session 7

**Miniature electrically tunable rotary dual-focus lenses**

Yongchao Zou, Wei Zhang, National Univ. of Singapore (Singapore); Tong Lin, Micro and Nano Systems Initiative, National University of Singapore (Singapore); Fook Siong Chau, Guangya Zhou, National Univ. of Singapore (Singapore)

The emerging dual-focus lenses are drawing increasing attention recently due to their wide applications, including laser cutting systems, holography and surface profilers. In this paper, a miniature electrically tunable rotary dual-focus lens is demonstrated. Such a lens consists of two optical elements, each having an optical flat surface and one freeform surface. The two freeform surfaces are initialized with the governing equation $Ar^2$ (A is the constant to be determined, r and $\theta$ denote the radii and angles in the polar coordinate system) and then optimized by ray tracing technique with additional polynomial terms for aberration correction. The freeform surfaces are created by a single-point diamond turning technique. A PDMS-based replication process is then utilized to materialize the final lens elements. To drive the two coaxial elements rotating independently, two MEMS thermal rotary actuators are developed and fabricated by a standard MUMPs process. Experimental results show that the MEMS thermal actuator provides a maximum rotary angle of about 10 degrees with an input DC voltage of 6 V, leading to a large tuning range for both the two focal lengths of the lens. Specifically, one focal length of the lens can be tuned from about 24 mm to 37 mm while the other one can be adjusted from about 37 mm to 90 mm.

9760-32, Session 7

**NanoPlasmonics tunable filter using NEMS technology**

Mohamed A. Swillam, Kareem Khirallah, The American Univ. in Cairo (Egypt)

Novel active resonance wavelength tuning scheme of plasmonics optical filter is proposed and discussed. The design is based on controlling the relative position between two stubs in metal-insulator-metal plasmonics waveguide using NEMS technology. The analysis of the optical design as well as the mechanical design is performed. Finally, a reasonable fabrication process of the device is proposed. For the suggested mechanical design parameters, the optical resonance wavelength can be tuned from 1.45 micrometer to 1.6 micrometre using 7VDC actuation voltage.

9760-35, Session 7

**Transition of optical regime in miniaturized optical systems: Light interactions beyond the refraction limit**

Myun-Sik Kim, Ecole Polytechnique Fédérale de Lausanne (Switzerland) and SUSS MicroOptics SA (Switzerland); Toralf Scharf, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Carsten Rockstuhl, Karlsruhe Institute of Technology (Germany); Wataru Nakagawa, Montana State Univ. (United States); Reinhard Vökel, SUSS MicroOptics SA (Switzerland); Hans Peter Herzig, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

In the miniaturized optical systems, the light response and interaction are often different from conventional pictures. Optical effects strongly depend on the size of optical components. We investigate the transition of optical regimes of miniaturized optical systems using two examples, a ball-lens and a solid immersion lens (SIL).

For the ball-lens examples, we investigate experimentally and theoretically the electromagnetic field behind ball-lenses across a wide range of diameters (from a millimeter scale down to a micrometer). Three different criteria are used to identify the refraction limit: the focal length, the spot size, and the amount of cross-polarization generated in the scattering process. For an ordinary glass as the ball-lens material at $\lambda = 642$ nm, we identify a diameter of approximately 10 µm as the refraction limit, where the emergence of the photonic nanojet overwhelms the cusp catastrophe. For the SIL examples, we investigate the light confinement effect observed in non-ideally shaped (i.e., non-spherical) nanoscale solid immersion lenses. When completely melted in reflow, non-circular pillars become spherical, while incomplete melting results in non-spherically shaped SILs. For such small-size SILs (wavelength or sub-wavelength scale), aberrations are negligible due to the short optical path length. Consequently, non-ideal SILs exhibit a spot size reduction comparable to that of spherical SILs.

In conclusion, beyond the refraction limit, the refractive interaction of light becomes less prominent, and it starts to minimize the influence of shape errors of optical elements. With our study we shed new light on the means necessary to describe miniaturized optical systems.

9760-17, Poster Session

**Optically pumped 1550nm wavelength tunable MEMS VCSEL**

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We present a novel design of an optically pumped 1550nm tunable MEMS VCSEL design with an enclosed MEMS structure. The enclosed structure is defined by direct bonding of SOI with MEMS to an InP wafer with quantum wells using Al2O3 as an intermediate layer. The design will bring in a great amount of flexibility where we can mix-n-match different active layers to MEMS structures to fabricate MEMS VCSELS for a wide range of wavelengths. The two mirrors for the MEMS VCSEL are defined by a High Contrast Grating MEMS structure on a SOI and 8 pairs of SiO2-TiO2 dielectric layers deposited on the top. The top DBR has been optimized for the device to get efficiently pumped at 1300nm and lase at 1550nm. There is no mesa structure defined with InP. The presence of InP layer over the entire chip helps in transfer of heat away from the lasing region. Also, metal pads are placed close to the device to study the dissipation of the generated heat. The paper will also discuss the effect of stiffness of the MEMS frame on the bandwidth of operation and the tuning range. The tunable MEMS VCSEL discussed has the potential to play a primary role as a swept source in OCT technology.

9760-33, Poster Session

**Analysis in effects of aperture size and applied voltage on the response time**

YooKwang Kim, Jin Su Lee, Yong Hyub Won, KAIST (Korea, Republic of)

Electrowetting lens is a promising technique for non-mechanical vari-focal...
lens, because of fast response time, wide expressible diopter, and etc. Although electrowetting related papers are actively published, no one did not clearly define the relationship among electrowetting parameters, especially in AC driven case. Analysis for AC voltage driving is needed because AC electrowetting has many advantages like low hysteresis and short settling time. In this experiment we confirmed that the response time depends on aperture size and applied voltage. Response time measurement for lens aperture of 200-1000um and applied voltage of 0-70V with 1kHz frequency was conducted. Experimental data was compared with simulation result by COMSOL Multiphysics program with the same condition, and they correspond with each other well. As voltage increases, the overshoot height becomes higher, so it has longer oscillation and settling time. On the other hand if aperture size decreases, the surface tension of lens wall could be delivered effectively to the center region of meniscus, so it has less oscillation and shorter settling time. The result was that in 500um aperture no more than 30V should be applied to ensure 1ms response time. In 200um aperture, the voltage limit increased to 70V.

9760-34, Poster Session

**A handheld confocal microscope for 3D biopsies**

Wibool Piyawattanametha, King Mongkut’s Institute of Technology Ladkrabang (Thailand)

Intravital single-axis confocal (SAC) microscope is a versatile tool in disease diagnosis enabling high-resolution three-dimensional (3-D) capability for imaging biological tissues. Its unique features are derived from a high numerical aperture (NA) lens to achieve high lateral resolution, and its optical sectioning property from a pinhole placed in front of the detector to reject out of focus light. Therefore, a high-resolution 3-D image from highly scattering media can be reconstructed by successively scanning each 2-D focal imaging plane. Furthermore, the combination of confocal and fluorescence microscopy, by fusing fluorescent molecules to proteins or enzymes to study cellular or molecular processes, heralds a new in vivo imaging era. As a result, in vivo 3-D functional images obtained from the combined techniques are unmatched by other imaging modalities. Nonetheless, SAC microscopes have trade-offs among resolution, field of view (FOV), and objective lens size, since a high NA objective is needed for sufficient resolution, and a long focal length is needed for a large FOV and working distance (WD). The dual-axis confocal (DAC) microscope architecture has been proposed utilizing two low NA objectives providing overlapping long working beams circumventing above tradeoffs. In this work, we present a handheld MEMS-scanner-based DAC microscope capable of 3-D real-time imaging for biopsy imaging.
The next generation of maskless lithography (Invited Paper)

Steffen Diez, Heidelberg Instruments Mikrotechnik GmbH (Germany)

The essential goal for fast prototyping of microstructures is to reduce the cycle time. Until now, conventional methods consist of creating designs with a CAD software, then fabricating or purchasing a Photomask and finally using a mask aligner to transfer the pattern to the photoresist. The cycle time for this traditional process is mainly defined by the Photomask fabrication process, which can take from several hours to many days. Changes in the artwork means fabricating a new Photomask.

The Maskless Aligner makes it possible to expose the pattern directly without fabricating a mask, which results in a significantly shorter prototyping cycle. Introducing a new optical engine based on the DLP™ device has considerably increased the writing speed. A big advantage of the DLP™ system is the possibility of using incoherent light sources. We have implemented a high power fiber-coupled diode laser to have enough intensity to also expose thick and low-sensitive resists. To further reduce the cycle time, we have optimized the alignment and exposure procedure to achieve a set-up time of only a few minutes. With all these efforts, we were able to reduce the cycle drastically in comparison to traditional UV Lithography.

Besides the obvious saving of time, the direct writing process offers a lot of additional advantages:

The alignment procedure is straightforward and very precise, because it only requires capturing the image of the alignment marks and applying image-processing algorithms to determine the position of the marks. Instead of spending additional time for mechanical compensation of displacements, all compensations are done in software. The software can compensate offset, rotation, scaling and orthogonality.

Real-time imaging inside the camera’s field of view, allows for exposing small patterns directly without creating and fracturing the design. Automatic labeling of wafer or wafer dies makes tracking and organization much easier. A real-time autofocus system guarantees good exposure even with non-uniform substrates and allows defining the focus-level in order to optimize the exposure quality.

Last but not least, the MLA is more economical than standard UV Lithography. The running costs are similar to those of the Mask Aligners. But you save the costs of Photomasks and thus also the equipment for cleaning, inspecting and storing of Photomasks.

The MLA is a new generation of lithography system, based on a disruptive technology, with the clear goal to replace conventional UV lithography in the research community.

Metal powder laser melting with variable mask image amplification systems using TI DMD, pulsed Nd:YAG lasers, and amplifiers

Farzan N. Ghauri, VardeX Laser Solutions LLC (United States)

Direct metal powder laser melting methods based on projection of amplified images provide better throughput performance compared to scanning based selective melting. A Texas Instrument Digital Micromirror Device (DMD) is used as a Variable Mask to generate images, the images are amplified to reach high peak power densities sufficient to melt metal powders over large areas (several mm²). Results are presented for an image amplification based metal powder melting system using Nd:YAG laser and amplifier(s).

A comparison of DLP-based 3D scanning methods to traditional methods

Badia Koudsi, Hakki H. Refai, Optecks, LLC (United States)

3D scanning of objects is an essential step in the construction of 3D models for use in applications as varied as archeology, fashion, medicine, security, and entertainment. For accurate and timely model construction, the 3D scanner must provide a wealth of high-resolution data in a short period of time. The cost and ease with which a person with limited technical knowledge can successfully operate the scanner are additional factors in whether 3D scanning and modeling are adopted for a given application.

We present the development of a DLP-based 3D scanner using active triangulation and compare its capabilities to those of existing 3D scanning systems. The DMD and its controlling DLP board are used to improve the properties of the illuminating source and its interaction with the sensor and processing systems. The flexibility and resolution of the DMD are shown to allow rapid display of a variety of very high resolution patterns in multiple colors, and thus increasing the resolution and depth of field of the scanning system, reducing the color-dependence of the system performance, and allowing color encoding to increase the information contained in the collected data. Example cases are presented to compare the capabilities of the DLP-based system and to demonstrate the magnitude of increased performance with respect to comparable non-DLP-based systems. The ability of the DLP to rapidly display calibration patterns in addition to data-collecting patterns that allow rapid, automatic system calibration, including synchronization between the source and sensors, is also discussed.

Wavefront shaping optical coherence tomography using a digital micromirror device for enhancing penetration depth in biological tissues (Invited Paper)

YongKeun Park, KAIST (Korea, Republic of)

Optical coherence tomography (OCT) is a non-invasive optical technique based on coherence gating. The penetration depth of OCT is limited up to a few millimeters, and can be further reduced when imaging highly turbid sample such as skin tissues. The limitation of the penetration depth in OCT is mainly resulted from multiple scattering. In OCT, only single back-scattered light is regarded as signal which exponentially decays as the penetration depth increases.

To address this issue, we showed that complex wavefront shaping in OCT can suppress multiple scattering and demonstrated the enhancement of the penetration depth and signal-to-noise ratio. The back-scattered coherence-gated light is utilized as the feedback to find the optimal incident wavefront, which maximizes the light delivery to a target depth. We achieved a high-speed synchronization between the wavefront shaping control using a dynamic micromirror device. We measured depth-enhanced 2-D OCT images with various tissue phantoms in which transport mean free paths are systematically varied. The enhancements of the penetration depth up to
Digital micromirror device (DMD) based fast digital optical phase conjugation (DOPC) system

Haojiang Zhou, California Institute of Technology (United States); Daifa Wang, California Institute of Technology (United States) and BeiHang Univ. (China); Joshua Brake, Changhuei Yang, California Institute of Technology (United States)

The optical opacity of tissue has long been one of the greatest challenges in biomedical optics as the strong scattering nature of biological tissue makes it difficult to focus light at depths greater than a few hundred microns. However, recent advances in the field of wavefront shaping such as optical phase conjugation (OPC) promise ways to overcome this challenge. Digital optical phase conjugation (DOPC) is particularly attractive as it intrinsically achieves a high fluence reflectivity in comparison to non-linear OPC approaches. However, two major obstacles for DOPC systems have been slow speed due to the low refresh rates of the LCOS-SLMs (Liquid Crystal on Silicon-Spatial Light Modulator) and high data throughput requirements. Thus far these limitations have made it difficult for DOPC systems to achieve playback latencies shorter than 200 ms and therefore have prevented DOPC from being practically applied to thick living samples. In this paper, we report a novel DOPC system whose playback latency is ~5.3 ms. This speed improvement of nearly two orders of magnitude is achieved by using a DMD (digital micromirror device) in place of the slower LCOS-SLM, field programmable gate array (FPGA) processing, and a single-shot binary phase retrieval technique. With this system, we demonstrate the ability to focus light through 2.3 mm living mouse dorsal skin with blood flowing through it (decorrelation time ~30 ms) and maintain the focus indefinitely.

Digital micromirror device based multispectral retinal imaging using optimized illumination schemes

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Multispectral imaging of the ocular fundus has attracted abundant interest in recent years. Having spectral information available at each spatial imaging point enables the quantitative imaging of physiological parameters. Multispectral imagers are usually based on a fundus camera or Scanning Laser Ophthalmoscope (SLO) design. We present initial results of a Digital Micro-mirror Device (DMD) based multispectral confocal SLO with LEDs as illumination source. The DMD does not need any scanning mirrors, operates at very high speeds, thereby reducing motion artifacts and offers flexibility to optimize the illumination scheme for fixation and Signal-to-noise-ratio (SNR).

The current version of our system uses the DMD to create parallel scanning spots/lines in the retina. The reflected light is collected using a CMOS camera and the confocal image is produced in post-processing. The modular design of the system also allows different wavelengths to be introduced easily at low cost.

Our initial experiments using a model eye with an artificial retina consisting of a scattering layer with scattering coefficient of 10mm-1 indicates that the system can acquire a multispectral image pattern of three different wavelengths in the 650-850 nm range in 30 ms exposure time. A full three wavelength image is produced in 600ms. The mean SNR of the image was 4 and the field of view was 23x17 degrees. By combining the advantages offered by the DMD technology and multispectral imaging, we aim to make the imager suitable for quantitative analysis with application to the diagnosis and screening of eye diseases.
We apply a near infrared (NIR) dynamic scene projection system to perform hardware-in-the-loop (HWIL) testing of a unit under test operating in the NIR band. The common and complex requirement of a class of these units is a dynamic scene that is spatio-temporal variant. We use digital micromirror devices (DMDs) integrated as the core of a NIF projection system to generate these dynamic scenes. We deploy the spatial pattern to the DMD controller to simultaneously yield the required amplitude by pulse width modulation (PWM) of the mirror elements as well as the spatial-temporal pattern. Desired modulation and coding of high stable, high power visible (Red laser at 633 nm) and NIR (Nd:YAG laser at 1064 nm) using the combination of different optical masks based on DMD were achieved. These spatial versatile active coding strategy at high frequencies in the range of kHz for irradiance of different targets were investigated and recorded using VIS-NIR fast cameras. The temporally-modulated laser pulse traces were measured using array of fast response photodetectors. Finally using a high resolution spectrometer, we evaluate the NIF dynamic scene projection system response in terms of preserving the wavelength and band spread of the NIF source after projection.

9761-11, Session 5
Real-time video imaging of gas plumes using a DMD-enabled full-frame programmable spectral filter
David L. Graff, Steven P. Love, Los Alamos National Lab. (United States)
Programmable spectral filters based on digital micromirror devices (DMDs) are typically restricted to imaging a 1D line across a scene, analogous to conventional “push-broom scanning” hyperspectral imagers. In previous work, however, we demonstrated that, by placing the diffraction grating at a telecentric image plane rather than at the more conventional location in collimated space, a spectral plane can be created at which light from the entire 2D scene focuses to a unique location for each wavelength. A DMD placed at this spectral plane can then spectrally manipulate an entire 2D image at once, enabling programmable matched filters to be applied to real-time video imaging. We have adapted this concept to imaging rapidly evolving gas plumes. We have constructed a high spectral resolution programmable spectral imager operating in the shortwave infrared region, capable of resolving the rotational-vibrational line structure of several gases at sub-nm spectral resolution. This ability to resolve the detailed gas-phase line structure enables implementation of highly selective filters that unambiguously separate the gas spectrum from background spectral clutter. On-line and between-line multi-band spectral filters, with bands individually weighted using the DMD’s duty-cycle-based grayscale capability, are alternately uploaded to the DMD, the resulting images differenced, and the result displayed in real time at rates of several frames per second to produce real-time video of the turbulent motion of the gas plume.

9761-12, Session 5
DLP-based system for flexible and portable spectroscopic measurements
Badia Koudsi, Hakki H. Refai, Optecks, LLC (United States)
Spectroscopic measurements have the potential to positively impact a wide range of research, development, monitoring and control applications. In many cases, this potential is not realized because the spectrometer cannot be brought out of the laboratory to the measurement site due to sensitivities to environmental factors, highly accurate data cannot be obtained in a timely manner, or customizing the spectrometer to a specific application is costly and precludes re-use of the device for other applications once its original purpose is served. We present the development of a DLP-based spectroscopic system in the near-infrared that is low-cost, compact and rugged, provides high resolution and is highly adaptable through straightforward software control. The key elements of the design include an efficient and compact optical pathway, a high-resolution DMD controlled by a fast DLP board, and a user-friendly, feature-rich software package that facilitates system configuration and data analysis. The DMD replaces the detector array in traditional spectrometers, and is shown to provide greater functionality while eliminating the need for mechanical scanning. We demonstrate how the long, thin columns of mirrors in the DMD provide high wavelength selectivity and capture more light at each wavelength, increasing measurement SNR. Selectively activating columns of mirrors is shown to adaptively tailor the resolution and the wavelengths collected and analyzed by the system allow one device to meet the needs of many different applications and to reduce measurement times. The software interface developed for accessing the many features of the spectrometer is discussed.

9761-13, Session 5
Powerful DMD-based light sources with a high throughput virtual slit
Arsen Hajian, Edward A. Gooding, Thomas V. Gunn, Steven Bradbury, Hindsight Imaging, Inc. (United States)
As described above, the High Throughput Virtual Slit (HTVS) enables higher spectral resolution than is achievable with conventional spectrometers by manipulating the beam profile in pupil space. Conventional imaging spectrograph designs use lenses or toroidal mirrors to image the entrance slit onto the exit focal plane after dispersing the spectrum, conventionally in the horizontal direction. Most often, near 1:1 imaging optics are used in order to optimize both entrance aperture and spectral resolution. This approach limits the spectral resolution to the product of the dispersion and the slit width. Achieving high resolution in a small instrument necessarily requires a narrow entrance slit, which limits instrumental throughput (etendue). By reshaping the instrument pupil with reflective optics, HTVS-equipped instruments create a tall, narrow image profile at the exit focal plane, typically delivering 5X or better the spectral resolution achievable with a conventional design. This approach works equally well in DMD-based programmable light sources as in single stage spectrometers; indeed, in a multi-stage instrument, the HTVS advantage is cumulative. Assuming a 5X improvement in etendue, a 500 W source can be replaced by a 100 W equivalent, creating a cooler, more efficient tunable light source with equal power density over the desired bandwidth.

9761-26, Session 5
DLP NIRscan Nano: an ultra-mobile DLP-based near-infrared Bluetooth spectrometer
Pedro Gelabert, Eric Pruett, Gavin Perrella, Sreeram Subramanian, Aravind Lakshminarayanan, Texas Instruments Inc. (United States)
The DLP NIRscan Nano is an ultra-portable spectrometer utilizing DLP technology to meet lower cost, small size, and higher performance than traditional spectrometer architectures. The use of a DLP DMD over traditional array detector architecture provides the ability to provide programmable spectral filters and sampling techniques that are not previously possible. This paper presents the hardware, software, and optical systems, as well as, the design considerations on implementing a DLP-based spectrometer.
Adaptive, direct spectral imaging classification (Invited Paper)

Michael E. Gehm, Duke Univ. (United States)

Spectroscopic and spectral imaging measurements are frequently acquired for some underlying task such as detection or classification. In this presentation, we discuss our work on designing instrumentation that directly performs the spectral classification task without acquiring conventional spectral measurements.

In our approach, two 4-f spectrographs are separated by a Digital Micromirror Device (DMD), with the dispersion in the second spectrograph oriented in opposition to the first. This arrangement cancels wavelength-dependent spatial shifts, resulting in a proper spatial image, but with the DMD mirror pattern inducing spatially-variant spectral filters at every location in the scene. The acquired measurement (and knowledge of the applied filter) at each location in the scene is then fed to a Bayesian inference engine that updates probabilistic estimates of the class identity for each location. These estimates then inform a filter-design approach that computes the DMD pattern (and hence spectral filter pattern) that would be maximally-discriminating for the next acquisition. The DMD is updated with this pattern and the process repeats.

Extensive simulation and experiment demonstrate that this approach has a dramatic impact on performance, particularly in ultra-low SNR environments. Improvements of more than three orders of magnitude are demonstrated relative to conventional and random sampling methods.

Design of a multi-spectral imager built using the compressive sensing single-pixel camera architecture

Lenore McMackin, Matthew A. Herman, Tyler Weston, InView Technology Corp. (United States)

We present the design of an imaging spectrometer built using the architecture of the single-pixel camera. The architecture is enabled by the novel sampling theory of compressive sensing implemented optically using the Texas Instruments DLP™ micromirror array, which also provides unique diffractive spectral features that result in a multi-spectral, high-spatial resolution imager design.

The new camera design not only provides multi-spectral imagery in a wavelength range that extends from the visible to the shortwave infrared, but provides multiple spectral bands without reduction in spatial resolution. In addition to the compressive imaging spectrometer design we present a diffractive model of the architecture that allows us to predict a variety of detailed functional spatial and spectral design features.

In traditional CS, a data vector is formed by forming an image onto the DLP, modulating it with a series of patterns, then focusing it onto a detector and taking an intensity measurement for each modulation pattern. An image is computed by using the data vector to solve an inverse problem. The key idea in CS theory is that most signals are sparse in some domain, and exploiting sparsity allows the full resolution image to be computed from far fewer samples than traditional FPA-based imaging. Extension of the CS architecture to the multi-spectral imager requires only minor modifications combining the diffractive features of the DLP with an additional diffraction grating. We present modeling results, architectural design and experimental results that prove the concept.

Hyperspectral scanning white light interferometry based on compressive imaging

Mohammad Azari, Nasim Habibi, The Univ. of North Carolina at Charlotte (United States); Mehrdad Abolbashari, Optoniks Corp. (United States); Faramarz Farahii, The Univ. of North Carolina at Charlotte (United States)

We have developed a compressive hyperspectral imaging system that is based on single-pixel camera architecture. We have employed the developed system on a scanning white-light interferometer (SWLI) and showed that by replacing SWLI’s CCD-based camera by the compressive hyperspectral imaging system, we have access to high-resolution multi-spectral images of interferometer’s fringes. Using these multi-spectral images, the system is capable of simultaneous spectroscopy of the surface, which can be used, for example, to eliminate the effect of surface contamination and providing new spectral information. We show that such system can also reduce the need for vertical scan, therefore it is more tolerant to object’s position.

Single-pixel architecture consists of two primary steps, namely measurement and image reconstruction. Measurement step contains a Spatial Light Modulator (SLM), optical system, a single detector (spectrometer), an analog-to-digital converter, and a digital storage. We have used a Digital Micromirror Device (DMD) as our SLM. DMD modulates the incoming light according to some particular patterns and for every pattern on the DMD, optical system collects the transmitted light from the SLM to a detector to generate a compressive measurement. Using these measurements, a recovery algorithm based on NESTA (Nesterov’s algorithm, a first order method for convex optimization) has been developed to reconstruct the high-resolution image. Because the dimensionality of recovery algorithm is very high, we have modified the NESTA algorithm to parallelize its different parts and achieve high speed requirement for building a usable high resolution single-pixel hyperspectral camera.

Time-of-flight compressed ultrafast photography for encrypted three-dimensional dynamic imaging (Invited Paper)

Jinyang Liang, Liang S. Gao, Pengfei Hai, Chiye Li, Lihong V. Wang, Washington Univ. in St. Louis (United States)

Three-dimensional (3D) imaging technologies have found widespread applications, including remote sensing, biology, and entertainment. We have developed compressed ultrafast photography (CUP), a computational imaging technique that can capture non-repetitive time-evolving events at up to 100 billion frames per second. CUP works by first spatially encoding the dynamic scene with a pseudo-random mask on a digital micromirror device (DMD), followed by temporal shearing by a streak camera. Finally, the spatially encoded, temporally sheared dynamic scene is compressively recorded by a CCD sensor. The dynamic scene is recovered by using compressed-sensing-based image restoration. Compared to existing ultrafast imaging techniques, CUP allows single-shot imaging of non-repetitive transient events occurring on a time scale down to tens of picoseconds.

Here, we applied CUP with a synchronized short-pulsed laser illumination to enable dynamic volumetric imaging. By leveraging the time-of-flight (ToF) information of pulsed light backscattered by the object, ToF-CUP can reconstruct a volumetric image from a single camera snapshot. Unlike other ToF-based 3D imaging technologies, ToF-CUP unites image encryption, compression, and acquisition in a single snapshot measurement.
9761-18, Session 7

Computational imaging expansion from visible to infrared and to THz systems (Invited Paper)

Zeev Zalevsky, Alex Zlotnik, Yuval Kapellner Rabinovitz, Amir Shemer, Ariel Schwarz, Bar-Ilan Univ. (Israel)

In this presentation two novel concepts of computational imaging applicable for infrared and THz systems will be discussed and demonstrated. In both cases a controllable array of digital micro mirrors (DMD) will be used. In the first concept a lensless imaging will be demonstrated. In the second an incorporation of two DMDs in the aperture plane of an imaging lens and in the intermediate image plane will show possible enhancement in the field of view and geometric resolution of the integrated imager.

Imaging systems generally involve tradeoffs between spatial resolution and signal to noise ratio. In a single pinhole based imaging system, the size of the aperture determines the spatial resolution. Up to a certain point, the smaller the aperture, the sharper the image, however, with a small pinhole the number of photons passing through decreases and the uncertainty of the measurements is increased. On the other hand, a larger pinhole allows more photons to pass through, which reduces the relative uncertainty of the measurements, but this comes at the price of degraded spatial resolution. In our first concept we propose a novel method for realizing an imaging system that can enhance the spatial resolution while preserving the energetic efficiency. The imaging system is a lensless configuration in which there is a time varied array of pinholes that is positioned in the aperture plane. The changeable and moving pinholes array is realized using a DMD matrix and the proposed concept can be applied both for infrared as well as for THz imaging.

In the second concept the usage of DMDs allows obtaining geometric resolution improvement and a significant enhancement of the field of view (FOV). The idea behind the above-mentioned imaging features is to use the DMDs to properly encode the spatial frequency domain such that the multiplexed information of the imaged object can later on be separated and reconstructed. The DMD positioned at the aperture plane fulfills the task of a fast switching aperture coding agent. This DMD allows generating very controllable point spread functions (PSFs) via the programmable mirror’s angle position. The PSFs have replicative features (“train” of impulse functions) due to the ordered grid of mirrors. We change the locations and values of these impulse functions in time in order to create different responses. As a result, the nature of the captured images is replicated and overlapped. Assuming known PSF parameters (obtained via calibration process), we can reconstruct the original imaged object while extending its FOV. In this case the PSF replicas are introduced into the sensor parts of the object’s FOV that, before the replications, were positioned outside the sensor’s FOV. In the case the DMD is positioned in the intermediate image plane, the time modulation of the micro mirrors can assist in realizing a geometric super resolution by encoding the geometric PSF of the pixels of the camera and then properly inverting it in image processing (and as a result realizing effectively smaller pixels).

We also apply compressed sensing concepts in order to allow capturing in time-less images than the obtainable improvement factor (of FOV or of resolution).

9761-19, Session 7

Experimental study of a DMD based compressive line sensing imaging system in the turbulence environment

Bing Ouyang, Harbor Branch Oceanographic Institute (United States); Weilin W. Hou, U.S. Naval Research Lab. (United States); Culing Gong, Texas Christian Univ. (United States); Frank M. Caimi, Fraser R. Dalgleish, Anni K. Vuorenkoski, Harbor Branch Oceanographic Institute (United States); Xifeng Xiao, David G. Voelz, New Mexico State Univ. (United States)

The Compressive Line Sensing (CLS) active imaging system has been demonstrated to be effective in scattering mediums, such as coastal turbid water, fog and mist, through simulations and test tank experiments. The CLS prototype hardware consists of a CW laser, a DMD, a photomultiplier tube, and a data acquisition instrument. CLS employs whiskbroom imaging formation that is compatible with traditional survey platforms. The sensing model adopts the distributed compressive sensing theoretical framework that exploits both intra-signal sparsity and highly correlated nature of adjacent areas in a natural scene. During sensing operation, the laser illuminates the spatial light modulator DMD to generate a series of ID binary sensing pattern from a codebook to “encode” current target line segment. A single element detector PMT acquires target reflections as encoder output. The target can then be recovered using the encoder output and a predicted on-target codebook that reflects the environmental interference of original codebook entries.

In this work, we investigated the effectiveness of the CLS imaging system in the turbulence environment. Turbulence poses challenges in many atmospheric and underwater surveillance applications. A series of experiments were conducted in the Naval Research Lab’s optical turbulence test facility with the target subjected to turbulence. The total-variation minimization sparsifying basis was used in imaging reconstruction. The preliminary experimental results showed that the current imaging system was able to recover target information through various turbulence strengths. The challenges of acquiring data through strong turbulence environment and future enhancements of the system will be discussed.

9761-20, Session 7

Reference-less measurement of the transmission matrix of a highly scattering material using a DMD and phase retrieval techniques

Angélique Drémeau, Ecole Nationale Supérieure de Techniques Avancées Bretagne (France); Antoine Liatkus, INRIA Nancy - Grand Est (France); David Martin, Ori Katz, Lab. Kastler Brossel (France); Christophe Schülke, Florent Krzakala, Ecole Normale Supérieure (France) and Univ. Pierre et Marie Curie (France); Laurent Daudet, Institut Langevin (France); Sylvain Gigan, Lab. Kastler Brossel (France)

Recently, wavefront shaping using spatial light modulators (SLM) has emerged as a unique tool to manipulate multiply scattered coherent light. It is in particular possible to measure the so-called transmission matrix (TM) of the medium [6], which fully describes light propagation through the linear medium, from the modulator device to the detector. This approach has been particularly efficient for focusing and imaging. Most of the works reported so far have relied on phase modulators which are usually slow (few tens of Hertz for liquid crystal modulators). A promising alternative for wave shaping in complex media are Digital Micromirror Device (DMD) They can been used as phase modulators, using appropriate diffraction and filtering,
Spatial and temporal control of thermal waves by using DMDs for interference based crack detection

Erik Thiel, Bundesanstalt für Materialforschung und -prüfung (Germany); Marc Kreutzbruck, Univ. Stuttgart (Germany); Mathias Ziegler, Bundesanstalt für Materialforschung und -prüfung (Germany)

Active Thermography is a well-established non-destructive testing method and used to detect cracks, voids or material inhomogeneities. It is based on applying thermal energy to a samples’ surface whereas inner defects alter the non-stationary heat flow. Conventional excitation of a sample is hereby done spatially, either planar (e.g. using a lamp) or local (e.g. using a focused laser) and temporally, either pulsed or periodical. Combining a high power laser with a Digital Micromirror Device allows us to merge all degrees of freedom to a spatially and temporally controlled heat source. This enables us to exploit the possibilities of coherent thermal wave shaping. Exciting periodically while controlling at the same time phase and amplitude of the illumination source induces – via absorption at the sample surface – a defined thermal wave propagation through a sample. That means thermal waves can be controlled almost like acoustical or optical waves. However, in contrast to optical or acoustical waves, thermal waves are highly damped due to the diffusive character of the thermal heat flow and therefore limited in penetration depth in relation to the achievable resolution. Nevertheless, the coherence length of thermal waves can be chosen in the mm-range for excitation frequencies below 10Hz which is perfectly met by DMD technology. This approach gives us the opportunity to transfer known technologies from wave shaping techniques to thermography methods. We will present experiments on spatial and temporal wave shaping, demonstrating interference based crack detection.
to 5% efficiency of S-DUPS can be expected with high efficiency gratings and optical components of proper coatings.


9761-25, Poster Session

**Generation of autofocusing vortex airy beam with a digital micromirror device**

Zhaoxiang Fang, Univ. of Science and Technology of China (China); Yuxuan Ren, Institute of Biochemistry and Cell Biology (China); Rongde Lu, Univ. of Science and Technology of China (China)

Airy beam tends to accelerate in transverse space with a parabolic trajectory, and exhibits self-healing property when partially blocked. Those properties have attracted a great deal of research interests and led to many applications. Circular Airy beam is an derivative of Airy beam exhibiting cylindrically symmetric intensity distribution and abruptly autofocusing characteristics in the linear media. We propose to generate the circular Airy beam with optical vortex, e.g., the vortex Airy beam. The vortex Airy beam is realized through binary amplitude modulation of the wavefront implemented with a digital micromirror device (DMD). The binary amplitude mask for autofocusing vortex Airy beam is created using a super-pixel method encoding technique. In the super-pixel method, the square regions of nearby n?n micromirrors are grouped into super-pixels, which can simultaneously modulate the amplitude and phase of the incident wavefront. Each super pixel defines a target complex field. The advantage of this method shares a high modulation fidelity and resolution with using a binary modulation. Meanwhile, the DMD is an excellent candidate for tailoring light fields due to its faster speed and higher fill factor compared with liquid crystal spatial light modulator. The micro-mirrors on the DMD could rotate either +12° or -12° with respect to the main diagonal according to the digital addressng signal. These two kinds of angular positions correspond to a defined “on” or “off” state, which represent reflecting the incident beam to the designed optical path or sending the output beam to the light absorber, respectively. Therefore, each mirror of DMD individually realizes the generation of beams with high quality. Furthermore, the propagation dynamics of the beams with various topological charges in free space are discussed. The experimental longitudinal beam profile along x-z with topological charge 1 is consistant with the theoretical predictions. The proposed method using DMD can also apply to study the dynamics of vortex non-diffracting beams.
9762-1, Session 1

**Intraneuronal traffic readout with fluorescent nanodiamonds**

François Treussart, Lab. Aimé Cotton (France); Simon Haziza, Lab. Aimé Cotton (France) and Ctr. de Psychiatrie et Neurosciences (France); Michel Simonneau, Yann Loe-Mie, Aude-Marie Lepagnol-Bestel, Ctr. de Psychiatrie et Neurosciences (France); Nitin Mohan, Lab. Aimé Cotton (France); Huan-Cheng Chang, Institute of Atomic and Molecular Science (Taiwan)

We present a live cultured neuron assay, which is able to reveal psychiatric disease related gene variants. Our approach relies on intradendritic endosome traffic monitoring inferred from tracking stable emitting fluorescent diamond nanocrystals. We established mouse lines in which microtubule-associated MARK1 and mitochondria-related SLC25A12 proteins were slightly overexpressed and in vitro shRNA-induced AUTS2 haploinsufficiency, to mimic low-penetrance common variants and rare variants of unknown penetrance, respectively. In both cases, the nanodiamond-tracking assay revealed significant changes in trafficking parameters, showing proof-of-principle for a simple screening methodology of functional impact of genetic variants.

9762-2, Session 1

**Multifunctional intracellular sensing with biologically-responsive nanodiamonds**

Zhiqin Chu, Univ. Stuttgart (Germany)

The development of multifunctional sensors working on submicron scales under physiological conditions enable monitoring of many intracellular species for various biological and medical applications. As the state of art magnetic sensor, the nitrogen vacancy (NV) center in nanodiamond holds single spin sensitivity and nanometer resolution at ambient conditions, combined with its long term stability and low cytotoxicity in biological systems. By combining clinical magnetic resonance imaging (MRI) agent Gd3+ complexes with nitrogen vacancy (NV) relaxometry in nanodiamonds, we therefore develop ultrasensitive hybrid sensor through monitoring the spin relaxation time changes of NV centers modulated by nearby Gd3+ complexes, which are sensitive to surrounding species. Using such novel sensing mechanism, we measured the pH, redox potential changes at submicron length scales in a microfluidic channel. By feeding cells with developed hybrid sensor, we further achieved monitoring the subtle environmental changes of hybrid sensor trafficking through endocytic organelles in real time. Finally, we demonstrated the intracellular pH environment changes of hybrid sensor trafficking through endocytic and succeeded in detection of (5nm)3 hydrogen nuclear spin magnetic resonance spectroscopy under ambient conditions.

9762-3, Session 1

**Single-protein spin resonance spectroscopy and imaging under ambient conditions**

Jiangfeng Du, Univ. of Science and Technology of China (China)

Single-molecule magnetic resonance spectroscopy and imaging is one of the ultimate goals in magnetic resonance and will has great applications in a broad range of scientific areas, from life science to physics and chemistry. We and co-workers have successfully obtained the first single-protein spin resonance spectroscopy under ambient conditions [1], realized atomic-scale structure analysis of single nuclear-spin clusters in diamond [3], detected nuclear magnetic resonance spectroscopy with single spin sensitivity [4], and succeeded in detection of (5nm)3 hydrogen nuclear spin magnetic resonance spectroscopy [6]. Among these works, I will specially introduce the “single-protein magnetic resonance spectroscopy under ambient conditions” [1]. The spin of a single nitrogen vacancy (NV) center in diamond is a highly sensitive magnetic-field sensor. We used the NV center to detect a nitroxide labeled protein and gained the world's first magnetic resonance spectrum of single protein through electron spin resonance under ambient conditions. We not only revealed the position and orientation of the spin label relative to the NV center, but also elucidate the dynamical motions of the protein on the diamond surface. Specially, “atmosphere with room temperature” provided necessary conditions for the broad applications of this technology in life science et al.

References:


9762-4, Session 2

**Kilograms of bright nanodiamonds and bio-functionalization** *(Invited Paper)*

Arfaan Rampersaud, Columbus NanoWorks (United States)
The nitrogen-vacancy (NV-) center in diamond is a molecular impurity within the diamond crystalline lattice in which a nitrogen atom is adjacent to a carbon vacancy. The NV center produces an intense fluorescence emission in the near-infrared region following its excitation by a 532 nm laser. The fluorescence of the NV-center is photostable, with an indefinite shelf-life and excellent quantum yield. The diamond is stable under nearly all environmental extremes and has excellent surface chemistry properties. We prepare fluorescent nanodiamonds (FND) by electron irradiation of high pressure high temperature (HPHT) nanodiamonds which are annealed and acid-treated to remove graphite from the nanodiamond surface. Following optical characterization, the nanodiamonds are conjugated with short-chain polyethylene glycol (PEG) having terminal alcohol groups. These are converted into reactive NHS-esters and used for bioconjugation with antibodies or proteins. Conjugation can be confirmed by a catalytic assay that employs an appropriate secondary antibody-Horse Radish Peroxidase (HRP) biocjugate. Unconjugated FNDs can be readily taken up by a macrophage cell line, which can be cultured for several days with virtually no toxic effects. Z-stack images of these cells, acquired through confocal microscopy, demonstrate that fluorescent nanodiamonds accumulate within the cytoplasm.

9762-5, Session 3

Optical quantum information with and without control (Invited Paper)

Geoff J. Pryde, Griffith Univ. (Australia)

Quantum control techniques are important because they can overcome noise in quantum information protocols and can even be an important step in obtaining a quantum advantage in noise-free scenarios. Alternatively, making protocols that are robust against noise - even without quantum control - is a valuable approach to practical demonstrations of quantum information technologies.

We report photonic quantum information experiments investigating these two regimes. Our recent work includes the investigation of:

* rapid purification of quantum states via weak quantum measurements and control;
* the limits of one-way and two-way quantum steering - in the presence of very high losses - for remote entanglement sharing, and quantum steering visualisation;
* optimally minimal-resource multi-copy quantum state discrimination;
* entanglement and adaptive measurement for phase estimation at the absolute Heisenberg limit.

9762-6, Session 3

Long distance compensation of nonlocal dispersion in frequency domain two-photon Bessel interferences scheme using WDM synchronization

Batiste Galmes, Luca Furfaro, Kien Phan Huy, Laurent Larger, John M. Dudley, Jean-Marc Merolla, FEMTO-ST (France)

Photon entanglement has appeared to play an important role in the foundations of quantum physics and is also relevant in disciplines such as quantum information processing, quantum communication, and quantum metrology. Different types of entanglements have been used, including entanglement in polarization, momentum angular momentum and time-energy. We recently investigated experiments related to time-energy configurations in which entanglement is directly manipulated in the frequency domain using electro-optic phase modulators driven by radio-frequency signals. Such method allows observation of an accurate and stable high-visibility (better than 99%) two-photon Bessel interference patterns. However in long distance fiber implementation this scheme remains sensitive to chromatic dispersion effect. We report a simple long-distance experimental nonlocal dispersion compensation solution based on dispersion control using a standard dispersion-compensation module. The relative phase between interacting quantum states can be reliably controlled by sending an optical reference signal over the fiber that transmits the quantum signal. The reference is respectively combined with the quantum state or separated from the quantum states using a standard wavelength-division-multiplexing (WDM) method. Experiments were carried out in the C-band telecom window (1550 nm), over two 30-km standard single-mode fiber spools. We observed that the introduction of a local negative dispersion through a commercial tunable dispersion-compensation module allowed compensating the non local dispersion effect up to 60 km and then retrieving the initial high-visibility two-photon Bessel interference patterns. Our results show that such frequency-bin photon entanglement is a promising alternate platform for the realization of various, reliable, stable, and long-distance quantum information experiments.

9762-7, Session 3

Photoelectrical detection of nitrogen-vacancy centre electron spin states in diamond (Invited Paper)

Milos Nesladek, Univ. Hasselt (Belgium)

We report on a novel scheme for reading out the state of electron spins of Nitrogen Vacancy (NV) centres in diamond as an advanced platform for quantum computation, metrology and sensing. At present, the readout of NV-centre’s electron spin state is typically performed optically, by detecting NV centre emitted photons using confocal microscopy. The proposed technique utilizes photocurrent as a tool for the detection of electric charge carriers delivered by spin conserving optical transitions. The photocurrent detected magnetic resonance (PDMR) method lifts up the constraints of confocal optics and offers a simple and sensitive way for the readout of diamond NV centres directly on the diamond chip using an electrode system.

Optically detected magnetic resonance (ODMR) and PDMR are compared. We discuss the photo-ionisation mechanism as well as the mechanism for spin-conserving spin-photoelectron transitions corresponding to |0> to |±1> spin sublevel occupation probability. The technique is evaluated for a wide range of microwave and light powers using NV centre ensembles as well as individual NV sites. We discuss the mechanism of magnetic resonance contrast, the detection limits of the PDMR technique as well as the photoelectric gain [1].


9762-8, Session 3

The next iteration of the small photon entangling quantum system (SPEQS-2.0)

Kadir Durak, Aitor Villar, Patrick C. Wade, Rakitha Chandrasekara, Zhongkan K. Tang, Alexander Ling, Ctr. for Quantum Technologies (Singapore)

The small photon entangling quantum system (SPEQS) is an integrated instrument where the pump, photon pair source and detectors are combined within a single optical tray and electronics package. The first generation of the instrument, SPEQS-1.0, is no longer than 10cm?10cm?3cm. This handheld source of entangled photons can be used as a quantum random number generator or to act as a source for quantum key distribution. Extensive design and testing effort has been made to show that the instrument is space qualified for LEO. The existing footprint enables the instrument to be placed onboard nanosatellites (such as CubeSats) or the CubeLab facility within the International Space Station to enable space-based quantum communication experiments.
In this paper we discuss the challenges and lessons learned from over three years of development and testing. We also discuss ongoing efforts to develop the next generation SPEQS-2.0 device and the science behind the quantum engineering efforts.

9762-9, Session 3

**Integrated quantum key distribution sender unit for daily-life implementations**

Gwenaelle Mélé, Tobias Vogl, Markus Rau, Ludwig-Maximilians-Univ. München (Germany); Giacomo Corrielli, Andrea Crespi, CNR-Istituto di Fotonica e Nanotecnologie (Italy); Roberto Osellame, CNR-Istituto di Fotonica e Nanotecnologie (Italy) and Politecnico di Milano (Italy); Harald Weinfurter, Ludwig-Maximilians-Univ. München (Germany) and Max-Planck-Institut für Quantenoptik (Germany)

We present a complete free-space Quantum Key Distribution (QKD) solution for daily-life secure communications. We focus on a practical scenario where the user owns an integrated QKD unit embedded in a mobile device, which allows him to generate on-demand secure keys with trusted nodes. Potential applications entail wireless transaction, key generation for online authentication and quantum network interfacing. While our modules are optimised for short-distance links, they can be easily adapted and integrated into long-distance schemes.

The system we developed implements BB84-like protocols. It includes a miniature QKD sender device (35 x 20 x 8 mm) emitting near-infrared polarised faint laser pulses with 100 MHz repetition rate. The integrated optics platform is fully controlled by a smartphone via an Android App that also establishes the classical channel with the receiver’s computer over Wi-Fi to perform post-processing and live-basis alignment. An additional bright, visible laser overlapped with the quantum signal enables both synchronisation with the receiver and efficient beam tracking for continuous operation. With a quantum link efficiency as high as 50 % stable over a few seconds, we expect a secret key rate close to 1 Mbit/s.

9762-11, Session 4

**Engineering frequency-time quantum correlation of narrow-band biphotons from cold atoms (Invited Paper)**

Yoon-Ho Kim, Pohang Univ. of Science and Technology (Korea, Republic of)

The nonclassical photon pair, generated via a parametric process, is naturally endowed with a specific form of frequency-time quantum correlations. Here, we report complete control of frequency-time quantum correlations of narrow-band biphotons generated via spontaneous four-wave mixing in a cold atomic ensemble. We have experimentally confirmed the generation of frequency-anticorrelated, frequency-correlated, and frequency-uncorrelated narrow-band biphoton states, as well as verifying the strong nonclassicality of the correlations. Our work opens up new possibilities for engineering narrow-band entangled photons for various quantum information applications, such as, quantum networks and quantum repeaters.

9762-12, Session 4

**One-way quantum computing with arbitrary-scale continuous-variable cluster states extending over time and frequency (Invited Paper)**

Rafael Alexander, The Univ. of Sydney (Australia); Pei Wang, Niranjan Sridhar, Moran Chen, Olivier Pfister, Univ. of Virginia (United States); Nicolas Menicucci, The Univ. of Sydney (Australia)

One-way quantum computing, the most refined variant of measurement-based quantum computing, makes use of a “quantum computing substrate,” a cluster entangled state that can be described by a graph of qubit nodes precisely linked by specific entangling interactions. The universal gate set can then be implemented solely by single-qubit measurements of the graph nodes and feedforward to their nearest neighbors. Although experimentally appealing because of its reliance on physical measurement to implement quantum logic, scalable one-way quantum computing has never been implemented in the lab. Recently, scalability breakthroughs have been demonstrated with the generation of massive-scale, one-dimensional, cluster-state entanglement over the continuous variables of the quantum electromagnetic field, a.k.a. qumodes, in the time domain (10000 sequentially entangled qumodes, limited only by the stability of the experiment) and in the frequency domain (60 simultaneously entangled qumodes, with 3000 expected in the near future). This paper presents a theoretical result on the combination of temporal and frequency entanglement in order to yield a two-dimensional square lattice, suitable for arbitrary-scale universal quantum computing.
Adaptive Gaussian quadrature detection for continuous-variable quantum key distribution

Laszlo Gyongyosi, Sandor Imre, Budapest Univ. of Technology and Economics (Hungary)

We propose the adaptive Gaussian quadrature detection for multichannel continuous-variable quantum key distribution (CVQKD). A multichannel CVQKD scheme uses Gaussian subcarrier continuous variables for the information conveying and Gaussian sub-channels for the transmission. The proposed multichannel detection scheme dynamically adapts to the sub-channel conditions using a corresponding statistics which is provided by our sophisticated sub-channel estimation procedure. The sub-channel estimation phase determines the transmissivity coefficients of the sub-channels, which information are used further in the adaptive quadrature decoding process. We define the technique called subcarrier spreading to estimate the transmissivity conditions of the sub-channels with a theoretical error minimum in the presence of a Gaussian noise. We introduce the terms of single and collective adaptive quadrature detection. We also extend the results for a multiuser multichannel CVQKD scenario. We prove the achievable error probabilities, the signal-to-noise ratios, and quantify the attributes of the framework. The adaptive detection scheme allows to utilize the extra resources of multichannel CVQKD and to maximize the amount of transmittable information.

Quantum properties of twisted light (Invited Paper)

Robert W. Boyd, Univ. of Ottawa (Canada)

We present recent work emphasizing the quantum properties of orbital angular momentum (OAM) of light. A key example is our studies of the entanglement of two photons in their OAM and angular degrees of freedom. We also make use of these quantum properties to show that quantum metrology using “weak measurements” can be performed for instance to perform sensitive measurements of the angular orientation of a structured light beam. We also present recent results that showing how to use the OAM degree of freedom to perform secure communication in which more than one bit of information is encoded onto each photon. This ability makes use of the fact that OAM lies in an unbounded state space, and there is thus no limit to how many bits of information can be carried by each photon.

Parity detection achieves Heisenberg limit in an SU(1,1) interferometer with coherent and squeezed vacuum input states

Dong Li, East China Normal Univ. (China) and Louisiana State Univ. (United States); Bryan Gard, Louisiana State Univ. (United States); Chun-Hua Yuan, Weiping Zhang, East China Normal Univ. (China); Hwang Lee, Jonathan P. Dowling, Louisiana State Univ. (United States)

In quantum optical metrology, parity detection was initially proposed to be applied with input NOON states and Fock states in SU(2) interferometers. Now parity detection invades SU(1,1) interferometers. Here we theoretically study parity detection on an SU(1,1) interferometer with coherent mixed with squeezed vacuum input states. Our work shows that parity detection achieved Heisenberg limit when the input coherent and squeezed vacuum light are mixed in roughly equal proportions with a strong parametric amplifier strength. Compared with homodyne detection, parity detection has a slightly better phase sensitivity with coherent and squeezed vacuum inputs. And parity detection is more suitable than homodyne detection in some certain situations.
nonlinearity. These results denote that the LN photonic chip is competent for practical applications of fully integrated quantum technologies.

9762-18, Session 6

On-chip quantum storage in a rare-earth-doped photonic nanocavity

Tian Zhong, Jonathan M. Kindem, Jake Rochman, California Institute of Technology (United States); Alban Ferrier, Philippe Goldner, Institut de Chimie et des Matériaux Paris-Est (France) and Univ. Pierre et Marie Curie (France); Andrei Farao, Evan Miyazono, California Institute of Technology (United States)

Rare-earth-ion doped crystals are state-of-the-art materials for macroscopic optical quantum memories and quantum transducers between optical photons, microwave photons, and spin waves. Their integration in an on-chip quantum nanophotonic platform would enable quantum repeaters and scalable quantum networks. Here we demonstrate quantum optical storage in a Rare-earth-doped Yttrium orthosilicate Y25O5 (YSO) photonic crystal nano-beam resonator with small mode volume of 1.6 cubic wavelengths. The coupling of the 883 nm transition of Neodymium (Nd3+) ions to the nano-resonator resulted in an increased optical depth, which facilitated efficient photon storage via cavity impedance matching. Lifetime-limited optical coherence time T2 of 120 ns at 3.5 K with low spectral diffusion was measured using photon echo technique.

Atomic frequency comb (AFC) quantum memory was implemented in the Nd:YSO device. The AFC was prepared by optically pumping the ions into the long-lived (~100 ms lifetime at 3.5 K) Zeeman state. The frequency spacing of the AFC comb was 1-4 MHz, resulting in a storage time of 250 ns to 1 ns with low noise. Coherent pulses attenuated to the single photon level were used to characterize the quantum memory. We currently measure a storage efficiency on the order of 0.1%, comparable to bulk crystal Nd:YSO memories that are millimeters long. We are also developing a memory-compatible entangled photon source based on a Lithium Niobate thin sheet cavity. High-fidelity quantum storage of the entangled state is expected using the nanocavity. Our results enable multiplexed on-chip quantum storage and thus quantum repeater devices using rare-earth-ions.

9762-19, Session 6

On-chip generation and sparsity tomography of entangled photons (Invited Paper)

Andrey A. Sukhorukov, The Australian National Univ. (Australia)

Generating entangled photons with specifically chosen spatial entanglement is an important functionality in on-chip quantum photonics. We show how photon pairs can be generated on-chip with fast all-optical control of their wavefunction. Here photon pairs are generated by spontaneous parametric down-conversion in a quadratically nonlinear waveguide array. By coupling driving lasers into multiple waveguides with special poling patterns, any desirable superposition of states in a multi-dimensional quantum space can be produced by tuning the driving lasers amplitude and relative phase.

We present a rigorous Green function approach describing entangled photon-pair state generation through spontaneous wave mixing in complex all-dielectric or metal-dielectric nanostructures. We derive explicit expressions with clear physical meaning for the spatially dependent two-photon detection probability, single-photon detection probability and single-photon density matrix. Furthermore, our results establish a classical-quantum correspondence for arbitrary nonlinear dielectric, plasmonic, and metamaterial nanostructures, enabling characterization of structure performance in quantum regime through classical sum-frequency generation.

Then we discuss the characterization of entangled photon pairs using quantum state tomography. Typical quantum tomography involves multiple measurements of the systems state under a variety of different linear transformations. We develop a sparsity based approach to on-chip tomography, where several inputs are mapped to larger number of output waveguides based on specially designed static pre-fabricated structure. The output two-photon correlations allow reconstruction of the full input density matrix. This approach could be particularly useful when combined with on-chip single photon detectors.

9762-21, Session 6

Experimental demonstration of long-range quantum interactions in hyperbolic media

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

We experimentally demonstrate long-range dipole-dipole interactions in hyperbolic metamaterials. Our work paves the way for engineering quantum interactions with artificial materials. Super-coulombic dipole-dipole interaction: To confirm the long range coupling between acceptors and donors, we study the time-resolved PL of Alq3 and R6G in our metamaterial geometry. A 400 nm, 120 fs-pulsed laser was used to pump the samples from below, the resulting PL was then imaged using a streak camera allowing us to directly observe the spontaneous emission lifetimes of both
the donor and acceptor. In addition, time-correlated single photon counting measurements were completed and shown to agree with these streak camera results. We observed PL streak camera traces as well as theoretical fits based on a bi-exponential decay model. Relative to “bulk Alq3” (isolated 13 nm film), we see that the metamaterial significantly reduces the spontaneous emission lifetime of Alq3 (“Alq3 only”) due to the presence of hyperbolic modes supported by the pentalayer. This is in agreement with previous studies. However, when R6G is present on top in the hybrid sample, we observe that the Alq3 spontaneous emission lifetime is decreased further due to the efficient energy transfer and interaction with R6G molecules on top. This additional lifetime reduction marks the long-range nature of the coupling between donor-acceptor pairs with a distance of 100 nm between them. This is the first experimental demonstration of efficient long-range molecular energy transfer. It can lead to a unique class of quantum interaction effects in metamaterials.

9762-32, Poster Session
Ultrathin fiber-taper coupling with nitrogen vacancy centers in nanodiamonds at cryogenic temperatures
Masazumi Fujiwara, Kwansei Gakuin Univ. (Japan) and Hokkaido Univ. (Japan) and Osaka Univ. (Japan); Hong-Quan Zhao, Hokkaido Univ. (Japan); Tetsuya Noda, Osaka Univ. (Japan) and Hokkaido Univ. (Japan); Kazuhiro Ikeda, Hitoshi Sumiya, Sumitomo Electric Industries Ltd. (Japan); Shigeki Takeuchi, Kyoto Univ. (Japan) and Hokkaido Univ. (Japan) and Osaka Univ. (Japan)

Diamond nitrogen vacancy (NV) centers are very promising solid-state quantum emitters for applications in quantum information and quantum metrology. At cryogenic temperatures, they have a lifetime-limited linewidth of optical transitions, which gaseous atoms actually have. It is therefore possible to coherently couple NV centers with photons like atoms. Most of quantum optical applications therefore require lifetime-limited linewidths of NV centers. In addition, such coherent photon-NV interface needs to be integrated in fiber devices for the future quantum networks. Fiber tapers are promising nanophotonic devices for efficiently interfacing photons and quantum nanoemitters, including diamond NV centers [12]. However, all of the previous studies were conducted only at room temperature, and not cryogenic temperatures. Fragility of ultrathin fiber tapers hindered the cryogenic cooling.

Here, we demonstrate successful cooling of ultrathin fiber tapers and their coupling with nitrogen vacancy (NV) centers in nanodiamonds at cryogenic temperatures [3]. Nanodiamonds containing multiple NV centers were deposited on ultrathin fiber tapers with diameters ranging from 450 to 500 nm. The fiber tapers were successfully cooled down to 9 K with our special fiber mount and an optimization of cooling speed. The fluorescence coupled to the tapers clearly showed characteristic sharp zero-phonon lines of neutral and negatively charged NV centers. The present demonstration is an important step toward fiber-based NV-based quantum information processing and sensitive nanoscale cryogenic magnetometry.


9762-33, Poster Session
Photonic crystal resonators in erbium-doped crystals for on-chip optical quantum memories
Evan Miyazono, Tian Zhong, Ioana Craiciu, Jonathan M. Kindem, Andrei Faraon, California Institute of Technology (United States)

Rare-earth dopants in crystalline materials possess long-lived and highly coherent quantum states. Developing on-chip devices based on these materials would enable scaling of optical quantum information processing hardware for computation and communication. In particular, optical memories based on erbium could leverage existing ubiquitous optical fiber networks due to its 1.5 micron transition. The excited state for this transition has a very long lifetime, which corresponds to a very small dipole moment for the transition. This results in weak interaction with control fields as well as suboptimal spin initialization, which in turn causes a decrease in fidelity for quantum state manipulation, including optical memory protocols. These effects can be ameliorated with no detrimental effects on coherence times by coupling the ions to a nanoscale cavity. With small mode volume and large quality factor, the resonator leverages cavity quantum electrodynamics to increase coupling efficiency and decrease the excited state lifetime via the Purcell effect.

We have fabricated a triangular nanobeam optical resonator directly in the erbium-doped rare-earth-host crystal, yttrium orthosilicate (Y2SiO5), using focused ion beam milling. The nanobeam cavity was tuned to be resonant with the erbium transition, and coupling between the ions and cavity was measured to increase the optical decay rate by a factor of 275 via the Purcell enhancement. This decay rate enhancement will allow for increased spin initialization in a Zeeman state for atomic frequency comb preparation. Progress measuring spin initialization efficiency and demonstrating optical memory protocols will be discussed.

9762-34, Poster Session
Fabrication of high-quality nanobeam photonic crystal cavities in 4H silicon carbide with embedded color centers
David O. Bracher, Evelyn L. Hu, Harvard Univ. (United States)

A wide band-gap semiconductor with a long history of growth and device fabrication, silicon carbide (SiC) has attracted recent attention for hosting several defects with properties similar to the nitrogen vacancy center in diamond. In the 4H polytype, these include the silicon vacancy center and the neutral divacancy, which have zero phonon lines (ZPL) in the near-IR and may be useful for quantum information and nanoscale sensing. For many such applications, it is critical to increase the defect emission into the ZPL by coupling the emission to an optical cavity. Accordingly, we have pursued the fabrication and characterization of high quality 1D nanobeam photonic crystal cavities (PCCs) in 4H-SiC, using homoepitaxially grown material and a photol electrochemical etch to provide optical isolation. These PCCs are distinctive in their high theoretical quality factors (Q > 10^6) and low modal volumes (V < 0.5 (?/n)^3). We fabricated devices with Qs of up to ~7,000, which are the first PCCs demonstrated in 4H-SiC. Additionally, we showed that the modes can be spectrally tuned by both plasma etching and laser irradiation. With these techniques, we coupled the emission of ion-implanted silicon vacancy centers (TV12) to the nanobeam PCCs and brought the TV2 ZPL into spectral overlap with the resonant mode, resulting in an intensity increase of up to 3-fold. We continue to refine our methods of defect generation and coupling with the cavities, and we believe this work is an important step in the development of SiC as a platform for quantum information and sensing.

9762-36, Poster Session
Coherent addressing, switching, and signal processing in a Raman-active array of waveguides
Igor V. Melnikov, National Research Univ. of Electronic Technology (Russian Federation) and Univ. of Illinois in
Urbana-Champaign (United States) and Moscow Institute of Physics and Technology (Russian Federation); Georgy L. Alfimov, Svetlana V. Nazarenko, National Research Univ. of Electronic Technology (Russian Federation)

In the past two decades there has been a growing interest in the study of discrete, lattice, and/or nanowire solitons. There are a diversity of fascinating phenomena pertinent to these waveguide array systems, for instance, discrete solitons and diffraction management which offer the potential of fabricating compact, all-optical switching and blocking devices for use in integrated optical systems. While weakly coupled waveguide arrays show different linear properties like anomalous diffraction when compared to continuous media, in the nonlinear regime they have shown analogous behavior where the self- and cross-phase modulation interactions allows the formation of discrete solitons. The dynamics of these waveguide arrays can be modeled by the discrete nonlinear Schrödinger equation (DNLSE), which considers a system of individual waveguides coupled with adjacent waveguides as a set of ordinary differential equations.

In this paper we propose, to our best knowledge for the first time, to employ the Raman nonlinearity combined with the always present Kerr effect for Raman soliton generation and interactions in a waveguide array. We present numerical modeling of discrete beam interactions in a nonlinear, Raman-active material, such as silicon or potassium gadolinium tungstate KGD(WO4)2 (KGW), illustrating addressing, blocking, switching, and wavelength conversion dynamics of this system. We demonstrate using numerical methods the potential of all-optical generation, wavelength conversion and beam steering of optical solitons in a discrete waveguide array using Raman and Kerr nonlinear processes. With the availability of this novel highly nonlinear and Raman efficient materials such as SOI or KGW, as well as new techniques in creating waveguides with these materials, there is much promise shown for applications of all optical conversion, switching, blocking, and logic functionality. Future work on discrete soliton blocking and steering are being directed towards examination of new features that may be brought by introducing non-stationary Raman response and additional phase mismatch in the waveguides.

Characterization of type-II spontaneous parametric down-conversion in domain-engineered PPLN

Paulina Kuo, Oliver Slattery, Lijun Ma, Xiao Tang, National Institute of Standards and Technology (United States)

We explore a new type of crystal for generating polarization-entangled photon pairs. Instead of using two distinct crystals to produce |HV> and |VH> signal and idler states, we utilize a single domain-engineered, quasi-phasematched, periodically poled lithium niobate (PPLN) crystal. The domain engineering consists of modulating the phases of the periodic domain inversions of the PPLN. This crystal enables distributed, simultaneous generation of the |HV> and |VH> polarization states. For the experiment, we used a continuous-wave pump at 775 nm to generate signal and idler pairs at 1532 nm and 1567 nm using spontaneous parametric down-conversion (SPDC). The SPDC photons were characterized by two methods: a grating monochromator with an InGaAs avalanche photodiode (APD), and upconversion spectroscopy. For the latter technique, we utilized high efficiency, sum-frequency generation in a PPLN waveguide. By tuning the waveguide pump wavelength near 1900 nm, we tuned the spectral acceptance band near 1550 nm, thereby spectrally resolving the 1532 nm and 1567 nm photons. Sum-frequency photons near 850 nm were detected by Si APDs. Because of the high efficiency and low noise counts of the Si APDs, better spectra with improved signal-to-noise ratios were obtained with upconversion spectroscopy compared to detection by InGaAs APDs. Preliminary data shows good indistinguishability of the photons and good prospects for high entanglement visibility. This source of polarization entangled photons can serve as a telecom-compatible building block for hybrid quantum networks.

Quantum phenomena in ultra-high Q whispering gallery mode resonators and applications to quantum information systems

Yanne K. Chembo, FEMTO-ST (France)

We investigate the non-classical behavior of Kerr optical frequency combs when pumped below and above threshold. These combs are obtained by pumping a monolithic ultra-high Q whispering gallery mode resonator with a laser. The intra-cavity photons are confined within the torus-like eigenmodes of the resonator, and they interact nonlinearly via the Kerr effect. In the configuration where the system is under threshold, the pump triggers the phenomenon of spontaneous four-wave mixing, where two photons from the pump are symmetrically up- and down-converted in the
Interaction that would result in slow response, the new approach rests on recently demonstrated. Rather than attempting to engineer highly resonant photon interaction, not subject to bandwidth constraints was proposed and Recognizing these limitations, a new class of resonance-free photon-slower than the conventional electronic gate and are often cryogenic. Unfortunately, while significant advances have been made in photon-photon experiments have shown that the classical data-carrying capacity of a terabit per second can be achieved using OAM states of light in an optical fiber. The potential of higher dimensional encoding of quantum information to achieve a higher bit rate can only be achieved if the photon can be protected from the decohering effect of optical index of refraction fluctuation in an optical fiber. We derive a decoherence model for orbital angular momentum states of a photon in a multimode optical fiber and show that rate of decoherence scales exponentially with \( l^2 \), where \( l \) is the azimuthal mode order. We also show numerically that for large values of \( l \) the orbital angular momentum photon state completely dephases. However for lower values of \( l \) the decoherence can be minimized by using dynamical decoupling to allow for multiplexed high-bandwidth communication and similar applications.

Dephasing of single-photon orbital angular momenntum qudit states in fiber: limits to correction via dynamical decoupling

Manish Kumar Gupta, Jonathan P. Dowling, Louisiana State Univ. (United States)

Photons have always been the choice for the information carrier in quantum information due to their quantum nature and low-loss coefficient pertaining to transmission. Information encoding based on the two-dimensional Hilbert space of photon polarization (or SAM) imposes a severe limitation on the rate of optical communication. To overcome such limitations the orbital angular momentum (OAM) of light has been proposed that uses the photon’s spatial mode structure and allows use of higher-dimensional Hilbert space, or a “qudit” encoding of a photon. This leads to an increased alphabet size and subsequently, increased rate of communication. Recent experiments have shown that the classical data-carrying capacity of a THz-class, few-photon all-fiber gate. Performance and application of the new device operated as a receiver and a switch is discussed in detail.

Gravity in the quantum lab (Invited Paper)

Ivette Fuentes Guridi, Vienna Ctr. for Quantum Science and Technology (Austria)

Quantum experiments are reaching relativistic regimes. Quantum communication protocols have been demonstrated at long length scales and experiments are underway to distribute entanglement between Earth and satellite-based links. At these regimes the Global Positioning System requires relativistic corrections. Therefore, it is necessary to understand how motion and gravity will affect long-range quantum experiments. Interestingly, relativistic effects can also be observed at small length scales. Some effects have been demonstrated in superconducting circuits involving boundary conditions moving at relativistic speeds and quantum clocks have been used to measure time dilation in table-top experiments. In this talk I will present formalism for the study of gravitational effects on quantum technologies. This formalism is also applicable in the development of new quantum technologies that can be used to deepen our understanding of physics in the overlap of quantum theory and relativity. Examples include gravimeters, accelerometers and space-time probes underpinned by quantum field theory in curved spacetime.

Realization of topological Anderson insulators (Invited Paper)

Alexander Szameit, Simon Stützer, Friedrich-Schiller-Univ. Jena (Germany); Yonatan Plotnik, Technion-Israel Institute of Technology (Israel); Julia M. Zeuner, Friedrich-Schiller-Univ. Jena (Germany); Yaakov Lumer, Miguel A. Bandres, Mordechai Segev, Technion-Israel Institute of Technology (Israel); Mikael C. Rechtsman, The Pennsylvania State Univ. (United States)

The discovery of topological insulators relying on spin-orbit coupling in condensed matter systems has created much interest in various fields, including in photonics. In two-dimensional electronic systems, topological insulators are insulating materials in the bulk, but conduct electric current on their edges such that the current is completely immune to scattering. However, demonstrating such effects in optics poses a major challenge because photons are bosons, which fundamentally do not exhibit fermionic spin-orbit interactions (i.e., Kramer’s theorem). At microwave frequencies, topological insulators have been realized in magneto-optic materials, relying on strong magnetic response to provide topological protection against backscattering – in the spirit of the quantum Hall effect. However, at optical frequencies the magneto-optic response is extremely weak, hence a photonic topological insulator would have to rely on some other property. Indeed, numerous theoretical proposals have been made for photonic topological insulators, but their first observation, made by our group, relied on a different idea: Floquet topological insulators. Later that year, another group reported imaging of topological edge states in silicon photonics. These experiments have generated much follow up, among them – as the arguably most intriguing one the area of “topological photonics” – our first experimental observation of topological Anderson insulators, where a system becomes topological only when disorder is introduced. The purpose of this talk is to review these developments, discuss new conceptual ideas, and suggest applications.
Exciton-polaritons in semiconductor microcavities have appeared as convenient platforms for photonic simulation of complex Hamiltonians. Using lithographic and dry etching techniques their potential landscape can be engineered allowing the design of the polariton dispersion. Here we present a 2D honeycomb lattice for polaritons showing Dirac cones and novel edge states. Using a 1D Lieb lattice we study polariton lasing in a flat band, a simulator for the interplay between kinetic energy and disorder. Our experimental results show the potential of using exciton-polaritons to study, for instance, artificial gauge fields in interacting systems.

Artificial magnetic fields for photons can significantly enrich the physics of coupled ring resonator arrays. We push this further to discuss how, under the addition of a harmonic potential, the photonic eigenstates can be recognised as novel Landau levels in momentum space [Phys. Rev. Lett. 113, 190403 (2014)]. We present two realistic experimental proposals in which this physics could be realised. Firstly, we discuss how to extend the experiment of [Hafezi et al., Nat. Photon., 7, 1001 (2013)] where the artificial magnetic field was created using link resonators in a 2D ring resonator array. Secondly, we expand on the proposal of [arXiv:1510.03910] in which an effective 2D photonic lattice is realised in a 1D ring resonator chain by exploiting a “synthetic” dimension for photons. We show that momentum-space Landau levels would have clear signatures in spectroscopic measurements in such experiments, and we discuss the insights gained in this way into geometrical energy bands and particles in magnetic fields [arXiv:1510.03054].
9763-1, Session 1

**Optical system for precision atomic clocks and stable oscillators (Invited Paper)**

Nasser N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States); Arturo Chavez-Pirson, NP Photonics, Inc. (United States); R. Jason Jones, College of Optical Sciences, The Univ. of Arizona (United States); Dan Trung Nguyen, NP Photonics, Inc. (United States); Xochitl Cooper, Ivan Hromada, College of Optical Sciences, The Univ. of Arizona (United States); Jie Zong, NP Photonics, Inc. (United States)

No Abstract Available

9763-2, Session 1

**Thermal design of high temperature alkaline-earth vapor cells**

Jordan Armstrong, Applied Technology Associates (United States); Nathan Lemke, Space Dynamics Laboratory (United States); Kyle Martin, Applied Technology Associates (United States); Christopher Erickson, Air Force Research Lab. (United States)

No Abstract Available

9763-3, Session 1

**A compact, high-performance all optical atomic clock based on telecom lasers (Invited Paper)**

John H Burke, Air Force Research Lab. (United States); Nathan D Lemke, Gretchen R Phelps, Space Dynamics Laboratory (United States); Kyle W Martin, Applied Technology Associates (United States)

No Abstract Available

9763-4, Session 1

**Scalar and vector magnetometry with coherent population trapping**

Ren Peng Fang, May Kim, Zifan Zhou, Selim M. Shahriar, Northwestern Univ. (United States)

No Abstract Available

9763-5, Session 1

**Compact clocks and sensors based on laser-cooled atoms (Invited Paper)**

Elizabeth Donley, National Institute of Standards and Technology (United States)

No Abstract Available

9763-6, Session 2

**Magnetometer using weak measurement enhanced slow light**

Weizhi Qu, Fudan Univ. (China); Jianming Wen, Liang Jiang, Yale Univ. (United States); Yanhong Xiao, Fudan Univ. (China)

The concept of weak measurement was initially proposed by Aharonov, Albert and Vaidman in 1998 (PRL 60, 1351). Weak measurement boosts the signal through post-selection, which is useful when the signal is very small and subject to technical noise with drifting mean value. It has been used in beam deflection measurement and quantum state tomography etc. However, its application in magnetometry has not been reported. Here we propose theoretically a scheme to use the thermal atomic state to measure the magnetic field with weak value amplification. The estimated sensitivity can reach 100 fT for an unshielded atomic vapor cell.

We consider an ensemble of identical atoms with X-type energy level scheme and under thermal state. When a linearly polarized pulsed laser field interacts with the atoms far-off-resonantly, the Faraday effect and slow light effect will coexist since the magnetic field influences the light polarization and different frequency components of the light corresponds to different detunings. Most importantly, the frequency operator and Stokes operator of the light are entangled with each other in the quantum picture. Although weak, the entanglement can be observed thanks to the weak value amplification. Post-selection of the Stokes operator can change the expectation value of the frequency operator, increase the delay time of slow light and maintain the sensitivity of the signal to the magnetic field in the mean time. The method is robust due to its employment of the thermal state. Application of this scheme in precision measurement and quantum control is expected.

9763-7, Session 2

**Synchronization of remote clocks over kilometer-scale turbulent air paths (Invited Paper)**

Laura C. Sinclair, National Institute of Science and Technology (United States)

No Abstract Available

9763-8, Session 2

**Atomic magnetometer based on sub-coherence-lifetime resonance**

Jian Sun, Weizhi Qu, Pengxiong Li, Yanhong Xiao, Fudan...
Previously, a sub-transit-time limited resonance technique was developed by our group [PRL 109, 233006(2012)], where a resonance linewidth 2.4 kHz was reported in a vacuum vapor cell with transit-time limited width of 75 kHz. This resonance is based on the measurement of the second-order cross-correlation between the intensity modulations in the two optical fields forming EIT (Electromagnetically induced transparency), where the intensity modulation is converted from the small phase modulation in the laser and through the \(\sigma\)-type EIT process. Here, we use an alkene coated vapor cell to demonstrate sub-coherence-lifetime limited resonance. Due to the anti-relaxation coating and other technical improvements in the experiments such as laser frequency lock and active laser intensity stabilization, we have obtained resonance linewidth of 0.13 Hz. Based on this narrow resonance, we can obtain DC magnetometer sensitivity of 11.5 fT per root Hz, even in a vapor cell at room temperature. Also, we found that higher-order correlation function can be applied to further improve the performance of this technique in certain parameter regime. This scheme can be also used for AC magnetic field measurement. Finally, we will prove how this resonance scheme can be viewed as a new type of weak measurement.

**9763-9, Session 2**

**Effect of electromagnetically-induced transparency delay generated by dynamic coherent population trapping in Rb vapour**

Sergey M. Kobtsev, Sergey A. Khripunov, Daba A. Radnatarov, Novosibirsk State Univ. (Russian Federation); Valeriy I. Yudin, Aleksei V. Taichenachev, Novosibirsk State Univ. (Russian Federation) and Institute of Laser Physics SB RAS (Russian Federation); Maxim Y. Basalaev, Novosibirsk State Technical Univ. (Russian Federation) and Institute of Laser Physics SB RAS (Russian Federation); Ivan Popkov, Valeriy Andryushkov, Novosibirsk State Univ (Russian Federation)

We present a study of the identified for the first time effect of electromagnetically induced transparency delay in Rb vapours in dynamically created coherent population trapping (CPT) resonance in conventional lambda-type energy configuration of the D1 line of 87Rb. The effect consists in the presence of a delay in the time of the maximal total transmission of atomic vapour relative to the moment when a two-photon resonance is reached as the frequency difference between two laser fields (FDLF) deviates around the clock transition frequency. In our experiments, it was found out that the identified delay is higher for higher frequencies of the FDLF deviation and is accompanied by substantial evolution of the width and shape of the CPT resonance. This work demonstrates the dependence of the identified delay upon the deviation frequency of the FDLF (mean difference 3.417 GHz) of the optical pump across the range between 1 Hz and 4 kHz. The experimental set-up is discussed in [1] and a theoretical basis is presented in [2]. Relatively high-frequency deviation of the FDLF is important, because it improves the signal-to-noise ratio when registering a CPT resonance. However, as our results demonstrate, higher deviation frequency of the FDLF leads to a considerable deformation of the CPT resonance shape. The present work discusses the influence of the discovered effect on the stability of atomic clocks.


**9763-10, Session 2**

**Anti-parity-time symmetric optics using EIT in an atomic vapor (Invited Paper)**

YanHong Xiao, Fudan Univ. (China)

No Abstract Available

**9763-11, Session 3**

**Effects of coherent population trapping in vibrational levels on group velocity and Raman scattering (Invited Paper)**

Pooja Singh, Yuri V. Rostovtsev, Univ. of North Texas (United States)

No Abstract Available

**9763-12, Session 3**

**Efficient polarization of high-angular-momentum systems (Invited Paper)**

Dmitry Budker, Univ. of California, Berkeley (United States)

No Abstract Available

**9763-13, Session 3**

**Cold atom for precision metrology: recent advances**

Matthew B. Squires, Air Force Research Lab. (United States)

No Abstract Available

**9763-14, Session 3**

**Ultra-high resolution spectroscopy of optical frequency combs (Invited Paper)**

Thomas Schneider, Stefan Preussler, Technische Univ. Braunschweig (Germany)

No Abstract Available

**9763-62, Session 3**

**Entangled states for quantum metrology (Invited Paper)**

Vladan Vuletic, Massachusetts Institute of Technology (United States)

No Abstract Available
9763-15, Session 4

Matter wave and light fields for precision measurements of inertial effects *(Invited Paper)*

Philippe Bouyer, Institut d’Optique Graduate School (France) and CNRS (France) and Universite de Bordeaux (France)

No Abstract Available

9763-16, Session 4

Microwave stimulated Raman adiabatic passage between hyperfine ground states of Rubidium 87 for chip-based atom interferometry *(Invited Paper)*

Sylvain Schwartz, Matthieu Dupont-Nivet, Christoph I. Westbrook, Massachusetts Institute of Technology (United States)

No Abstract Available

9763-17, Session 4

Coherent matter wave circuits for atom interferometry *(Invited Paper)*

Malcom Boshier, Los Alamos National Lab. (United States)

No Abstract Available

9763-18, Session 4

Spin squeezed collective state atomic interferometer and clock

Resham Sarkar, May Kim, Ren Peng Fang, Selim M. Shahriar, Northwestern Univ. (United States)

No Abstract Available

9763-19, Session 4

Breaking quantum and thermal limits for precision measurements *(Invited Paper)*

James K. Thompson, JILA (United States)

No Abstract Available

9763-20, Session 5

Future quantum sensing and computing applications of diamond color centers *(Invited Paper)*

Philip R. Hemmer, Texas A&M Univ. (United States)

Color centers in diamond, particularly the nitrogen-vacancy (NV), have attracted much interest over the past years for their potential application as nanoscale sensors of magnetic fields and quantum registers. However, recently other color centers like the silicon-vacancy (SiV) have shown some distinct advantages over the NV for certain applications. In this talk I will compare the SiV and NV and discuss other possible alternatives in solid state systems. I will also briefly discuss a novel approach to fabricating “designer color centers.”

9763-21, Session 5

Interacting cold atoms with tightly guided light *(Invited Paper)*

Julien Laurat, Lab. Kastler Brossel (France)

No Abstract Available

9763-22, Session 5

Quantum optics in photonic band-gap fibers *(Invited Paper)*

Alexander L. Gaeta, Columbia Univ. (United States)

No Abstract Available

9763-23, Session 5

Experimental demonstration of spinor slow light *(Invited Paper)*

Meng-Jung Lee, National Tsing Hua Univ. (Taiwan); Julius Ruseckas, Vilnius University (Lithuania); Chin-Yuan Lee, National Tsing Hua Univ. (Taiwan); Via?eslav Kudria?ov, Vilnius University (Lithuania); Kao-Fang Chang, Hung-Wen Cho, National Tsing Hua Univ. (Taiwan); Gediminas Juzeli?nas, Vilnius University (Lithuania); Ite A Yu, National Tsing Hua Univ. (Taiwan)

No Abstract Available

9763-24, Session 5

Highly efficient photon-echo-based quantum memory using a persistent spectral hole burning induced slow light *(Invited Paper)*

Byoung Seung Ham, Gwangju Institute of Science and Technology (Korea, Republic of)

No Abstract Available

9763-25, Session 6

Temperature sensitivity of the optical cavity scale factor enhancement for a fast light gyroscope *(Invited Paper)*

Krishna Myneni, U.S. Army Research, Development and Engineering Command (United States); David D. Smith,
9763-26, Session 6

**Gain in EIT system for broadband gravitational wave detection (Invited Paper)**

Minchuan Zhou, Zifan Zhou, Selim M. Shahriar, Northwestern Univ. (United States)

No Abstract Available

9763-27, Session 6

**Progress towards a passive superluminal gyroscope (Invited Paper)**

David D. Smith, NASA Marshall Space Flight Ctr. (United States); Hongrok Chang, Ducommun Miltec (United States); Heather A. Luckay, The Univ. of Alabama in Huntsville (United States); Krishna Myneni, U.S. Army Research, Development and Engineering Command (United States)

No Abstract Available

9763-28, Session 6

**Studies of fast light and interferometry using a phase-sensitive amplifier (Invited Paper)**

Brian E. Anderson, Paul D. Lett, National Institute of Standards and Technology (United States)

No Abstract Available

9763-29, Session 6

**Long-distance superluminal propagation in optical fibers: recent advances (Invited Paper)**

Li Zhan, Liang Zhang, Minglei Qin, Shanghai Jiao Tong Univ. (China); Jinmei Liu, East China Normal University (China)

No Abstract Available

9763-30, Session 6

**Experimental study of induced transparency or absorption and slow or fast light using orthogonally-polarized whispering-gallery modes of a single microresonator**

Khoa Bui, Albert T. Rosenberger, Oklahoma State Univ. (United States)

No Abstract Available

9763-31, Session 7

**How to deal with loss in plasmonics and metamaterials (Invited Paper)**

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

No Abstract Available

9763-32, Session 7

**Interplay of nonlocal response, damping, and low group velocity in surface-plasmon polaritons (Invited Paper)**

Søren Raza, Technical Univ. of Denmark (Denmark); N. Asger Mortensen, DTU Fotonik (Denmark)

No Abstract Available

9763-33, Session 7

**Slow plasmons in grating cavities (Invited Paper)**

Atilla Aydinli, Bilkent Univ. (Turkey); Ertugrul Karademir, School of Physics and CRANN, Trinity College Dublin, (Ireland); Sinan Balci, Department of Astronautical Engineering, University of Turkish Aeronautical Association (Turkey); Coskun Kocabas, Bilkent Univ. (Turkey)

No Abstract Available

9763-34, Session 8

**Slow plasmonic and diamond NV centers for delicate metrology (Invited Paper)**

Meir Orenstein, Technion-Israel Institute of Technology (Israel)

No Abstract Available
9763-35, Session 8

**Slow-light in graphene waveguides: recent advances** *(Invited Paper)*
Zheng Wang, The Univ. of Texas at Austin (United States)
No Abstract Available

9763-36, Session 8

**Slow light, Purcell factor, and losses in hyperbolic metamaterials and surface plasmon polaritons: a critical assessment** *(Invited Paper)*
Jacob B. Khurgin, Johns Hopkins Univ. (United States)
Hyperbolic metamaterials (HMM) have attracted significant interest in the research community due to their ability to guide light with large wave-vectors as well as due to their ability to enhance radiative processes via large Purcell factor. Naturally, the group (and energy) velocity in these materials can be quite low, so it is important to investigate it and to compare 3D HMM’s with 2D surface plasmon polaritons (SPP’s) We develop a simple yet rigorous theory based on Kronig-Penney approach and obtain a number of interesting results, which, in hindsight should have been anticipated by the community. First of all, large Purcell factor and Slow group velocity in both HMM’s and SPP’s always occur when significant (up to 50%) fraction of energy is coupled to the free electrons in the metal, leading to large loss. Hence, while the radiative decay can be enhanced significantly, most of the emitted light stays in the metal. Second, the large wave-vector modes in both HMM’s and SPP’ are always slow propagating, lossy, and have high impedance, making them difficult to couple outside of the material. Third, and most critical, HMM’s are nothing but arrays of coupled SPP’s and offer no advantage whatsoever over a simple SPP in a single layer of metal or in a slot, when it comes to slow light, enhancing radiative decay, or near field imaging.

9763-37, Session 9

**Nanophotonics for controlling the response of atomic vapors** *(Invited Paper)*
Uriel Levy, Liron Stern, The Hebrew Univ. of Jerusalem (Israel)
No Abstract Available

9763-38, Session 9

**Nanophotonic magnetic resonance spectrometer for trace chemical and biomolecular sensing** *(Invited Paper)*
Victor M. Acosta, The Univ. of New Mexico (United States)
No Abstract Available

9763-39, Session 9

**Parametric interactions in dispersion-engineered photonic crystal waveguides** *(Invited Paper)*
Gadi Eisenstein, Technion-Israel Institute of Technology (Israel)
No Abstract Available

9763-40, Session 9

**Photonic crystal Fano lasers** *(Invited Paper)*
Jesper Mork, Technical Univ. of Denmark (Denmark)
No Abstract Available

9763-41, Session 10

**Measuring attostrains in a slow-light fiber Bragg grating** *(Invited Paper)*
Michel D. F. Digonnet, Stanford Univ. (United States)
No Abstract Available

9763-42, Session 10

**Tunable photonic crystals by holographic optical tweezers**
Maya Yevnin, Yael Roichman, Jacob Scheuer, Tel Aviv Univ. (Israel)
No Abstract Available

9763-43, Session 10

**Miniature slow light optical buffers** *(Invited Paper)*
Misha Sumetsky, Aston Univ. (United Kingdom)
No Abstract Available

9763-44, Session 10

**Adaptive holography for optical sensing applications** *(Invited Paper)*
Stefania Residori, Umberto Bortolozzo, Institut Non Linéaire de Nice Sophia Antipolis (France)
No Abstract Available
Spectroscopy of atoms confined in hollow-core photonic crystal fibers (Invited Paper)
Fetah Benabid, Univ. de Limoges (France)
No Abstract Available

Co- and counter-propagating slow light systems (Invited Paper)
Toshihiko Baba, Yokohama National Univ. (Japan)
No Abstract Available

Tunable optical delay line based on micro-ring resonators (Invited Paper)
Yundong Zhang, Yongfeng Wu, Changqiu Yu, Hui Li, Chunyu Zhang, Tuo Zhang, Ping Yuan, Harbin Institute of Technology (China)
No Abstract Available

Comparison of methods for achieving induced transparency or absorption with pulse delay or advancement in a single microresonator (Invited Paper)
Albert T Rosenberger, Oklahoma State Univ. (United States)
No Abstract Available

Rotation rate optimization by nonlinear phase shift in optical resonant microring waveguide (Invited Paper)
Hao Zhang, Junjie Jin, Jian Lin, Jiayang Chen, Anping Huang, Zhisong Xiao, BeiHang Univ. (China)
Chip-scale optical inertial rotation sensors based on Sagnac effect have distinct advantages in aspects of physical size, weight, power consumption and cost, and have the most potential to become the next generation optical gyroscopes. In this paper we theoretically analyse that nonlinear phase shift is introduced into microring resonant, in which quality factor (Q) is enhanced by the nonlinear phase shift. At the same time, the sensitivity of gyro is also enhanced by nonlinear phase shift. Comparison is done for three different descriptions of gyroscope sensitivity, and the relations and differences among them are demonstrated.

Photon drag effects in a slow-light medium: recent progress (Invited Paper)
Robert W. Boyd, Univ. of Ottawa (Canada)
No Abstract Available

Optical nonlinearities using lossy resonances (Invited Paper)
Michelle L. Povinelli, The Univ. of Southern California (United States)
No Abstract Available

Optical properties of NaLuF4: Yb3+: Tm3+/Ho3+ rare earth nanocrystals in microstructure hollow fiber
Yundong Zhang, Hui Li, hanyang Li, yongfeng Wu, changqiu Yu, Tuo Zhang, Ping Yuan, Harbin Institute of Technology (China)
No Abstract Available

Slow and fast light through Brillouin scattering-induced transparency (Invited Paper)
Gaurav Bahl, Univ. of Illinois at Urbana-Champaign (United States)
No Abstract Available

Employing biological matter as active optical elements: a new route in nanophotonics (Invited Paper)
Pietro Ferraro, Istituto di Scienze applicata e Sistemi Intelligenti (Italy)
No Abstract Available

Signal revivals in pulsed Rydberg four-wave mixing in thermal ensembles (Invited Paper)
Yi-Hsin Chen, Fabian Ripka, Robert Löw, Tilman Pfau. 5. Physikalisches Institut, Universität Stuttgart (Germany)
No Abstract Available
9763-55, Session 13
**Scanning-free characterization of local Brillouin spectra based on transient analysis (Invited Paper)**
Avinoam Zadok, Eyal Preter, Bar-Ilan Univ. (Israel)
No Abstract Available

9763-56, Session 14
**Light pulse slowing down using backward-wave four-wave mixing (Invited Paper)**
Konstantin Shcherbin, The Institute of Physics (Ukraine); Pierre Mathey, Univ. de Bourgogne (France)
The nonlinear phase shift per unit length obtained by the transmitted and phase conjugate waves in the backward-wave four-wave mixing may be considered as effective refractive index. Analysis of the spectral profiles of the nonlinear phase shift shows high potential of the technique for slowing down of light pulses. The slowing down is achieved using backward-wave four-wave mixing in media with local and nonlocal response. The delay and shape transformation of output pulses are studied and compared for the transmitted and phase conjugate channels. It is shown that the phase conjugate pulse achieves a longer delay under typical experimental conditions.

9763-57, Session 14
**Transmission matrix approach to light control in diffusive media (Invited Paper)**
Sylvain Gigan, Lab. Kastler Brossel (France)
No Abstract Available

9763-58, Session 14
**Classical, semi-classical, and quantized-field descriptions of light propagation in general non-local and non-stationary dispersive and absorbing media (Invited Paper)**
Verne L Jacobs, U.S. Naval Research Lab. (United States)
No Abstract Available

9763-59, Session 14
**Influence of nanorod absorption spectrum width on superluminality effect for laser pulse propagation**
Vyacheslav A. Trofimov, Tatiana M. Lysak, Lomonosov Moscow State Univ. (Russian Federation)
In this paper we investigate of superluminality effect at the femtosecond pulse propagation in a medium with gold nanorods. We take into account two-photon absorption (TPA) of laser radiation by nanorods, and time-dependent nanorod aspect ratio changing due to their melting because of the laser energy absorption, and the nanorod absorption spectrum width. On the basis of computer simulation we demonstrate this effect in a medium with positive phase-amplitude grating, induced by laser radiation if a weak laser energy absorption takes place on the laser pulse dispersion length. We show analytically the similarity between the pulse propagation in a medium with positive phase-amplitude grating and chirped incident pulse propagation in a medium with amplitude grating.

9763-60, Session 14
**Photon probability control**
Benjamin T. Solomon, Xodus One Foundation (United States)
Quantum theory does not have a mechanism that explains how Nature implements probabilities. Thus, the main objective of this paper is to present new directions for the research into the control of photon localization from probabilistic properties with the expectation of improving photon collection and loss mitigation. It is known that photons are not affected by the presence of electric or magnetic fields. Therefore, an alternative question is, can photon probabilities be controlled? Probability control means vectoring and modulation. Vectoring is the control of the direction of localization, and modulation is the control of the distance to localization. Therefore, this paper proposes a control mechanism by rethinking the foundations of quantum theory, using (i) a modified Schrödinger wave function [19], (ii) a new structure for particle design [20], (iii) the existence of subspace (x, y, z & no t), (iv) that all particles consists of a disc of the modified Schrödinger or probabilistic wave function, orthogonal to the particle’s motion vector [20] and (v) all other particle properties (e.g. em wave, charge, mass, etc.) are added to this structure [20]. The shape of the new probabilistic wave function is very close to that of the Schrödinger wave function, but it is not integrable, and not distinguishable without very sensitive experiments. It is proposed the proof of subspace lies in the photon’s electromagnetic wave in a manner consistent (iv) & (v). A Glass Thought Experiment is used to clarify how probabilities are effected and as a result it is proposed that the random distribution of photons across an Airy disc is not due to the photon probability but due to the random behavior of electron shells receiving the photon localization. Finally, it is proposed that probabilities can be controlled [22] by altering the electric and magnetic field densities, and a modified Airy disc experiment is proposed to confirm these findings.
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9764-1, Session 1

Selective seminal optics and photonics processes (Invited Paper)
Robert R. Alfano, The City College of New York (United States) and Institute for Ultrafast Spectroscopy and Lasers (United States)

This talk presents an overview on seminal research in optical science, condensed matter physics, biophysics, biology, biomedical, nonlinear optics, and structure light propagation and interactions at CCNY.

The advent of ultrafast laser pulses with picosecond and femtosecond pulse has led to unravel some of mysteries in the molecular world leading to breakthroughs in various areas of science. These are:

• The discovery of White Light Continuum called now Supercontinuum (SC) in three seminal papers in PRL 24, 1970. The main mechanism behind SC is nonlinear Kerr index n2 causes self phase modulation (SPM). The use of an addition Seed pulse can enhance spectral broadening by Cross phase modulation (XPM) in optical fibers with Solitons and Rogue waves. SC is used in many diverse applications: pump – probe, communications, accurate comb clocks, and super resolution microscopes to name a few

• The first Direct measurement of Optical Phonon’s lifetimes in calcite and observation of creation of daughter vibrations in time from excited mother vibration in liquids

• The first Direct measurement of creation and decay of Spin Angular Momentum of electrons in GaAs under Picosecond Circular Polarized Light carrying Optical Spin Angular Momentum

• Discovered light pulse breaking up into ballistic, snack and diffusive components in scattering, media such as um beads and tissues with the aim to develop optical mammography. Ballistic light is heart of OCT and 2-Photon Excitation fluorescence microscopes in tissues: brain and eye.

Steady state optical spectroscopy research lead to using optical spectroscopy (Fluorescence and Raman) to:

• First apply to cancer detection in label free tissues to open the field of Optical Biopsy.

• Current advances in Biomedical Optics shows that Tryptophan as a key biomarker for aggressive cancers; and shows there are three new optical windows with the Golden window #5 the best for penetrating tissue from 1600 nm to 1800nm where the penetration length is the longest despite the slightly more absorption but signification reduction in Mie scattering which blurs images more for therapy window at 650 nm to 900 nm.

The use of Complex light with OAM offers potential deeper tissue penetration:

• LG and Bessel beams offer possible observing hidden transitions via selection rules OAM L

• Bessel beams possible slowing down in free space and dielectrics for optical buffer.

9764-2, Session 1

Extraordinary momentum and spin in structured light (Invited Paper)
Konstantin Y. Bliokh, RIKEN (Japan)

I will overview recent theoretical and experimental studies, which revisit fundamental dynamical properties of light: momentum and angular momentum. I will show that the commonly accepted approach based on the use of the Poynting vector and the corresponding angular momentum does not work well for optical fields and laboratory experiments. An alternative approach requires revisiting the electromagnetic field theory and its connection with optics and quantum mechanics. It turns out that the canonical (rather than kinetic) field-theory picture of gauge-dependent momentum and spin densities of the massless electromagnetic field is perfectly consistent with the laboratory optical experience, provided that the Coulomb gauge is chosen.

The above analysis is not of purely theoretical interest. This new ‘canonical’ approach to the momentum and angular momentum of light has allowed us to predict qualitatively new types of the spin and momentum in structured optical fields [1–5]. These are:

1. The transverse spin angular momentum, which is orthogonal to the wave vector and is independent of the helicity;

2. The anomalous transverse momentum, which depends on the helicity of light and exerts a weak anomalous optical pressure orthogonal to the wave vector.

Both these quantities have attracted considerable attention and have been described and measured experimentally in several optical systems.


9764-3, Session 1

Optical angular momentum transfer to trapped particles in vacuum (Invited Paper)
Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

Optical manipulation of mesoscopic particles remains a very powerful method for both fundamental and applied science. The field has seen great advances for the biosciences including new studies of single molecules and force studies on cells. In the physical sciences, studies have also seen groundbreaking work in many areas. In this paper we describe some of the recent work looking particularly at the trapping of particles in vacuum with an emphasis on optical angular momentum transfer. In particular the talk will describe

i) the transfer of spin angular momentum to one or more birefringent particles held in vacuum. The dynamics of particle motion and interaction between particles will be discussed

ii) Work towards a complete understanding of orbital angular momentum transfer in vacuum and dependency of particle dynamics on particle properties and azimuthal index of the light field

9764-4, Session 1

High-resolution optical imaging and control using speckle patterns and photonic force microscopy with nanostructures (Invited Paper)
Yong-Hoon Cho, KAIST (Korea, Republic of)

High-resolution optical imaging and control play an important role for the study of processes in biological cells and nanostructures with subdiffraction resolution. First, we present a super-resolution method that can be
performed by utilizing general fluorophores with any intrinsic blinking properties. Temporal emission fluctuation of fluorophores is induced and controlled by speckle patterns illumination. Using our method, we demonstrate the capability of produce sub-diffraction resolution images. Next, we investigate translational and rotational Brownian dynamics of a nanowire confined in an optical trap using dual particle tracking system. We obtained the isolated angular fluctuations extracted from rotational Brownian motions. We measured the physical properties of scanning probe in optical trap such as stiffness and torque constants, depending on laser power, polarization direction and the length of the nanowire, suggesting an accurate measurement of Brownian motions and physical properties of nanowire as a scanning probe in a photonic force microscopy.

9764-6, Session 2

Waveguide quantum electro dynamics with spin-orbit coupling of light (Invited Paper)

Sahand Mahmoodian, Immo Söllner, Sofie Lindskov Hansen, Alisa Javadi, Leonardo Midolo, Gabija Kirsanke, Tommaso Pregnolato, Søren Stobbe, Peter Lodahl, Niels Bohr Institute (Denmark)

Waveguide quantum electrodynamics (QED) studies the interaction between a quantum emitter and a one-dimensional photonic reservoir. Such systems have been proposed to form the operational basis for single photon transistors, photon sorters and quantum gates. High fidelity operation of such devices requires the coupling rate between the quantum emitter and the waveguide mode be much higher than that of other modes. Such a regime has recently been demonstrated with quantum-dots in photonic crystal waveguides (PCWs).

Here we show that the physics of waveguide QED changes drastically when the effects of the spin-orbit coupling of light are harnessed. When light is confined to a region on the wavelength scale, due to the transversality condition, it acquires a non-transverse electric field component. This can lead to spatial positions where the local electric field is circularly polarized. Since counter propagating modes are related through complex conjugation, they have circular polarizations of the opposite handedness. The handedness of the local electric field polarization is therefore locked to the propagation direction. When such a waveguide is coupled to a quantum emitter with circularly polarized transition dipole moments, spontaneous emission becomes unidirectional and photon scattering becomes non-reciprocal. We show that this can be used to realize electron spin-photon interfaces, non-reciprocal photon transport, and quantum gates for both flying and static qubits.

9764-7, Session 2

Quantum issues with structured light

Mathew D. Williams, Univ. of East Anglia (United Kingdom); David S Bradshaw, University of East Anglia (United Kingdom); David L. Andrews, Univ. of East Anglia (United Kingdom)

Descriptions of optical beams with structured wavefronts or vector polarizations are widely cast in terms of classical field theory. The corresponding fully quantum counterparts to such representations often present new insights into what is physically observed, and they are especially of interest when tackling issues such as entanglement. Similarly, when determining angular momentum densities, it appears that the separate roles of photon spin and beam topological charge can only be satisfactorily addressed within a quantum framework. In some such respects the quantum versions of theory might be considered to introduce an additional layer of complexity; in others, they can clearly and very substantially simplify the theoretical representation.

At the photon level, the fully quantized descriptions of topologically structured and singular beams nonetheless raise important fundamental questions and puzzles, whose resolution continue to invite attention. It is not simply the notion of a photon travelling along a path ostensibly longer than a straight line (as several recent papers have suggested) that offers a puzzle. Many of the less contentious mechanistic interpretations and predictions - those that appear to be supported by a congruence between classical and quantum optical descriptions, essentially confining electromagnetic field and state wavefunction concepts - prove to fail in quantum systems beyond single photon input. This paper explores some of the theoretical pitfalls, and it highlights some physical implications that emerge from a fully quantum treatment of theory.
Structured amplitude and phase fields behind microstructures: The quest for high contrast modulation at proximity. (Invited Paper)

Toralf Scharf, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Microstructures can be used to realize repetitive and singular high contrast features at different distances behind the structure. For practical applications the amplitude field needs to be considered. To realize defined amplitude features at long distances behind the surface of reference the phase of the light field plays a crucial role. The highest contrast can be reached if phase singularities (or phase jumps) can be used because at the positions of their appearance in space the intensity becomes zero. For practical applications it is important to identify cases where phase singularities can be design in position in space. As a first example we will discuss the case of phase fields produced by Talbot light carpets for wavelength scale amplitude gratings. Such systems are used today in lithography to print small repetitive structures. For arbitrary structures to be printed different design strategies need to be applied. As a second example we will discuss the case of ruled based design phase mask technique to realize high-resolution prints at proximity. In such a case phase singularities are created at the phase level and can be found still at long distances, which leads to high contrast modulation far behind the microstructure. An interesting situation appears if a fully optimized diffractive optical structure is used to create particular amplitude fields at defined proximity distances. We will discuss the appearance of phase singularities behind the structure in such a case and give details of their behavior at long proximity distances.

Compact solutions for optical fiber tweezers using Fresnel zone and phase plates fabricated using focused ion beam milling

Ana Rita S. Rodrigues Ribeiro, INESC TEC (Portugal); Pabitra Dahal, Masdar Institute of Science & Technology (United Arab Emirates); Ariel R. N. S. Guerreiro, Pedro A. S. Jorge, INESC TEC (Portugal); Jaime Viegas, Masdar Institute of Science & Technology (United Arab Emirates)

Fresnel Zone and Phase Plates (FZP and FPP) offer compact and reliable solutions for light focusing since these are essentially planar diffractive structures with supple control of the focal distance. In the framework of beam shaping, these devices can be used in free space optics applications, in laser technologies, or, for instance in optical trapping.

In this work FZP and FPP fabricated using Focused Ion Beam (FIB) milling on optical fibers tips are presented. Primary, single mode fibers are spliced to a segment of multimode fiber allowing to expand the core region. Subsequently, distinct designs of FZP and FPP with several focusing distances are milled on the fiber tips. In this regard, the zone and phase plates offer distinct focusing characteristics which are here presented and analyzed. Moreover, the output optical intensity field of the FPP and FZP are experimentally measured and validated with simulations using an implementation of the finite difference time domain method. Lastly, these tools (FZP and FPP) are tested and their efficiency compared as fiber optical tweezers using yeast cells in compact setups.

Simultaneous spatial frequency modulation imaging and micromachining with a femtosecond laser (Invited Paper)

Michael D. Young, Erica K. Block, Colorado School of Mines (United States); David G. Winters, Jeffrey J. Field, Keith Wernsing, Randy A. Bartels, Colorado State Univ. (United States); Jeffrey A. Squier, Colorado School of Mines (United States)

A Ti:Al2O3 chirped pulse amplification system is used to simultaneously image while machining. By combining Simultaneous Spatial and Temporal Focusing (SSTF) with SPatial Frequency modulation for Imaging (SPIFI) we are able to decouple the imaging and cutting beams in order to attain a resolution and a field of view that is independent of the cutting beam while maintaining single element detection. This setup allows for real time feedback with potential for simultaneous nonlinear imaging and imaging through scattering media. The novel SSTF machining platform uses complex refractive optics that are in general prohibitive for energetic, amplified pulses that might otherwise compromise the integrity of the focus as a result of nonlinear effects.

SPIFI in this context has multiple inherent advantages compared to traditional imaging with a two-dimensional detector such as a CCD. One, as stated, it utilizes single element detection rendering it compatible when imaging within specimens that may scatter the signal photons, two, it can exceed resolution limits inherent with standard imaging, and three, these resolution limits can be exceeded in multiple modalities – direct or nonlinear imaging. Finally, SPIFI uses an extended source geometry, which when compared to traditional point-scanning imaging methods, greatly facilitates high-speed imaging. The line focus is ascribed unique modulation frequencies as a function of position along the line, by a 2D spatial light modulator (SLM). The SLM allows for the creation of continuous or grayscale masks, and the quick implementation of experimental mask designs.

Spatial coherence engineering of optical beams (Invited Paper)

Laura Waller, Univ. of California, Berkeley (United States)

Partially coherent wave-fields are inherently richer than coherent wave-fields, having many more degrees-of-freedom. Coherence engineering – the measurement and control of such high-dimensional beams - brings new dimensions to microscopy, enabling improved 3D imaging, digital refocusing and digital aberration correction as a post-processing step. This talk will describe new methods for experimental wave-field measurement and control of spatial coherence based on computational imaging approaches. Characterizing coherence of a 2D beam requires 4D functions (e.g. mutual intensity, Wigner function) and so becomes a large-scale imaging problem if one wishes to maintain high resolution in all four dimensions. We will show how coherence information can be obtained from multiple images in a defocused intensity stack or from multiple images taken with varying Fourier space coded apertures. In particular, we describe these advances within the framework of phase-space imaging. By leveraging recent advances in computational microscopy, we achieve gigapixel-sized datasets in a practical system and demonstrate how this information can be used for improved 3D microscopy.

Cell sorting using efficient light shaping approaches

Andrew R. Bañas, OptoRobotix ApS (Denmark);
Early detection of diseases can save lives. Hence, there is emphasis in sorting rare disease-indicating cells within small dilute quantities such as in the confines of lab-on-a-chip devices. In our work, we use optical forces to isolate red blood cells detected by machine vision. This approach is gentler, less invasive and more economical compared to conventional FACS systems. As cells are less responsive than plastic or glass beads commonly used in the optical manipulation literature, and since laser safety would be an issue in clinical use, we develop efficient approaches in utilizing lasers and light modulation devices. The Generalized Phase Contrast (GPC) method that can be used for efficiently illuminating spatial light modulators or creating well-defined contiguous optical traps is supplemented by diffractive techniques capable of integrating the available light and creating 2D or 3D beam distributions aimed at the positions of the detected cells. Furthermore, the beam shaping freedom provided by GPC can allow optimizations in the beam's propagation and interaction with the captured cells.

**9764-16, Session 4**

**Holo-GPC**

Jesper Glückstad, Technical Univ. of Denmark (Denmark)

Shaping light based on phase-only techniques is important in many commercial, industrial or research applications due to its efficient energy utilization. Phase-only light shaping approaches can save around ~90% the energy that is lost if using simple blocks or absorbing filters. Generalized Phase Contrast (GPC), a phase-to-intensity light shaping technique that can generate contiguous speckle-free extended shapes. As GPC is a point-to-point mapping of an input phase mask into output intensity, the input phase mask sets constraints on the distribution of the output beam, limiting the output to a single copy of the intensity pattern to the imaging plane. Another widely commonly practiced light shaping method, holography, generally suffers from noisy or speckled output when creating extended shapes. Holography, however, is advantageous for generating sparse diffraction-limited spots with controllable axial and lateral locations. A hybrid of holography and GPC, Holo-GPC, combines the strengths of GPC and holography and is therefore capable of distributing a plurality of well-defined speckle-free extended optical shapes over a wider working volume. Potential uses of this new light shaping approach include optical trapping and manipulation, cell sorting, advanced microscopy, laser materials processing and stimulation for biological research such as neurophotonics and optogenetics.

**9764-17, Session 4**

**Dark GPC**

Jesper Glückstad, Technical Univ. of Denmark (Denmark)

Generalized Phase Contrast (GPC) is an efficient method for generating speckle-free contiguous optical distributions useful in diverse applications such as static beam shaping, optical manipulation and two-photon optogenetics. GPC thus allows efficient utilization of typical Gaussian lasers in such applications using binary-only phase modulation. Using a spatial light modulator, we have demonstrated simple and efficient beam shaping of arbitrary shapes geared towards materials processing, biophotonics research and other contemporary applications. However, GPC-configurations can also be adjusted to generate coherent beams with extended nodal areas of darkness. This so-called Dark-GPC method will be presented theoretically and backed-up by new experimental demonstrations. Using only binary phase modulation extended nodal areas of darkness surrounded by high brightness borders can be dynamically generated on the fly using a fast binary-only spatial phase modulator.

**9764-18, Session 5**

**Optical quantification of forces at play during stem cell differentiation (Invited Paper)**

Christine M Ritter, Niels Bohr Institute, University of Copenhagen (Denmark); Joshua M Brickman, DanStem, University of Copenhagen (Denmark); Lene B. Oddershede, Niels Bohr Institute (Denmark)

Optical tweezers are the only nano-tool capable of reaching inside a living organism in a nearly non-invasive manner to measure forces and distances within the living cell. There is an increasing awareness of the crucial influence mechanical forces has on live cell processes, for instance on cell fate. With the ability to develop into any specialized cell, stem cells are regarded the holy grail of regenerative medicine. During embryonic development the cells are exposed to mechanical forces and have themselves mechanical properties that change upon differentiation. We here use advanced optical trapping techniques to quantify the mechanical properties of stem cells and how these change upon specification. The stem cell culture used consists of two cell types priming either towards the primitive endoderm or towards the epiblast; at a certain stage during embryonic development, these two cell types co-exist in a dynamic equilibrium. The functional properties of these cells are very different; however, the transcriptional differences are quite small. Using endogenously occurring lipid granules as handles for the optical trap, we probe the mechanical properties of the viscoelastic properties of these two sub-populations. As the optical traps are implemented in a confocal microscope, we simultaneously follow the development of the cells which express fluorescent reporters. We observe significantly different mechanical properties of stem cells at different developmental stages. After establishing this correlation, we use the mechanical properties as markers of cell fate and show how external factors determine cell fate.

**9764-19, Session 5**

**Time domain analysis of the Brownian motion of trapped particles in optical tweezers**

Sudipta K. Bera, Indian Institute of Science Education and Research Kolkata (India); Ronoojye Adhikari, Institute of
Mathematical Sciences (India); Rajesh K. Nayak, Ayan Banerjee, Indian Institute of Science Education and Research Kolkata (India)

The motion of an optically trapped Brownian particle located away from walls is well-described by the Ornstein-Uhlenbeck (OU) stochastic process. The drift and diffusion coefficients of the process are related to the trap stiffness and to the particle mobility, respectively. While most conventional analyses of the motion of trapped particles is performed by analyzing the power spectral density (PSD) of the Brownian motion, that method requires a large number of data points for trap characterization, and is often inaccurate for weak traps. We have developed two processes for analyzing the dynamics of the Brownian motion in the time domain: a) by an exact Bayesian inference, and b) by an auto-regressive (AR) model, to obtain the trap stiffness and particle mobility directly from particle trajectories. For the Bayesian model, the maximum a posteriori estimates of the parameters are obtained from the joint probability density functions, while for the AR model, properties of the AR(1) coefficient can be directly related to the trap stiffness and mobility. We perform exhaustive theoretical simulations to validate our techniques and show that both methods yield closer matches to input parameters compared to the PSD method. We also use both techniques in actual experimental data and obtain accurate estimates of the trap stiffness and the diffusion coefficient of the aqueous trapping medium. Our techniques are ideal for low trap stiffness regimes which is particularly relevant for biological cells, and also provides accurate results for a low number of data points, thus reducing restrictions on sampling rates for data collection in optical tweezers.

9764-20, Session 5
Measurement and accumulation of electric charge on a single dielectric particle trapped in air
Haesung Park, Thomas W. LeBrun, National Institute of Standards and Technology (United States)

We have developed an instrument to controllably load selected dielectric microparticles into an optical trap using a piezoelectric transducer. During loading, particles may be repeatedly landed on the substrate and relaunched, leading to charge transfer and accumulation. The net charge on the particle becomes sufficient to allow electrostatic forcing to drive ballistic motion and measure optical forces over a two micrometer range of displacement — two orders of magnitude greater than thermal fluctuations of 20nm. Unlike nebulizer-based methods, this approach allows tracking the selected dielectric particle over repeated cycles of launching and introduction into the optical trap by modulating the incident power of the trapping laser. The induced motion of the trapped particle is simply described using classical mechanics. Using the transient response combined with video microscopy, the net charge on a single microparticle is non-invasively measured with simultaneous calibration of positional detector and trap stiffness in real-time for each measurement. As a result, we are able to experimentally measure the successive accumulation of electric charge on a single polystyrene microparticle using transient response analysis during 200 cycles of particle launching.

9764-21, Session 5
Wavelength detection with sub-femtometer resolution
Nikolaus Metzger, Kishan Dholakia, Michael Mazilu, Univ. of St. Andrews (United Kingdom)

Light scattering effects in media has been researched extensively due to its adverse effect on the performance of an optical system. Similar light propagation in a disordered or random media is generally regarded as a randomization process of the optical field destroying the information contained within the initial beam. However, a coherent beam propagating in a disordered medium yields a unique speckle pattern. The underlying key principle is that the scattered beam maintains its initial spatial and temporal coherence. The resulting interference is the key for the creation of a distinct speckle pattern dependent on the incident light field. Speckle pattern are the optical phenomena resulting from the interference of coherent light and can be used as a fingerprint to identify characteristic like in this presentation its wavelength.

In this work the prospect of using a speckle pattern for wavelength fluctuation detection from the femtometer level is presented. Physical key parameters that influence the speckle creation, spatial sampling and analysis are investigated. Their subsequent influence and optimization on the maximum achievable resolution and bandwidth are explored. The wavelength detection system is subsequently applied to resolve the dither signal of a Rubidium locked laser system. Additionally a theoretical model of the optical system is presented that shows qualitative agreement with the experimental observations and aids to understand the system performance.

9764-22, Session 5
Calibration of non-optical forces in optical tweezers
Ann A. Bui, Anatoliy Kashchuk, Alexander B. Stilgoe, Timo A. Nieminen, Halina Rubinsztein-Dunlop, The Univ. of Queensland (Australia)

Calibration of optical tweezers involves finding the force acting on the trapped particle for a given position. It can be done through Boltzmann statistics, which finds the occupation probability over the trap, thus giving the trap potential, then the trapping force. However, not all forces acting on the particle may be optical forces. For example, the particle might be near a wall, which exerts an additional force on the particle and leads to changes in the occupation probability. Assuming that one were able to find the force acting on the particle, as well as the position of the particle in a series of measurements which were not necessarily synchronised, one would be able to construct the potential curve of a trapped particle.

We carry out a calculation of the optical force numerically based on the T-matrix method and generalised Lorenz-Mie theory. Experimentally, we trap a particle with varying distances to the wall and map the position of this particle using a quadrant photodiode, or position-sensitive detector. The measurement of the deflection in the trapping beam gives a measurement of the optical force. Here we use simulation and experiment to show the effectiveness of using these two calibration methods to find non-optical forces acting on a trapped particle. If we, in simulations, add an exponential wall the non - optical forces can be tractable.

9764-23, Session 5
Mapping the spectral twist of few cycle vortex pulses
Martin Bock, Ruediger Grunwald, Max-Born-Institut für Nichtlineare Optik und Kurzzeitenspektroskopie (Germany)

The defined preparation and reliable detection of orbital angular momenta (OAM) maps in ultrashort wavepackets opens additional channels for optical communication, information processing and ultrafast laser-matter interaction. Topological charges, torsional directions and other spatio-temporal characteristics of the optical field can be identified by interferometric methods or analyzing Poynting-vector maps with Shack-Hartmann type wavefront sensors. Such techniques were recently studied in extenso, whereas much less attention was up to now directed to the spectral domain. The ultrabroad bandwidth of few-cycle pulses, however, contains highly specific information about the fine structure of vortex fields has the capability for a more effective encoding information or selective excitation...
of matter states. In astrophysics, e.g., the fine structure of OAM maps indicates interactions of light with massive objects over large distances. In our experiments, spectral vortex signatures of few-cycle laser pulses were detected by spatially resolved spectroscopy and compared to time-wavefront measurements. The results of recent experimental and theoretical studies are presented. Characteristic spectral vortex patterns were scanned by a fiber-coupled spectrometer and their statistical moment were analyzed. Further implications of spatio-spectral information content for singular optics are discussed.

9764-24, Session 6

**Single-beam interference from plain Gaussian and OAM wavefronts (Invited Paper)**

Sergei Popov, KTH Royal Institute of Technology (Sweden); Maxime Favier, Observatoire de Paris (France)

Liquid crystal SLM is used to generate an interference pattern from plain-wave Gaussian and Laguerre-Gaussian beam (carrying an orbital angular momentum, OAM) originating from one laser source. Feeding linearly polarized light through the SLM operating in the mode of a standard gray-scale phase retardation plate, radial phase modulation of the incident beam can be realized. In the simplest case, gray scale variations of the retardation phase correspond to discretized phase modulation between 0 and 2π per one azimuthal rotation in the plane. A plane wave modulated by such a phase plate with radially varying phase produces intensity pattern with a dark spot in the central area. With increased phase modulation to 4π and 6π per one rotation, high-order OAM beams produce intensity patterns with two or three dark spots, respectively, across the plane of beam propagation. Making use of interference of such beams with zero-order component of the incident beam, it is possible to realize an interference pattern without an additional arm. However, due to discretized pixels of the SLM, continues phase modulation (as realized with traditional approaches) cannot be done. Furthermore, along with the phase modulation, a control voltage applied to each pixel induces additional birefringence. This should be compensated by proper modification of the incident light polarization. Using a matrix technique, we can identify modified states of light polarization to compensate local birefringence effect from pixels, and obtain clearly visible interference between zero-order Gaussian and higher order OAM beams.

9764-26, Session 6

**Space-variant polarization of collinear and non-collinear optical beams**

Enrique J. Galvez, Joshua Jones, Behzad Khajavi, Colgate Univ. (United States)

We present our study of space-variant polarization patterns that occur when two optical beams are combined, with at least one containing an optical vortex. When the two beams are collinear we investigate the symmetric and non-symmetric polarization singularities that are generated. In the case when the component beams are Laguerre-Gauss eigenmodes we observe C-points and high-order C-points, also known as hyper-Cpoints. When we create asymmetric C-points we also find hyper monsters. For non-eigenmodes we observe arrays of C-points spatially distributed. When the beams are made non-collinear, we see the appearance of polarization fringes, which in most cases imply a 3-dimensional pattern of polarization ellipses that describe Mobius strips or twisted ribbons along a closed loop.

9764-27, Session 6

**Soliton formation by interacting Airy beams**

Falko Diebel, Westfälische Wilhelms-Univ. Münster (Germany); Dejan V. Timotijevic, Dragana M. Jovi? Savi?, Univ. of Belgrade (Serbia); Cornelia Denz, Westfälische Wilhelms-Univ. Münster (Germany)

Photonics and especially nonlinear photonics experience explosive growth during the last decade. Important roles in this development are played by the fascinating accelerated Airy beams on the one hand and by nonlinear effects such as solitons on the other. The potential arising from combining both topics to investigate nonlinear interaction of accelerated beams opens completely new aspects of research. The Airy function initially has been introduced as a free-particle solution of the nonlinear Schrödinger equation whose wave packet envelope shows two outstanding features: it stays unchanged and follows a parabolic trajectory while evolution. With the first realization of optical Airy beams [1] an active field of research was initiated, leading to a number of systematic investigations of the general properties of Airy beams in linear and nonlinear regimes. The unique ballistic-like, self-accelerating properties of the Airy beams moreover made them ideally suited for various applications ranging from micromanipulation, optical snow-blowers [2], all-optical routers [3], and even to ultrafast self-accelerating pulses [4]. Also the interplay between Airy beams and photonic lattices [5] has been investigated experimentally. In this contribution, we experimentally demonstrate a new type of spatial solitons arising from the mutual interaction of multiple two-dimensional Airy beams in a photorefractive nonlinear medium. We show the generation of solitons and soliton pairs depending on the number and phase relation of the superimposed Airy beams and support all experiments with comprehensive numerical simulations. Our experimental setup offers unprecedented flexibility for precise and reproducible studies of nonlinear dynamics of Airy beams, but is not limited to this particular class of beams.

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9764-28, Session 7

Liquid crystals as a test-bed for chiral optomechanics (Invited Paper)
Etienne Brasselet, Univ. Bordeaux 1 (France)

Forces exerted by light on matter basically results from the absorption, modification or redirection of the linear momentum of light. A well-known example is the optical radiation pressure exerted by light on the interface between two media. Tailoring the optical radiation forces generally consists in engineering the scattering of light. We will discuss how the helicity of light can be used to control optomechanical effects, which relies on the interplay between the chirality of matter and that of light. This will be illustrated by recent developments on helicity-controlled optomechanics of chiral liquid crystals.

9764-29, Session 7

Circular dichroism in topological Floquet insulators: Implications for polarization sensitive devices and topologically protected quantum information processing
Parijat Sengupta, Enrico Bellotti, Boston Univ. (United States)

Optical chirality is manifest through circular dichroism (CD) which relates to a differential absorption of left and right circularly polarized light and is a key component of chiral meta-materials used in polarization sensitive imaging devices and display technologies. Topological insulators (TI) with their helical spin structure offer an active control over chiral handedness observed through a varying degree of polarization-dependent absorption. In a band gap open T1 with C2v symmetry which is described by a combination of the Rashba and Dresselhaus spin-orbit Hamiltonians, CD can be smoothly varied without any reconfiguration of the surface. CD, measured by the degree of circular polarization [1] which is the difference in absorption of right and left-handed light, normalized by the total absorption is then related to Berry curvature (derived from the geometric Berry phase) which describes the chirality of the surface electrons. Further, to externally modulate the inherent dichroism, we place the TI slab under the influence of a laser field, the so-called Floquet topological insulator [2], to renormalize the intrinsic band gap and tune the Berry curvature as a function of the light-induced mass term. The changed Berry curvature, dependent on the incident light frequency, manifests as an anomalous velocity to alter CD. Finally, we discuss implications for dichroic photo-currents and applications where the polarization of light can be turned into useful topologically protected electronic information via Chern number calculations.

References:

9764-30, Session 7

Chiral separation and twin-beam photonics
David S. Bradshaw, David L. Andrews, Univ. of East Anglia (United Kingdom)

It is well-known that, in a homogeneous fluid medium, most optical means that afford discrimination between molecules of opposite handedness are intrinsically weak effects. The reason is simple: the wide variety of origins for differential response commonly feature real or virtual electronic transitions that break a parity condition. Despite being electric dipole allowed, they manifest the chirality of the material in which they occur by breaking a selection rule that would otherwise preclude the simultaneous involvement of magnetic dipole or electric quadrupole forms of coupling. Although the latter are typically weaker than electric dipole effects by several orders of magnitude, it is the involvement of these weak forms of interaction that are responsible for chiral sensitivity.

There have been a number of attempts to cleverly exploit novel optical configurations to enhance the relative magnitude - and hence potentially the efficiency - of chiral discrimination. The prospect of success in any such venture is enticing, because of the huge impact that such an advance might be expected to have in the health, food and medical sectors. Some of these proposals have utilised mirror reflection, and others surface plasmon coupling, or optical binding methods. Several recent works in the literature have drawn attention to a further possibility: the deployment of optical beam interference as a means to achieve chiral separations of sizeable extent. In this paper the underlying theory is fully developed to identify the true scope and limitations of such an approach.

9764-31, Session 7

The spatial distribution of forces in highly focused beams
Daryl Preece, Univ. of California, San Diego (United States); Alexander B. Stilgoe, Timo A. Nieminen, Halina Rubinsztein-Dunlop, The Univ. of Queensland (Australia)

Recently experiments have indicated that spin in circularly polarized non-paraxial beams can generate orbital motion. Indeed it has been shown that tightly focused circularly polarized Bessel beams can generate a significant orbital motion even when no phase vortex is present. It is not entirely clear how this change in momentum occurs. We discuss the changes in the force distribution of highly focused beams as they propagate and how this affects experimental observation of the applied force.

Theoretical modeling can give a useful insight into how spin-orbit coupling practically manifests itself as highly focused beam propagate. We present theoretical data on the spin-orbital content of the beam with respect to position in the beam. Such modeling has shown significant differences between the spatial distribution of forces in the focused beams and those in beams, which are considered paraxial. We also discuss how spin-orbital coupling changes as beams propagate.

9764-32, Session 8

Untangled modes in multimode waveguides (Invited Paper)
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Small, fibre-based endoscopes have already improved our ability to image deep within the human body. Current fibre-based devices consist of fibre-
bundles in which individual fibres represent single pixels of the transmitted image. A novel approach introduced recently utilized disordered light within a standard multimode optical fibre for lensless imaging. Importantly, this approach brought very significant reduction of the instrument’s footprint to dimensions below 100 m. Such device may be used for imaging of structures deep inside living organisms directly through centimeters of living tissues without bringing about their extended collateral damage. In Neuroscience, this technology may assist to address important unanswered questions related to formation and recall of memories as well as onset and progression of severe neuronal disorders such as Alzheimer’s disease.

The two most important limitations of this exciting technology are (i) the lack of bending flexibility (imaging is only possible as long as the fibre remains stationary) and (ii) high demands on computational power, making the performance of such systems slow.

We discuss routes to allow flexibility of such endoscopes by broader understanding of light transport processes within. We show that typical fibers retain highly ordered propagation of light over remarkably large distances, which allows correction operators to be introduced in imaging geometries in order to maintain high-quality performance even in such flexible micro-endoscopes. Separately, we introduce a GPU toolbox to make these technique faster and accessible to researchers. The toolbox optimizes acquisition time of the transformation matrix of the fibre by synchronous operation of CCD and SLM. Further, it uses the acquired transformation matrix retained within the GPU memory to generate any desired holographic mask for on-the-fly modulation of the output light fields. We demonstrate the functionality of the toolbox by displaying an on-demand oriented cube, at the distal end of the fibre with refresh-rate of 20 ms.

9764-33, Session 8

Fiber communication using vector vortex beams

Bienvenu I. Ndagano, Melanie G. McLaren, Andrew Forbes, Univ. of the Witwatersrand (South Africa)

Spatial modes of light that carry orbital angular momentum (OAM) have been, over the past two decades, used to enhance the bandwidth of optical communication. Using the orthogonality of these modes, it has been shown that they can be used as information channels to significantly increase information transfer through both free space and optical fibres. This increase in bandwidth has however only been demonstrated using scalar modes; spatial modes with uniform polarization. Here we present a new class of spatial modes in the form of vector vortex beams. In these modes, the spatial and polarization degrees of freedom are preserved through turbulence. We demonstrate that by manipulating the geometric phase of light with a specially designed birefringent phase plate, we can generate these vector vortex modes. We propagated these modes through an optical fiber and evaluated the degree of non-separability at the fibre output. We showed that the spatial and polarization degrees of freedom are preserved through fibre propagation, thereby showing the superior robustness of vector vortex modes in carrying information in optical fibres.

9764-34, Session 8

Optical vortex beam transmission with different OAM in scattering beads and brain tissue media

Wubao B. Wang, Lingyan Shi, The City College of New York (United States); Lukas Lindwasser, The City Univ. of New York (United States); Paulo Marque, The City College of New York (United States); Martin P. Lavery, Univ. of Glasgow (United Kingdom); Robert R. Alfano, The City College of New York (United States)

Optical vortex beams carrying orbital angular momentum (OAM) have wide applications in trapping particles, imaging and medical diagnosis, micro-machines, spintronics, and quantum information. It is of great interest to reveal the influence of different OAM of optical vortex beams on propagation and penetration capabilities through the turbid media.

In this study, light transmission of Laguerre Gaussian (LG) and Bessel vortex beams with different OAM values (L) in scattering beads and mouse brain tissue media were investigated in comparison with Gaussian (G) beams. The LG and Bessel OAM beams were generated using a spatial light modulator (SLM) in reflection mode. The scattering media consist of various sizes and concentrations of latex beads in water solutions. The transmissions of LG, Bessel and G beams through scattering beads and brain tissue media were measured with different ratios of thicknesses (z) to scattering mean free path (ls) of the turbid media. The results indicate that within the regions where z/ls is small, the LG, Bessel and G beams show no significant difference, while in the regions where z/ls is 10 or higher, the vortex beams show higher transmission than G beams. In the diffusive region, the LG beams with higher L values show higher transmission than the beams with lower L values. The transition points from ballistic to diffusive regions for different scattering beads and brain tissue media were studied.

9764-35, Session 8

Resilience of vector vortex beams to atmospheric turbulence

Bienvenu I. Ndagano, Othmane Mouane, Melanie G. McLaren, Andrew Forbes, Univ. of the Witwatersrand (South Africa)

That light carries orbital angular momentum (OAM) has been demonstrated more than two decades ago. Since then, an emphasis has been made on using spatial modes of light that carry OAM to transmit digital information in long distance optical link. The spatial degree of freedom is highly affected by atmospheric turbulence which induces modal crosstalk between OAM channels, decreasing the signal purity. The atmosphere is however not birefringent and as such, does not affect the polarization degree of freedom. In this work we present a non-separable mixture of the spatial and polarization degrees of freedom in the form of vector vortex modes. We demonstrate techniques to generate and measure these vector vortex modes and applied them to study the propagation of vector vortex beams through turbulence. We characterized the modal coupling between vector modes and show that vector vortex modes are highly resilient to turbulence. We performed a comparative study of the degree of non-separability as a function of the turbulence strength and showed that the concurrence – a measure of non-separability – although affected by the turbulence, remains relatively high. This shows that the non-separability of the spatial and polarization degrees of freedom enhances the robustness of information channels when passing through turbulence.

9764-36, Session 8

Controlling quantum interference in highly multimodal systems

Tom A. W. Wolterink, Ravitej Uppu, Univ. Twente (Netherlands); Georgios Ctistis, Univ. Twente (Netherlands) and Saxion Univ. of Applied Sciences (Netherlands); Allard P. Mosk, Pepijn W. H. Pinkse, Univ. Twente (Netherlands)

Light transport in random scattering media strongly mixes light across the large number of involved modes. The resultant speckle pattern is highly sensitive to the scatterers’ configuration as well as the incident field. This sensitivity was recently exploited in quantum-secure authentication [1].

In recent years, wavefront shaping has been used to control light propagation in random scattering media. This enabled the demonstration
of linear optical circuits such as programmable multiport beam splitters [2], with scalability in the number as well as the functionality of the output ports without increasing the complexity and size of the optical setup. Recently, we demonstrated wavefront shaping of single photons in a random medium [3]. Here, by utilizing two single photons from a bright quantum light source, we demonstrate Hong-Ou-Mandel interference in a programmable two-port beam splitter realized with a random scattering medium.


9764-53, Poster Session

Chemical imaging at the nanoscale with photo-induced force microscopy

Junghoon Jahng, Faezeh Tork Ladani, Ryan Muhammad Khan, Eric O. Potma, Hemantha Kumar Wickramasinghe, Dmitry Fishman, Univ. of California, Irvine (United States); Sung I. Park, Molecular Vista, Inc. (United States)

A light-matter interaction has become ubiquitous, driven by both curiosity and a multitude of applications in fields ranging from biosensing to quantum optics. The nanoscale optical force microscopy and spectroscopy is a powerful tool for exploring the light-matter interaction under a diffraction limit. Because the near-field distribution is intimately linked to an object’s geometry and optical properties such as permittivity and polarizability, investigating the near-field distribution is a crucial for controlling light-matter interactions of nanostructure.

Recently developed Photo-induced Force Microscopy (PiFM) is very useful to deal with the near-field distribution by using metallic coated probe. When the light illuminates to the junction between the gold coated cantilever probe and the sample, the probe is able to pick up the longitudinal field distribution as an (induced) dipole force. Because the force comes from the light-matter interaction near the object, the force signal is very strong compared to the perturbation methods such as near-field scanning optical microscopy and tip-enhanced Raman spectroscopy. In this work, we will show the theoretical and experimental results to pick up the longitudinal evanescent field distribution with a total internal reflection based PiFM. Then, we will apply this technique to visualize the surface plasmon polariton. This photo-induced dipole force mechanism is a background free detection so that it is possible to address to a single molecule optical study.

9764-56, Poster Session

Propagation of vector vortex beams through turbulence

Bienvenu I. Ndagano, Melanie G McLaren, Andrew Forbes, Univ of the Witwatersrand (South Africa)

Using spatial modes of light is poised to be the next step in free-space bandwidth increase in point-to-point optical communication. Light carrying orbital angular momentum (OAM) is being extensively studied for this very purpose as it provides an additional degree of freedom that spans a discrete and infinite dimensional Hilbert space. As such, it would allow an infinite amount of information to be encoded on a photon. The propagation of spatial modes of light is however hindered by atmospheric turbulence which introduces random intermodal coupling, thereby affecting the fidelity of the detected signals. Here we propose a scheme in which vector vortex modes would be for communication instead of OAM modes. In vector vortex modes, the polarization and spatial degree of freedom are non-separable - a fundamental property of quantum entangled states. As the atmosphere is non-birefringent the polarization degree of freedom remains unaffected during propagation. We built an optical setup to generate and detect vector vortex modes using a q-plate. We simulate the atmospheric turbulence with the help of phase plate based on Kolmogorov’s theory of turbulence. We determined the intermodal coupling between four nearly degenerate vector modes as well as the energy transfer to higher order spatial modes as result of the turbulence plate. By evaluating the non-separability of the vector modes through a measurement of the concurrence, we showed that the polarization enhances the resilience of OAM modes to atmospheric turbulence.

9764-57, Poster Session

Propagation of vector vortex modes through fibers

Bienvenu I Ndagano, Melanie G McLaren, Andrew Forbes, Univ of the Witwatersrand (South Africa)

In recent years, light carrying orbital angular momentum (OAM) has been used in various multiplexing schemes to enhance the bandwidth of optical fibres. This stems from the fact that the OAM is quantized, defining a discrete and infinite dimensional Hilbert space, making them suitable to encode digital information. Spatial modes carrying OAM arise in the description of optical fibre modes which are vectorial in nature. This vector nature manifests itself in the non-separability, traditionally associated with quantum mechanics, of the polarisation and spatial degrees of freedom. We demonstrate techniques to generate and detect these fiber vector vortex modes by spin-orbital angular momentum coupling. This coupling is achieved using a birefringent phase plate (a q-plate) that changes locally the phase of light. We incorporated these techniques to an optical setup we built to study the propagation of vector vortex beams through an optical fibre. Using a vector mode filter we were able to characterize the coupling induced by the fiber. We evaluated the degree of non-separability of these vector modes by comparing the concurrence which, in quantum mechanics, is a measure of entanglement. We showed that vector vortex modes possess a high concurrence at the fiber output, implying that the spatial and polarization degrees of freedom are preserved as they propagate through fibers. This showed that vector vortex modes are very robust in carrying information through optical fibers.

9764-37, Session 9

Optical binding between nanowires

(Invited Paper)

Simon Hanna, Univ. of Bristol (United Kingdom); Stephen H. Simpson, Academy of Sciences of the Czech Republic (Czech Republic)

Optical binding occurs in systems of both dielectric and metal particles and results in the formation of clusters and coupled dynamical behaviour. Optical binding between spherical particles has been long studied, but comparatively little work has appeared describing binding in lower symmetry systems. In this paper we discuss recent theoretical work and computer simulations of optical binding between nanowires in both linearly and circularly polarised counter propagating beams. The reduction in symmetry introduces the possibility of different types of ordering, including ladder-like structures and oriented lattices. Asymmetric arrangements of nanowires are possible which exhibit non-conservative effects, including translation perpendicular to the propagation direction. The use of circular polarisation results in synchronous rotations in clusters on nanowires.
Visualizing surface plasmon polaritons in photo-induced force microscopy

Junghoon Jahng, Eric O. Potma, Faezeh Ladani, Ryan M. Khan, Univ. of California, Irvine (United States)

Surface plasmon polaritons (SPP) are propagating surface plasmon modes, relevant to a wide range of photonics devices. SPP modes are manifest in the near field, and their measurement usually requires coupling the near field information to a far field detector, for example through leakage radiation, through coupling to a waveguide, or through light scattering at near-field objects. Here we visualize the SPP directly in the near field through the photo-induced force exerted by the surface field. We use a photo-induced force microscopy (PiFM) configuration to probe the propagating surface plasmon modes, by allowing a gold-coated tip to interact with the surface field of an SPP launched in a gold film. Our analysis shows that the SPP surface field interacts uniquely through the attractive gradient force with the tip, enabling the generation of SPP maps with sub-10 nm spatial resolution. This high-resolution approach opens up opportunities for directly measuring surface plasmon fields in a variety of photonic devices that rely on surface plasmon-enhanced optical effects.

Novel non-imaging optic design for uniform illumination

Sina Babadi, Roberto Ramirez-Iniguez, Tuleen Boutaleb, Glasgow Caledonian Univ. (United Kingdom); Tapas Mallick, Univ. of Exeter (United Kingdom)

The Dielectric Totally Internally Reflecting Concentrator (DTIRC) has been developed in the past for wireless infrared communications and solar energy applications. This paper proposes a new DTIRC design for use in illumination applications. The novel optic can be integrated with a light emitting diode (LED); and can be tailored to meet specific requirement. The proposed DTIRC can be used as a first or secondary optic to provide uniform illumination within a circular target area with a desired radius. This paper provides first a brief introduction to the light sources and the LEDs. Next, an overview of non-imaging optics is presented. Afterwards, the illumination properties of the traditional DTIRC integrated with the LED are discussed and simulated before presenting a design approach to optimise the DTIRC for uniform illumination, the traditional DTIRC design only provides 5% uniform illumination.

The optimisation process has been divided into two sections; first section, the light rays reached to the top section of the lens directly then refracted to the target plane. In the second part, the light after total internal reflection (TIR) in the optic reached to the top section of the lens and then refracted to the target plane, the most optimisation process has been carried out on the side profile of the DTIRC.

The analysis of the optimised design is then evaluated by the ZEMAX ray tracing simulation. A summary and conclusion are presented at the end of the paper. The results from this work show that, with the optimised DTIRC, it is possible to achieve a uniformity of illumination of over 95%.

Quantum interference of engineered states of light through the interaction with plasmonic nanostructures

Alexander Büse, Mathieu L. Juan, Gabriel Molina-Terriza, Macquarie Univ. (Australia)

Quantum interference of two photons is a fundamental building block for all photonic quantum information technologies. It is based on the indistinguishability of two or more outcomes of the transformation of the modes of each photon. This indistinguishability allows their amplitudes to add coherently and interfere. Two identical photons impinging on a beamsplitter, as in the famous Hong-Ou-Mandel experiment, is not the only realization of such interference. We experimentally demonstrate the successful transfer of this concept to a novel system. A specifically engineered two-photon state passing through a nano-structure, which instead of opening two spatial pathways, can change the polarization and spatial mode of each photon. Quantum interference is then possible between the two channels of changed and un-changed polarizations for each photon. By manipulating a phase inside the input state, we can switch the quantum interference on and off. Essential for this experiment is an excellent control over all degrees of freedom of both photons. We employ a collinear, type II, spontaneous parametric down-conversion source for the pair creation and then achieve indistinguishability by controlling the phase-matching conditions, compensating the time-delay and bringing the pair into the desired state of polarization and orbital angular momentum. The nano-structure in our experiment is a sub-wavelength aperture in a gold film. We believe that this work will allow us to effectively use quantum metrology schemes in plasmonic nanostructures.

3D particle tracking in microfluidic flows using ultra-high-speed variable focus optics (Invited Paper)

Craig B. Arnold, Princeton Univ. (United States)

The ability to track particles and image microfluidic flows can be easily accomplished in a single plane using standard fixed optics and high speed cameras. However, the use of fixed optical elements presents a limitation for the visualization of the three dimensional flow in a system. In this presentation, we discuss the development and use of ultra high-speed variable focus lenses that enable the real time acquisition of images from multiple planes within a flow. Based on this data it is possible to reconstruct the 3D flow of particles as they move. Our approach is based on the tunable acoustic gradient index of refraction (TAG) lens which provides a variable focal length with microsecond time resolution while maintaining high optical throughput and low aberration. We will first introduce the fundamental principles of operation and the unique approach to high-speed focal length scanning with this resonating device. We will then highlight a simple but powerful imaging technique in which multiple focal planes are acquired from the volume of a sample in real-time without the need for image processing, complex illumination or mechanical translation of the optics or sample. Finally, we will discuss the combination of such a system with high speed cameras for 3D particle tracking in microfluidic flows.

Optical diffraction tomography for simultaneous 3D visualization and tracking of optically trapped particles (Invited Paper)

YongKeun Park, KAIST (Korea, Republic of)

Optical tweezers have been an invaluable tool for exerting tiny force on microscopic samples near optical focus as well as manipulating three-dimensional (3-D) positions of the samples. Tracking 3-D position of optically trapped particles provides information about biomechanical properties of biological samples as well as rheological parameters of colloidal samples in surrounding media. To precisely measure 3-D position of optically trapped particles, various measurement techniques have been developed. However, these existing methods rely on a priori information about the optical and morphological properties of the optical trapped...
samples. In addition, these methods cannot be applied to samples having complicated structures such as biological samples, especially when samples are stacked along the optical axis.

Here, we present a novel technique integrating holographic optical tweezers with ODT which can simultaneously perform 3-D position tracking and visualization of optically trapped samples with the high acquisition rate. In order to measure 3-D RI distribution of samples which positions are optically controlled in three dimensions, we integrate ODT with holographic optical tweezers. A spatial light modulator controls the wavefront of the incident beam from a high-power laser by displaying phase-only holograms for optical traps at desired positions in three dimensions, and a high numerical-aperture objective lens generates tightly focused optical traps at the sample plane. The measurement speed of 100 tomograms per second was achieved. We expect the present technique can be implemented for the real-time manipulation and visualization of various microscopic system at the same time.

9764-44, Session 10

Tractor beams for optical micromanipulation
Aaron Yevick, David G. Grier, New York Univ. (United States)

The theory of photokinetic effects expresses the forces and torques exerted by a beam of light in terms of experimentally controlled parameters. We use it to show how the intensity, phase and polarization of a beam of light can be engineered to create practical realizations of tractor beams: traveling waves that pull on objects, rather than pushing them. We derive theoretical constraints on the ability of light to pull small particles. We experimentally demonstrate the ability of light to exert retrograde forces over a long range, with particular emphasis on the realizations of the solenoid beam and the optical conveyor.

An ideal realization of a long-range tractor beam involves propagation-invariant beams of light, known as Bessel beams. Within scalar, paraxial diffraction theory Bessel beams are straightforward and easily formed; complexity arises in the non-paraxial regime. Vector Bessel beams can have either the electric or the magnetic field linearly, transversely, and circularly polarized, and we investigate techniques to accurately project these beams employing angular spectrum decomposition, enabling us to develop long-range solenoidal beams.

9764-45, Session 10

Rotation of rotating light
Daryl Preece, Univ. of California, San Diego (United States); Halina Rubinsztein-Dunlop, The Univ. of Queensland (Australia)

In recent years computer generated holograms have become a mainstay of many optical systems. Though traditional approaches to calculating holograms often exploit the principles of Fourier optics, holograms are often used in combination with high numerical aperture lenses, which do not obey these principles exactly.

Such high NA systems do however give a significant amount of freedom in the angle at which rays can arrive at the focal point.

Though simple kinoforms exist which can translate diffraction-limited spots there is no simple analogue to perform rotations. We discuss a new simple methodology for rotational control of arbitrary light fields created by computer-generated holograms. We demonstrate the method practically in optical tweezers by rotating micro-rods in three dimensions. The methods discussed are non iterative and quick to calculate. We also discuss the implications of this study for the generation of other novel types of beams such as those with unconventional angular momentum states.

9764-46, Session 11

Holographic vector-wave femtosecond laser processing (Invited Paper)
Yoshio Hayasaki, Satoshi Hasegawa, Utsunomiya Univ. (Japan)

Arbitrary and variable beam shaping of femtosecond pulses by a computer-generated hologram (CGH) displayed on a spatial light modulator (SLM) have been used to material processing. The holographic femtosecond laser processing with high-throughput and high energy-use efficiency has been widely used in many applications, such as two-photon polymerization, optical waveguide fabrication, fabrication of volume phase gratings in polymers, and surface nanostructuring. These applications were performed by parallel laser processing based on a wavefront control of the pulses. A polarization control of the pulses is essential to enhance the processing capability. In particular, a light field with spatially inhomogeneous states of polarization, called a vector beam, has attracted attention due to the novel properties it offers, such as selective excitation of an anisotropic molecule, orientation of the three-dimensional (3D) orientation of a single molecule, effective laser cutting, and fabrication of periodic nanostructures with femtosecond laser light. Therefore, a femtosecond vector beam has the potential to expand the functionality of existing optical systems and develop novel applications in various research fields. In this presentation, femtosecond laser processing with a full control of phase and polarization distributions using a pair of SLMs displaying two types of CGH, one for modulating the wavefront of the pulse, and the other for modulating the polarization fields of the pulse, is demonstrated. The 3D laser processing inside a transparent material with multifocal vector beams is also demonstrated.

9764-47, Session 11

Complex light in 3D printing (Invited Paper)
Christophe Moser, Paul Delrot, Damien Loterie, Edgar E. Morales Delgado, Miguel A. Modestino, Demetri Psaltis, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We propose a new scheme to produce drop-on-demand droplets by use of light. Droplets are ejected from a capillary by focusing pulsed light. We show that it is possible to control the ejection speed of the droplets to below 5 m/s, approximately the speed of inkjet printers. In addition, the viscosity of the droplet that can be emitted is several times higher than what is obtainable with thermal or piezo-electric nozzles. The combined low ejection speed and high viscosity produce droplets that maintain their integrity upon impact. An interesting aspect towards high resolution printing is that the size of the ejected droplets are significantly smaller (approximately a factor 5) than the diameter of the nozzle. This effect is due to a flow-focusing phenomenon. It further helps avoid clogging the nozzle as it is often the case for piezo-electric nozzles providing similar droplet size.

We envision bringing the pulse light by multimode fibers so as to have a spatial and temporal control of the ejected droplets. Furthermore, fast high resolution imaging is necessary to provide feedback to the droplet ejection system so as to make smooth and accurate structures. Compact imaging systems based on capillaries and multimode fibers have been developed in recent years and are well suited as an imaging companion to the proposed capillary based drop-on-demand system.

9764-48, Session 11

Optical screw-wrench for 2PP-microstructure interlocking
Jannis Köhler, Gordon Zyla, Sarah I. Ksouri, Cemal Esen, Andreas Ostendorf, Ruhr-Univ. Bochum (Germany)
Two-photon polymerization (2PP) has emerged as a powerful platform for processing three-dimensional microstructures with high resolution in the nanometer range. Furthermore, the addition of nanoparticles to the photopolymer causes a functionalization of those microstructures, e.g., magnetic or electric properties can be adjusted. However, to combine different functions within one microstructure or to manufacture complex Microsystems, assembling techniques are required. In this paper, a qualitative approach for assembling multiple 2PP written building blocks utilizing optical forces is presented. Therefore, screw and nut shaped subcomponents are produced by 2PP-technique and screwed together using a holographic optical tweezer (HOT). The interlocking structures are trapped and rotated into each other to cause positive-fit connection. The purpose of this paper is to discuss appropriate processing parameters and possible designs of the interlocking connection. These findings do not only provide the assembling of building blocks to complex Microsystems, rather different functionalized 2PP-microstructures can be combined by simply screwing them together with the use of optical forces in an all-optical system.

9764-49, Session 12

Photothermal heating in metal-embedded microtools for material transport (Invited Paper)
Mark Jayson M. Villangca, Darwin Palima, Andrew R. Bañas, Jesper Glückstad, DTU Fotonik (Denmark)

Plasmon resonance of gold nanoparticles as well thin films has been used as localized heat sources. Microfluidic mixing1, fluid flow control2 and convection currents3 have been demonstrated both experimentally and numerically. However these have been demonstrated for static metal thin films or passively floating nanoparticles. In this work, we make use of optically actuated microtools as vehicle to maneuver plasmonic heat sources. The new microtools take advantage of the plasmon-assisted convection and it is also designed to function as a material transport vehicle. As proof of concept, we demonstrate loading, transport and subsequently unloading of beads. This can be extended to controlled transport and release of genetic material, bio-molecules, fluorescent probes. The microtools are coated with thin layers of gold using standard metal sputtering process. Selective coating of the microtools is done by fabricating a mask on top of the structure during the 2PP lithography. The mask is removed during the collection of the microtools. The microtool has been designed using COMSOL to identify flow speed and direction with varying gold layer configurations and laser power using the methods presented in literature.3 We envisioned this microtool to be an important addition to the portfolio of structure-mediated contemporary biophotonics.

References:

9764-50, Session 12

The role of light’s angular momentum in plasmonic optical tweezers using stochastic optical beams: a statistical Maxwell’s stress tensor approach
Shaloa Rakheja, New York Univ. (United States)

The linear and angular momentum of light can be manifest as a radiation force [1] that can be utilized to manipulate optical tweezers on a microscopic scale. Plasmonic optical tweezers (POTs), in contrast to conventional ones which use an applied optical field and are limited by diffraction effects offer a useful alternative with improved performance metrics. POTs rely on an enhanced local electromagnetic (EM) field when plasmon resonance conditions are met in a suitable nanostructure. In this work, we calculate the angular momentum density dependent radiation torque imparted through the local EM field by excitation of surface plasmon polaritons (SPPs). SPPs are excited by a partially coherent p-polarized light source at an air-dielectric interface in the Kretschmann configuration by tightly focused beams characterized by their width and a twist parameter [2]. We show that the distribution and periodicity of angular momentum and energy density of excited SPPs and its maximum is controllable by adjusting the beam coherence length, degree and type of polarization, and magnitude of the twist parameter. Additionally, the role of spectral coherence of the incident stochastic beam in inducing an optimal mechanical torque by relating it to the Maxwell’s stress tensor that governs the angular momentum of the EM field and selective trapping of particles based on chirality of light is emphasized.

References:

9764-51, Session 12

Slow light for enhancement of optical forces in a photonic crystal waveguide
Mark Scullion, The Univ. of York (United Kingdom); Yoshihiko Arita, Univ. of St. Andrews (United Kingdom); Thomas F. Krauss, The Univ. of York (United Kingdom); Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

Slow light has been a major topic in the field of optics, particularly for photonic crystal waveguides. This has led to the observations of nonlinear interactions and applications in optical switching. The paradigm of slow light implies a highly reduced group velocity. By consideration of optical forces, we find that slow light may lead to an enhancement of optical forces that can be accessed by appropriate tuning of the photonic crystal waveguide properties. Our work uses sub-micron dielectric particles and shows the slow light effect can lead to a four fold enhancement of the particle guiding velocities on an appropriate photonic crystal waveguide.

The experiment employs a PhC microstructure that has a design wavelength of 1550 nm. The four fold enhancement in the slow light regime of the photonic crystal waveguide is verified by wavelength tuning around the slow light region. Power levels as low as 2.5 mW are used for the experiment. The work opens up new avenues for using tuning of optical wavelength and slow light effects for controlling optical forces in photonic crystal waveguide geometries.
Understanding photophoretic forces from the Brownian motion of trapped absorbing particles in air

Sudipta K. Bera, Avinash K. Gupta, Ayan Banerjee, Indian Institute of Science Education and Research Kolkata (India)

Photophoretic forces are have extensive manifestations in nature and are responsible for fundamental natural processes such as planet formation and asteroids. However, the detailed characterization of photophoretic forces is non-trivial, and is even more difficult in the case of macroscopic objects. Optical tweezers offer the opportunity of trapping single absorbing micro-particles in air by photophoretic forces so that these can be studied in great detail. Here we describe our experiments in analysing photophoretic forces from the Brownian motion of single trapped absorbing 10 micron size toner particles in air. The Brownian motion demonstrates clear indication of being ballistic in nature, as we observe from the nature of its power spectral density (PSD) and mean squared displacement (MSD). The PSD has oscillations which are a result of the viscosity of air varying in the environment of the trapped particle due to the strong temperature gradients, which are able to reproduce numerically by a solution of the Langevin equation with the inertial term and a position dependent viscosity. We are also able to measure the instantaneous velocity of a trapped particle, which, importantly, is only defined in the ballistic domain and not in the diffusive domain where optical tweezers are predominantly used. In addition, measurements of the PACF (position autocorrelation function) of the Brownian motion reveal that its nature is slightly different from that expected due to the presence of an inertial term in the Langevin equation. This suggests that the nature of the photophoretic potential, while being harmonic in general, may have additional linear terms in it.
9765-1, Session 1

Increasing cooling efficiency in co-doped fluorides (Invited Paper)

Mauro Tonelli, Alberto Di Lieto, Univ. di Pisa (Italy); Azzurra Volpi, Univ. di Pisa (Italy) and Istituto Nanoscienze (Italy); Gianni Cattidino, Univ. di Pisa (Italy); Seth D. Melgaard, The Univ. of New Mexico (United States) and Air Force Research Labs. (United States) and Sandia National Labs. (United States); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

Anti-Stokes cooling in solids is based on thermal energy removal via annihilation of lattice phonons. Currently high-quality Yb doped YLF single crystals have been cooled at very low cryogenic temperature. In this work we report on investigation of novel fluoride materials for enhancement of laser cooling efficiency. Energy-transfer assisted Yb anti-Stokes efficiency has been demonstrated in Yb-Tm co-doped YLF single crystals. Different relative concentrations were investigated to optimize the efficiency of energy-transfer contribution. Novel Yb doped crystalline hosts were investigated and compared to Yb doped YLF single crystals. Growth parameters, assessment of crystal optical quality, spectroscopic characterization and cooling measurements are presented.

9765-2, Session 1

Progress in the spectroscopic and thermal studies of Er-doped oxysulfide crystal powders (Invited Paper)

Joaquin Fernández, Rolindes Balda, Macarena Barredo-Zuriarrain, Univ. del Pais Vasco (Spain); Odile Merdrignac-Conanc, Noha Hakmeh, Univ. de Rennes 1 (France); Sara García-Revilla, Univ. del Pais Vasco (Spain)

Upconversion processes in trivalent rare earth-doped (RE) low phonon energy materials have received increasing attention in biosciences not only for image representation but also for thermometry and medical therapeutics. On the other side, the investigation of new hosts for rare earth ions with low phonon energies appears to be a promising way to find efficient cooling materials, especially for dopant ions with low-energy band-gaps between active levels. Among RE-doped oxides, oxysulfides (RE2O2S) are one of the most efficient phosphors investigated for commercial television and lighting applications [1]. In particular, gadolinium oxysulfide crystal matrix, a uniaxial wide-gap semiconductor material, is known as an excellent host lattice for trivalent RE ions [2]. Each gadolinium atom is coordinated by four oxygen atoms and three sulfur atoms in its nearest neighborhood [3]. The gadolinium site symmetry is C3v.

Here we report a detailed study of the spectroscopic properties of Er3+ ion in gadolinium oxysulfide crystal powders under excitation in the 419/2 manifold as well as experimental evidences of anti-Stokes laser-induced cooling. The wavelength and pump power dependence of the spectroscopic properties and temperature field are also considered.


9765-3, Session 1

Optical cryo-cooling of devices

Aram Gragossian, Mohammadreza R. Ghasemkhani, The Univ. of New Mexico (United States); Seth D. Melgaard, Sandia National Labs. (United States); Alexander R. Albrecht, The Univ. of New Mexico (United States); Markus P. Hehlen, Los Alamos National Lab. (United States); Bernardo G. Farfan, Guy Symonds, Richard I. Epstein, Thermodynamic Films (United States); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

Optically cooling rare earth doped crystals to coldest achievable temperatures has made it possible to build solid state vibration free cryo-coolers for devices. Infrared detectors, for example, have much lower noise at lower temperatures. They can also benefit from the vibration free cooling since much of the microphonic noise generated by conventional cryo-coolers is eliminated in optical cryo-coolers. Major improvements have been made to purify rare earth doped crystals and with proper thermal management they can now be routinely cooled to less than 100K. In order to utilize this capability for cooling infrared detectors these crystals have to be connected to devices by a thermal link. The link needs to reject the fluorescence and guide the heat from the device to the cooling crystal.

Based on ray tracing and heat transfer analysis and measurements, sapphire is the ideal candidate. If designed correctly, the sapphire link will reject most of the fluorescence and the remaining photons are rejected by the metallic coating at the end of the link. Due to its high thermal conductivity sapphire can efficiently transfer heat from the device to the cooling crystal. Using a 50W fiber laser at 1020 nm the thermal link and the device can be cooled to cryogenic temperatures. We confirm cooling of the device by measuring the crystal temperature using Differential Luminescence Thermometry (DLT) and measuring the dark current and the temperature on the infrared detector.

9765-4, Session 1

Coupled-cavity-enhanced laser cooling in Yb:YLF crystals using VECSELS

Mohammadreza R. Ghasemkhani, Alexander R. Albrecht, Seth D. Melgaard, The Univ. of New Mexico (United States); Denis V. Seletskiy, Univ. Konstanz (Germany); Jeffrey G. Cederberg, Sandia National Labs. (United States); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

Optical refrigeration uses anti-Stokes fluorescence to remove heat (lattice vibrations) from a glass or crystal. Optical cryocoolers have a clear advantage over mechanical cryocoolers in vibration, ruggedness, moving parts, and mass. Thus far, rare-earth ions doped into a low phonon energy high purity host have shown the best cooling performance. Due to Boltzmann distribution of electrons, the absorption of the cooling samples drastically decrease at low temperatures. Several methods have been utilized to increase the absorption at low temperatures, for example multi-pass non-resonant cavity method and resonant cavity technique by applying critical coupling condition. Here, we have placed a 10% Yb:YLF cooling sample inside a resonant Fabry-Perot cavity that is coherently coupled to another laser cavity and cooled it to 150 K starting from room temperature. The laser is a tunable high-power InGaAs/GaAs MQW vertical external cavity surface emitting laser (VECSEL) capable of producing in excess of 20 Watts at 1020 nm, directly at the E4–E5 transition of the Yb ion. In the coupled cavities arrangement, the absorption of the Fabry-Perot cavity should be made equal to the optimal output coupling of the VECSEL.
system in order to efficiently absorb the laser light in the cooling crystal. The fluorescence emitted by the crystal is utilized to measure its temperature using differential luminescence thermometry method.

9765-5, Session 1

Laser cooling performance of Yb3+-doped LuLiF4 crystal (Invited Paper)

Biao Zhong, Hao Luo, Lin Chen, Yanling Shi, Jianping Yin, East China Normal Univ. (China)

In the atmosphere, the size of Swt.% Yb3+: LuLiF4 crystal with Brewster angle 37375 mm pumped by the fiber laser with the power of 3 W, and the thermal camera observed the temperature drops of sample -9.5 K from the room temperature about -295 K. The cooling power and the cooling efficiency of sample is estimated as -20.8 mW and -3.2% respectively. When the crystal pumped by the laser in the vacuum, the temperature drops of crystal over 50 K from the room temperature is observed by utilizing the DLT measurement methods. The polarized fluorescence spectroscopy, and the average fluorescence wavelength function with temperature of crystal was measured within the temperature range of 80 K-100 K.

9765-6, Session 2

Thermoelectric and spin-caloritronic coolers: from basics to recent developments (Keynote Presentation)

Joseph P. Heremans, The Ohio State Univ. (United States)

The ZT of classical thermoelectric materials used in Peltier coolers is a function of mutually counter-indicated materials properties, the Seebeck coefficient S, and the electrical and thermal conductivity ? and ?. The thermoelectric coefficient S, and the electrical and thermal conductivity ? and ? function of mutually counter-indicated materials properties, the Seebeck coefficient S, and the electrical and thermal conductivity ? and ?.

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9765-7, Session 2

Enhancing the transverse Seebeck coefficient for p x n transverse thermoelectric cooling (Invited Paper)

Matthew Grayson, Yang Tang, Northwestern Univ. (United States); Hubert Riedl, Gregor Koblmueller, Walter Schottky Institut (Germany) and Technische Univ. München (Germany)

Transverse thermoelectrics offer an alternate path for integrated solid-state cryogenic cooling, provided materials with sufficiently large transverse Seebeck coefficients can be identified. Under the p ? n-type transverse thermoelectric paradigm [1] electrons dominate conduction in one direction and holes dominate perpendicularly, allowing electrical current to drive transverse heat flow. Whereas bulk anisotropic crystals, superlattices, and nanowire arrays have been previously considered as p ? n materials, this work focuses on sequential ion implantation and regrowth as a strategy for engineering a large transverse Seebeck coefficient in a thin p ? n film. Individual p- and n-type AlGaAs layers with thickness d = 500 nm are grown successively on GaAs substrate via molecular beam epitaxy. After each layer growth, proton ion-implantation with energy E = 50 keV is used to create non-conductive strips of width W = 5-20 ?m to separate conductive strips of similar width. Such n-type strips are orthogonal to aligned ato p-type strips. Secondary ion mass spectroscopy (SIMS) on single layers confirms H-implantation depth commensurate with layer thickness even after 430 degrees Celsius anneal. Electrical transport measurements show desired conduction anisotropy within each layer, with the strip direction 10,000 times more conductive than transverse. The separate Seebeck coefficient for the implanted p- and n-type layers approaches S = 400 uV/K, and results of the transverse Seebeck measurement will be reported for the two-layer structure, demonstrating proof-of-principle for ion implantation as a means of fabricating artificial p ? n transverse thermoelectrics.


9765-8, Session 2

High-performance bulk thermoelectric nanocomposites from solution-grown Bi chalcogenide 2D crystals

Qi Hua Xiong, Chaohua Zhang, Nanyang Technological Univ. (Singapore)

Thermoelectric power generation by harvesting and converting waste heat into useful electricity and cryogen-free solid-state thermoelectric refrigeration are both important in combating the energy and global warming challenges. Bismuth telluride (Bi2Te3)-based thermoelectric materials are the only promising materials that can be used in both power generation and refrigeration near room temperature region, but the further improvement of the figure of merit ZT is challenged by reducing the thermal conductivity and enhancing the power factor simultaneously, which are unfortunately mutually dependent. Nanostructuring approach has been proved to be an effective strategy to enhance the thermoelectric performance by reducing the lattice thermal conductivity. Here we report our recent effort in large-scale solution synthesis of 2D bismuth chalcogenide crystals, and spark plasma sintering (SPS) leading to highly anisotropic bulk thermoelectric materials. Using this approach, the lattice thermal conductivity can be greatly reduced without degrading the power factor, measured by both electrical and thermal transports. The optimized ZT of p-type Bi0.5Sb1.5Te3 can boost from 0.51 to 1.6 at 375K, and the ZT of the n-type Bi2Te2.7Se0.3 can boost from 0.51 to 1.6 at 375K.

References
Optical refrigeration in Tm:YLF crystals

Saeid Rostami, Mohammadreza R. Ghasemkhani, Alexander R. Albercht, The Univ. of New Mexico (United States); Seth D. Melgaard, The Univ. of New Mexico (United States) and Sandia National Labs. (United States); Aram Gragossian, The Univ. of New Mexico (United States); Mauro Tonelli, Univ. di Pisa (Italy); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

We report the observation of laser cooling in Tm:YLF crystals by 0.3 Kelvin in air starting from room temperature. For this purpose, we have designed and constructed a high power, broadly tunable (1855nm–2039nm) CW OPO with $5\,\text{mmol}$ MgO-doped PPLN crystal, pumped by a narrow linewidth, high power 1030nm laser to cool down a (3 mm)$^3$ 3% doped Tm:YLF crystal. Cooling for this sample was observed from 1873nm to 1915nm where the absorption cross-section of Tm:YLF crystal is around 0.0370-0.20cm$^2$ for both $\pi$ and $\sigma$-polarizations. The cooling setup is a single pass configuration in air with an OPO signal power of 0.9W in the cooling range. Temperature was measured using a thermal camera. The optical refrigeration of Tm:YLF crystal can be enhanced to much lower temperatures by using higher power OPO signal beams, having multiple passes through the cooling sample, and placing the cooling sample in vacuum to reduce the convective heat load.

Non-resonant optical cavity design for optical refrigeration

Bernardo G. Farfan, Guy Symonds, Thermodynamic Films (United States) and The Univ. of New Mexico (United States); Mohammad R. Ghasemkhani, Alexander R. Albrecht, Mansoor Sheik-Bahae, The Univ. of New Mexico (United States); Richard I. Epstein, Thermodynamic Films (United States)

We present a study of optical refrigerators with non-resonant optical cavities. Designs have been studied to maximize pump light trapping to increase cooling power in optical refrigeration. The approaches of non-resonant optical cavities through highly reflective mirrors arrangement and the monolithic optical maze were studied. Ray-tracing simulations were performed to characterize and analyze the different light trapping configurations. Light trapping was studied for laser sources with high quality beams and for beams with large divergences, roughly corresponding to the output from fiber lasers and from diode lasers, respectively. We present a trade-off analysis between performance, reliability and manufacturability.

Recent progress of laser cooling in semiconductors (Invited Paper)

Qi Hua Xiong, Nanyang Technological Univ. (Singapore)

Recent progress in laser cooling of semiconductors and rare-earth doped materials has advanced the field of optical refrigeration considerably. Much effort has been devoted to improve the materials quality and thermal management to push the cooling towards liquid nitrogen temperature, or explore new materials towards optical refrigeration. In this talk, we will summarize our recent effort in laser cooling of semiconductor materials, starting from the demonstration of net laser cooling in group II-VI CdS nanobelts followed by sideband Raman cooling of optical phonons in ZnTe. Then we will discuss our recent progress in realization of net optical cooling effect in inorganic-organic perovskite layered crystals, which consists of alternating lead halide octahedral layers with methyl amino-groups or cesium (thus completely inorganic) intercalating into the pockets formed by the adjacent octohedrals. If the length of the alkane chain is increased, a decoupled 2D perovskite is formed, which showed even larger cooling effect. The synthesis of perovskite crystals, optical properties and laser cooling measurement will be discussed in detail. Our work expands the laser cooling toolbox and advocates the promise of a family of materials with facile synthesis approach and low crystallization temperature towards practical applications.

Resonant Stokes and anti-Stokes Raman scattering in semiconductors and its application to optical refrigeration (Invited Paper)

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

Anti-Stokes Raman scattering, just like Anti-Stokes photoluminescence can be used for laser refrigeration. Normally Anti-Stokes Raman is much weaker than Stokes Raman which makes cooling impossible. However, in the vicinity of the resonance Anti-Stokes scattering can surpass Stokes scattering, enabling optical refrigeration. In this talk I will present comparative analysis of Raman cooling in different III-V and II-VI semiconductors.

Probing dynamics of laser cooling cycle in III-V semiconductor heterostructures

Jan F. Schmidt, Jannis Oelmann, Denis V. Seletskiy, Univ. Konstanz (Germany)

Time domain analysis of the laser cooling cycle is necessary for obtaining a microscopic picture of optical refrigeration. This is especially important in semiconductors, where the governing many-body interactions and parasitic heating sources still remain not well understood. Here we report our systematic measurements of ultrafast transient absorption in III-V semiconductor heterostructures under various excitation conditions and as a function of temperature. We conclude by outlining our developments of a new multi-branch femtosecond fiber laser source optimized for time-domain investigations of laser cooling in higher bandgap II-VI semiconductors.

CdTe/MgCdTe double heterostructures with ultra-long lifetime and ultra-low interface recombination velocity and their potential for luminescence refrigeration (Invited Paper)

Shi Liu, Xin-Hao Zhao, Calli Campbell, Maxwell B. Lassise, Yuan Zhao, Yong-Hang Zhang, Arizona State Univ. (United States)

Ultra-long minority carrier lifetime of 2.7 $\mu$s and ultra-low interface recombination velocity $< 1 \text{cm/s}$ have been achieved in CdTe/MgCdTe double heterostructures (OH) grown on lattice-matched InSb (100) substrates by using molecular beam epitaxy. These numbers are comparable to or better than the best values reported for GaAs based DHs. Both the lifetime and the interface recombination velocity are found to be dependent on the barrier height and width due to the thermionic emission and tunneling processes. These results are nicely interpreted with a theoretical model and indicate that CdTe is a promising candidate for semiconductor luminescence refrigeration.
9765-14, Session 4

Realistic modeling of low quantum defect lasers (Invited Paper)

Steven R. Bowman, U.S. Naval Research Lab. (United States)

Near resonant pumping of solid-state lasers offers the potential for high efficiency and minimal thermal loading. These lasers inherently operate in the regime where fluorescence cooling plays an important role. Here a model is developed to optimize efficiency and minimize heating for these laser systems. The model includes radiative cooling and fluorescence trapping. It also handles background absorption and excitation quenching. The model will be illustrated with example laser materials.

9765-15, Session 4

Analytical predictions of the temperature profile within semiconductor nanostructures for solid-state laser refrigeration (Invited Paper)

Peter J. Pauzauskie, Univ. of Washington (United States) and Pacific Northwest National Lab. (United States); Bennett E. Smith, Xuezhe Zhou, E. James Davis, Univ. of Washington (United States)

The laser refrigeration of solid-state materials with nanoscale dimensions has been demonstrated for both semiconducting (cadmium sulfide, CdS) and insulating dielectrics (Yb:YLF, YLF) in recent years. During laser refrigeration it is possible to observe morphology dependent resonances (MDRs), analogous to what is well-known in classical (Mie) light scattering theory, when the characteristic dimensions of the nanostructure are comparable to the wavelength of light used to initiate the laser cooling process. Mie resonances can create substantial increases for internal optical fields within a given nanostructure with the potential to enhance the absorption efficiency at the beginning of the cooling cycle. Recent breakthroughs in the laser refrigeration of semiconductor nanostructures have relied on materials that exhibit rectangular symmetry (nanoribbons). This talk will present recent analytical, closed-form solutions to the energy partial differential equation that can be used to calculate the internal spatial temperature profile with a given semiconductor nanoribbon during irradiation by a continuous-wave laser. First, the energy equation is made dimensionless through the substitution of variables before being solved using the classical separation-of-variables approach. In particular, calculations will be presented for chalcogenide (CdS) nanoribbons using a pump wavelength of 532 nm. For nanostructures with lower symmetry (such as YLF truncated tetragonal bipyramids) it is also possible to observe MDRs through numerical simulations using either the discrete-dipole-approximation or finite-difference time-domain simulations, and the resulting temperature profile can be calculated using the finite-element method. Theoretical predictions are compared with experimental observations using single-beam laser trapping and also cantilevered nanostructures.

9765-16, Session 5

Spectroscopy and thermalization of dense atomic gases in redistributional laser cooling (Invited Paper)

Stavros Christopoulos, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany); Lars Weller, Rheinische Friedrich Wilhelms Univ Bonn (Germany); Peter Moroshkin, RIKEN (Japan); Dominik Möller, Rheinische Friedrich Wilhelms-Universität-Bonn (Germany); Martin Weitz, Rheinische Friedrich-Wilhelms-Univ Bonn (Germany)

Laser cooling by collisional redistribution is an optical cooling technique applicable to ultradense gas mixtures. Frequent alkali-noble gas collisions shift an alkali atom into resonance with a highly red detuned laser beam, while spontaneous decay occurs close to the unperturbed laser frequency. For the determination of the local temperature in samples with relative cooling of same order of magnitude as the absolute temperature we are developing spectroscopic techniques for precise determination of the local gas temperature. We report results on the Kennard-Stepanov relation, a thermodynamic Boltzmann-type scaling of the ratio of absorption and emission profiles for atomic and molecular lines.

9765-17, Session 5

Brillouin and Raman cooling in resonant and non-resonant systems (Invited Paper)

Yin-Chung Chen, Gaurav Bahl, Univ. of Illinois at Urbana-Champaign (United States)

We investigate the possibility of using spontaneous Brillouin and Raman scattering for the laser-cooling of solid-state materials. We show that photonic density of states (DoS) engineering can address the fundamental requirements for enabling these cooling mechanisms. These requirements include suppression of the dominance of Stokes (heating) transitions, and the enhancement of anti-Stokes (cooling) efficiency beyond the natural optical absorption of the material.

9765-18, Session 5

Observation of excitonic super-radiance in quantum well structures and its application for laser cooling of solids (Invited Paper)

Iman Hassani Nia, David J. Weinberg, Emily Weiss, Hooman Mohseni, Northwestern Univ. (United States)

Optical refrigeration has emerged as a viable solution for cooling rare-earth doped glasses below 100 K. However, the cooling of semiconductors still lags behind. It is of high interest to cool semiconductors with such a compact and vibration-free technique because of the dramatic improvement in signal to noise ratio of electronic devices at low temperatures. The main challenges involved in laser cooling of semiconductors are the parasitic absorption of the pump laser and photoluminescence and the insufficient external quantum efficiency. Previously, rigorous theoretical evaluations of excitonic effects have put the emphasis on “Coulomb-induced steepening of absorption band-tail” that can be employed to increase the optimum laser detuning and the cooling power and to overcome the adverse effects of parasitic absorption of the pump laser. In this talk, we present our experimental results on a QW structure that exhibits excitonic super-radiance. In such confined 2D structures, the excitonic effects are much more pronounced compared to bulk materials. Our observation suggests that this behavior is a dominant recombination process for low pump intensities from 78 K up to room temperature. To interpret the results, we provide details of the bandstructure and the wavefunctions of the sample by solving the Poisson and Schrodinger equations self-consistently. In addition, the carrier densities were found using the absorption spectra, ray-tracing, and also by solving the carrier rate equations. To clarify the applicability of this method, the potential of employing excitonic super-radiance along with its limitations for laser cooling of semiconductors are explained.
Optical losses of high-reflectivity substrate-transferred crystalline coatings (Invited Paper)
Garrett D. Cole, Crystalline Mirror Solutions, LLC (United States)
Coating Brownian noise, driven by the excess mechanical damping of high-reflectivity thin film coatings, currently limits the stability of precision optical interferometers. Overcoming this limitation, Crystalline Mirror Solutions has developed a novel “crystalline coating” technology that enables the transfer of low-loss single-crystal semiconductor heterostructures onto arbitrary optical substrates. With a significantly reduced mechanical loss, these coatings yield high-reflectivity cavity end mirrors with minimal Brownian noise, while simultaneously exhibiting parts-per-million levels of optical losses in the near- and mid-infrared. In this presentation I outline recent results including optical cavities employing crystalline-coated end mirrors exhibiting an optical finesse in excess of 200,000.

Progress in rare-earth-doped nanocrystalline glass-ceramics for laser cooling (Invited Paper)
Venkata Krishnaiah, Ecole Polytechnique de Montréal (Canada) and Ctr. d’Optique, Photonique et Laser (Canada); Yannick Ledemi, Ctr. d’Optique, Photonique et Laser (Canada); Elton Soares de Lima Filho, Sébastien Loranger, Galina A. Nemova, Ecole Polytechnique de Montréal (Canada); Younés Messaddeq, Ctr. d’Optique, Photonique et Laser (Canada); Raman Kashyap, Ecole Polytechnique de Montréal (Canada)

Laser cooling was predicted by Pringsheim in 1929[1], but it was only possible to demonstrate it in 1995 [2]. There are many difficulties which have hindered laser assisted cooling, principally the purity of a sample and the availability of suitable hosts. Recent progress has seen the cooled temperature plummet to 93K [3] in Yb:YLF. For laser cooling to become ubiquitous, the challenge is incorporating the cooling ion in a more versatile optical refrigerator. This work focuses on minimizing energy losses in the near- and mid-infrared. In this presentation I outline recent results including optical cavities employing crystalline-coated end mirrors exhibiting an optical finesse in excess of 200,000.
Raman cooling in silicon photonic crystals

Yin-Chung Chen, Gaurav Bahl, Univ. of Illinois at Urbana-Champaign (United States)

Laser cooling of solids relies on photon up-conversion processes in which phonons are annihilated from a material. This can be achieved using photoluminescence of rare-earth elements or with optical forces at the structural scale. The ability to cool solids using the fundamental inelastic scattering processes of Brillouin Scattering and Raman Scattering, has not yet been fully explored. In both processes, the incident photon is annihilated and a higher energy photon (anti-Stokes) or a lower energy photon (Stokes) is created, accompanied by the annihilation or creation of a phonon. Brillouin scattering manipulates with acoustic phonons (MHz-GHz), whereas Raman scattering deals with optical (THz) phonons.

In recent work, using naturally occurring photonic states of a resonator, Bahl et al. [1] showed that anti-Stokes Brillouin scattering can be enhanced while suppressing Stokes Brillouin scattering. This led to the demonstration of net Brillouin cooling in solids. However, relatively little effort has been devoted to study of engineering the optical density of states to enable cooling through Raman scattering. For inelastic scattering in bulk materials, Stokes scattering is proportional to (n₀ + 1), and the anti-Stokes scattering is proportional to n₀, where n₀ is the phonon occupation number. This factor gives a large Stokes to anti-Stokes intensity ratio using optical phonons (≈ 10 : 1 for silicon crystals), resulting in a natural heating of the medium. Here we show for the first time that engineering of the optical density of states of a solid can be used to enable Raman cooling, far away from any natural absorption near band edges, two-photon and excitonic interactions.

It is known that the intensity of spontaneous emission and scattering process can be modified by the photonic density of states [2, 3]. Using this concept, we derive an expression for the Raman scattering efficiency of any material patterned with a modified density of states. We consider several different 2D, and 3D photonic crystal structures in crystalline silicon. When the pump laser frequency below the band gap to avoid photoluminescence effects and resonant Raman scattering, we show that cooling is reached by significantly enhancing anti-Stokes Raman scattering over the optical absorption probability, along with simultaneous rejection of Stokes scattering events.

References
What makes VCSELs so special? (Invited Paper)
Jack Jewell, Consultant (United States)
No Abstract Available.

Twenty years of VCSEL technical and industrial development at SPIE Photonics West (Invited Paper)
Kent D. Choquette, Univ. of Illinois at Urbana-Champaign (United States); James Guenter, Finisar Corp. (United States)
In this presentation the authors will both review the highlights in the development, applications, and manufacturing of vertical cavity surface emitting lasers as reported during the past 20 years of the VCSEL Conference at Photonics West.

Beam steering and vortex beam creation in VCSEL photonics (Invited Paper)
Fumio Koyama, Tokyo Institute of Technology (Japan)
The 38 years’ R&D of VCSELs opened up various applications including datacom, sensors, optical interconnects, spectroscopy, printers, and so on. A key challenge is to establish a platform to integrate functional devices with VCSELs. In this paper, we address a lateral integration platform and new functions, including high-resolution beam scanner, and vortex beam emitters.

A schematic structure of the VCSEL-based beam steering device is similar to a conventional VCSEL in the vertical direction. An active region and an oxidation confinement layer are sandwiched by two distributed Bragg reflectors (DBR) as mirrors. A portion of light radiates from the surface. Thanks to the large angular dispersion, we are able to realize beam-steering of the radiated light by tuning the wavelength of incident light or tuning the refractive index. We achieved a record number of resolution points N larger than 1,000.

We present the monolithic integration of a compact vortex beam emitter and VCSEL for the creation and multiplexing of vortex beams. The device generates an azimuthally polarized vortex beam from a ring-shape waveguide laterally coupled with an electrically pumped 980 nm VCSEL. We also demonstrate a double-ring vortex beam emitter array integrated with a VCSEL array pumped simultaneously. The result exhibits the possibility of the creation and multiplexing of vortex beams with different orbital momentums in a compact and scalable fashion.

780nm-range VCSEL array for laser printer system and other applications in Ricoh (Invited Paper)
Naoto Jikutani, Akihiro Itoh, Kazuhiro Harasaka, Toshihide Sasaki, Shunichi Sato, RICOH Co., Ltd. (Japan)
A vertical-cavity surface-emitting laser (VCSEL) is a suitable light source for high-speed and high-quality laser printer systems due to an easiness to fabricate high-positioning-precision and high-density two-dimensional monolithic arrays. We have developed the 780nm-range 40-channels VCSEL array for printers with orthogonal-polarization suppression-ratio (OPSR) of over 22 dB and side-mode suppression-ratio (SMSR) of 30 dB at operation power of 3mW at same time for wide oxide-aperture range below 50 ?m2. We employed 15°-off misoriented GaAs substrate, GainAsP/GaInP compressively-strained multiple quantum wells and an anisotropically-shaped transverse mode filter to control polarization. The anisotropically-shaped transverse mode filter also suppresses higher transverse mode and enable high-power single-mode operation. Moreover, we reduced a thermal resistance of bottom distributed Bragg reflector (DBR) for 38% by increasing thickness of high thermal conductivity layers (37/4-A1As layers) near the cavity. By this structure, the peak-power increased to 1.3 times. And the power-fall at pulse-rise that causing by self-heating decreased to 10% and the one causing by thermal-crosstalk decreased to 46%. As for the optical-crosstalk, the optical-feedback from neighbor channels, which reflected by protection mirror, strongly affect output stability. Therefore we tilted protection grass and completely suppressed power instability. Then, we mounted a photodiode near a VCSEL array to monitor output power from a tilted glass. Thus we have developed polarization controlled, high single-mode power, less thermal and optical-crosstalk VCSEL array package for printer systems. We also report on other applications of VCSEL in Ricoh.

VCSELs for interferometric readout of MEMS sensors (Invited Paper)
Darwin K. Serkland, Kent M. Geib, Gordon A. Keeler, Gregory M. Peake, Michael S. Baker, Michael J. Shaw, Bion J. Merchant, Brian D. Homeijer, Matthew Eichenfield, Sandia National Labs. (United States); Murat Okandan, EIOS, Inc. (United States)
We report on the development of VCSELs (vertical-cavity surface-emitting lasers) for interferometric readout of the position of a MEMS (micro-electro-mechanical systems) proof mass. Tiny low-cost MEMS sensors have become widely available in the last decade, including accelerometers, gyroscopes, and pressure sensors. The raw measurement of most MEMS sensors is the mechanical position of a moving part, typically sensed as a change in capacitance. Capacitive measurement of position typically trades sensitivity (minimum detectable movement) for dynamic range (total range of motion). The use of VCSEL based optical interferometers alleviates the trade-off between sensitivity and dynamic range for MEMS position sensing, enabling higher performance MEMS sensors. In this talk we will discuss the VCSEL performance characteristics for interferometric sensors. Similar to other spectroscopic sensors, the VCSELs should operate in a single mode: single frequency and single polarization. Since the VCSEL wavelength determines the position scale, long-term wavelength stability is desirable. For applications that sense over a long range of positions, narrow linewidth and long coherence lengths are...
desirable. When integrating the VCSEL with the MEMS sensor, it is important to retain the MEMS sensor advantages: small size, low cost, and low power consumption.

9766-6, Session 2

Dynamic properties of silicon-integrated short-wavelength hybrid-cavity VCSEL

Emanuel P. Haglund, Chalmers Univ. of Technology (Sweden); Sulakshna Kumari, Univ. Gent (Belgium); Petter Westbergh, Johan S. Gustavsson, Chalmers Univ. of Technology (Sweden); Gunther Roelkens, Roel G. Baets, Univ. Gent (Belgium); Anders Larsson, Chalmers Univ. of Technology (Sweden)

A promising technique to obtain an integrated efficient and high-speed light source for silicon photonics transceivers is heterogeneous integration of direct bandgap III-V material. This makes the GaAs-based vertical-cavity surface-emitting laser (VCSEL) an attractive option. GaAs-based VCSELs are the most energy efficient and high-speed light sources available today with modulation bandwidths up to 30 GHz. By using divinylsiloxane-bis-benzocyclobutene (DVS-BCB) adhesive bonding, a GaAs “half-VCSEL” can be heterogeneously integrated on a Si-based reflector creating a VCSEL with hybrid cavity where the optical field extends over both the GaAs- and the Si-based parts of the cavity. With the optical field extending into the Si-based part, some of the light can potentially be tapped off to an in-plane waveguide. Since GaAs-based VCSELs operate at wavelengths that are absorbed by silicon, the waveguide core material could be silicon nitride (SiN).

As a first step towards integration of GaAs-based VCSELs on a Si waveguide platform we present a VCSEL where a GaAs “half-VCSEL” has been attached to a silicon-based dielectric distributed Bragg reflector using ultra-thin DVS-BCB adhesive bonding. After removal of the GaAs substrate, oxide confined VCSELs were fabricated using a process for low pad capacitance. A VCSEL with an oxide aperture diameter of 5 μm and a threshold current of 0.5 mA provides 1.3 mW output power at a wavelength of 844 nm. With sufficient damping of the modulation response, set by the photon lifetime, the VCSEL exhibits a modulation bandwidth of 11 GHz and can transmit data up to 20 Gbps.

9766-7, Session 2

Direct visualization of the in-plane leakage of high-order transverse modes in vertical-cavity surface-emitting lasers mediated by oxide-aperture engineering

Nikolay N. Ledentsov Jr., Vitaly A. Shchukin, Joerg Kropp, VI Systems GmbH (Germany); Sven Burger, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Frank Schmidt, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Nikolay N. Ledentsov Jr., VI Systems GmbH (Germany)

Oxide-confined apertures in vertical cavity surface emitting laser (VCSEL) can be engineered such that they promote leakage of the transverse optical modes from the non-oxidized core region to the selectively oxidized perimeter of the device [1, 2]. The reason of the leakage is that the VCSEL modes in the core can be coupled to tilted modes in the perimeter if the orthogonality between the core mode and the modes at the perimeter is broken by the oxidation-induced optical field redistribution. Three-dimensional modeling reveals i) significantly stronger leakage losses for high-order transverse modes than that of the fundamental one as high-order modes have a higher field intensity close to the oxide layers and ii) narrow peaks in the far-field profile generated by the leaky component of the optical modes at 37 degrees. Experimental 850-nm GaAlAs leaky VCSELs produced in the modeled design demonstrate i) single-mode lasing with the aperture diameters up to 5μm with side mode suppression ratio >20dB at the current density of 10kA/cm2; and ii) narrow peaks tilted at 37 degrees with respect to the vertical axis confirming the leaky nature of the modes and the proposed mechanism of mode selection. The results indicate that in-plane coupling of VCSELs, VCSELs and PINs, VCSEL and delay lines is possible allowing novel photonic integrated circuits.


9766-8, Session 2

Passive cavity surface-emitting lasers: option of temperature-insensitive lasing wavelength for uncooled dense wavelength division multiplexing systems

Vitaly A. Shchukin, Nikolay N. Ledentsov Jr., VI Systems GmbH (Germany); Thomas Slight, Wyn Meredith, Compound Semiconductor Technologies Global Ltd. (United Kingdom); Nikita Gordyev, Alexei M. Nadtochy, Alexey S. Payusov, Mikhail V. Maximov, Ioffe Physical-Technical Institute (Russian Federation); Kent D. Choquette, Univ. of Illinois at Urbana-Champaign (United States)

Shifting of the gain medium in surface-emitting lasers from the resonance cavity to a distributed Bragg reflector (DBR) enables new functionalities of surface-emitting devices [1, 2]. First, once gain medium is placed in a bottom DBR, both the resonance cavity and the top DBR can be formed of dielectric material (the cavity is just a passive cavity), and the cavity can be etched through forming a photonic crystal device, in which modifications of the optical modes are much stronger than in conventional photonic crystal VCSELs [3] where only a part of the top DBR is etched. Second, the thermal shift of the lasing wavelength is now controlled by temperature dependence of the refractive indices of dielectric materials. The refractive index thermal coefficients of the dielectric are widely varied allowing positive, zero, or negative thermal shift of the lasing wavelength on purpose. We show that the structure containing a passive cavity and a top DBR formed of conventional dielectric materials may reveal a negative thermal shift (~0.04 nm/K) of the resonance in the range from 640 nm to 850 nm. Combining the passive cavity dielectric structure with the active GaAlAs-based bottom DBR allows surface-emitting lasers with an ultralow thermal shift of the wavelength within the interval (~0.02 nm/K) and, hence, uncooled dense wavelength division multiplexing (WDM) systems with a few times smaller spacing between the channels as compared to 20nm spacing in coarse WDM.


9766-9, Session 3

VCSEL-based sensors for distance and velocity (Invited Paper)

Holger Moench, Philips Technologie GmbH (Germany); Mark Carpaj, Philips Research (Netherlands); Philipp
Gerlach, Philips GmbH U-L-M Photonics (Germany); Stephan Gronenbron, Philips GmbH (Germany); Ralph Guinne, Jochen Hellmig, Philips Research (Netherlands); Johanna Kolb, Philips Technologie GmbH (Germany); Alexander van der Lee, Philips Research (Netherlands)

VCSELs based sensors can measure distance and velocity in three dimensional space and are already produced in high quantities for professional and consumer applications. This paper will discuss two complementary approaches:

Self-mixing interference works with coherent laser photons scattered back into the cavity and is therefore completely insensitive to environmental light. The method is used to measure target velocity and distance with very high accuracy at distances up to 1 m. Single-mode VCSELs with integrated photodiode and gratating stabilized polarization enable very compact and cost effective products. Besides the well know application as computer input device new applications with even higher accuracy or for speed over ground measurement in automobiles and up to 300km/h will be presented.

On the other hand time-of-flight methods use a pulsed VCSEL as light source, either with strong single pulses at low duty cycle or with pulse trains. Because of the sensitivity to background light and the strong decrease of the signal with distance multiple Watts or tens of Watts are needed at 10m-100m distance. VCSEL arrays enable power scaling and can provide very short pulses at much higher power density than in cw operation. Applications range from extended functions in a smartphone over industrial sensors up to automotive LIDAR for driver assistance and autonomous driving.

Both measurement methods exploit the good VCSEL properties like robustness, stability over temperature and the potential for packages with integrated optics and electronics. This makes VCSEL sensors ideally suited for new mass applications in the consumer and automotive markets.

9766-10, Session 3
Progress in high-power high-speed VCSEL arrays (Invited Paper)
Richard F. Carson, Mial E. Warren, Preethi Dacha, Thomas Wilcox, David J. Abell, Kirk J. Otis, TriLumina Corp. (United States); James A. Lott, Technische Univ. Berlin (Germany)

Flip-chip bonding enables a unique architecture for two-dimensional arrays of VCSEL devices. Such arrays feature scalable power outputs and the capability to separately address sub-array regions while maintaining fast turn-on and turn-off response times. These substrate-emitting VCSEL arrays can also make use of integrated micro-lenses for beam shaping and directional control. Advances in the performance of these laser arrays will be reviewed and some of their emerging applications will be discussed.

9766-11, Session 3
Developments of VCSELs for printers and optical communications at Fuji Xerox (Invited Paper)
Takashi Kondo, Kazutaka Takeda, Hiromi Otoma, Akemi Murakami, Jun Sakurai, Hideo Nakayama, Fuji Xerox Co., Ltd. (Japan); Fumio Koyama, Tokyo Institute of Technology (Japan)

We introduce the characteristics of vertical-cavity surface-emitting lasers (VCSELs) for printers and optical communications. In 2003, we launched the world’s first laser printer with a 780-nm single-mode 874 VCSEL array introduced to the light exposure system in order to meet the market demands for an improved image quality and speed for laser printers. The design of the VCSEL array has increased the pixel density and the printing speed by projecting 32 beams at a time to the photoconductor in the exposure process. High uniformity with less than 5% of variation has been achieved for both the optical output and the divergence angle. Currently, our high-end color printer is capable of producing the resolution of 2400 dpi (dots per inch) at the speed of 137 ppm (pages per minute).

In the field of optical interconnections and networks, 850-nm VCSELs are needed as high-speed optical transmitters (at10Gbps). In order to address communication traffic that will increase further as well as to reduce their electricity consumption to an even lower level, we assessed the lasing characteristics of 850-nm VCSELs with InGaAs strained quantum-well (QW) active layers by changing the ratio of Indium composition. As a result, we succeeded in reducing the power consumption to 43 fJ/bit at the 10-Gbps modulation rate, which is lower than those of conventional GaAs QW VCSELs that are commercially available. Also, we studied 850-nm transverse-coupled-cavity VCSELs, which helped us achieve a high 3dB modulation bandwidth (>23 GHz) and gain eye-openings at the large-signal modulation rate of 36 Gbps.

9766-12, Session 3
High-efficiency VCSEL arrays for illumination and sensing in consumer applications
Jean-Francois Seurin, Delai Zhou, Guoyang Xu, Alexander Miglo, Daizong Li, Tong Chen, Baiming Guo, Chuni L. Ghosh, Princeton Optronics, Inc. (United States)

There has been increased interest in vertical-cavity surface-emitting lasers (VCSELs) for illumination and sensing in the consumer market, especially for 3D sensing (“gesture recognition”) and 3D image capture. For these applications, the typical wavelength range of interest is 830–950nm and power levels vary from a few milli-Watts to several Watts. The devices are operated in short pulse mode (a few nano-seconds) with fast rise and fall times for time-of-flight applications (ToF), or in CW/quasi-CW for structured light applications. In VCSELs, the narrow spectrum and low temperature dependence with respect to temperature allows the use of narrower filters and therefore better signal-to-noise performance, especially for outdoors applications.

In portable devices (mobile devices, wearable devices, laptops, …) the size of the illumination module (VCSEL and optics) is a primary consideration. VCSELs offer a unique benefit compared to other laser sources in that they are “surface-mountable” and can therefore be easily integrated along with other electronics components on a printed circuit board (PCB). A critical concern is the power-conversion efficiency of the illumination source, especially at high temperatures (>50 deg C). Princeton Optronics will report on VCSEL devices with high efficiency at high temperatures designed for these new consumer applications. We will also show results on sub-nano-second rise and fall time for high-power arrays for ToF applications. Results for devices designed for structured light applications will also be presented.

9766-13, Session 4
Reliability requirements for VCSELs in engineered computer systems (Invited Paper)
David K. McElfresh, John E. Cunningham, Xuezhe Zheng, Kannan Raj, Oracle (United States)

850nm multi-mode VCSELs are often used in short reach data links in systems that push the limits of the then-current technologies, striving for higher speed and higher bandwidth density. In such applications, substantial changes to the VCSELs and packaging from the previous generation...
are required. Essentially, the optical devices are new with little reliability information to leverage. To meet the product marketplace timing, systems have to be released well before the reliability of the new optical devices and their components have been sufficiently measured and before the effects of changes to the VCSELs, packaging, assembly, handling, and use conditions have been found. Each new generation uses more VCSEL channels under harsher drive and environmental conditions while also requiring greater reliability at the system level. We will discuss past, present, and future applications of VCSELs in systems and the concomitant impact to reliability requirements; the data that are typically available when fielding leading edge optical devices and the inadequacies of those data. We will also discuss the failure mechanisms that have created actual problems and which are not covered by reliability testing of most suppliers.

9766-14, Session 4
Failure mode analysis of degraded InGaAs-AlGaAs strained quantum-well multi-mode vertical-cavity surface-emitting lasers
Yongkun Sin, Nathan Presser, Michael Huang, Zachary Lingley, Miles Brodie, Jesse Theiss, Mark Peterson, Stephen L. LaLumondiere, Brendan Foran, Steven C. Moss, The Aerospace Corp. (United States)

Remarkable progress made in VCSELs emitting at 850 and 980 nm has led them to find an increasing number of applications in high speed data communications as well as in potential space satellite systems. However, little has been reported on reliability and failure modes of InGaAs VCSELs emitting at 980 nm although it is crucial to understand failure modes and underlying degradation mechanisms for space missions. The active layer of multi-mode oxide-VCSELs that we studied consisted of InGaAs quantum wells. Failures were generated via accelerated lifetesting of VCSELs. For the present study, we report on failure mode analysis of degraded oxide-VCSELs using various techniques. We employed nondestructive techniques including EBIC, OBIC, and time-resolved photoluminescence (TR-PL) techniques as well as destructive techniques including FIB and high-resolution TEM techniques to study VCSELs that showed different degradation behaviors including gradual degradation and catastrophic/sudden degradation. Especially, we employed FIB to locally remove a portion of top-DBR mirrors of degraded VCSELs, which made it possible for our EBIC and OBIC techniques to locate damaged areas (dark spots and dark lines) that were generated as a result of catastrophic bulk degradation and also for our HR-TEM technique to prepare TEM cross sections from damaged areas. In addition, TR-PL techniques were employed to study carrier dynamics in gradually degraded VCSELs to identify mechanisms responsible for this type of degradation. Our detailed destructive and nondestructive physical analysis results will be presented including defect, structural and chemical analysis results from degraded VCSELs lifetested under different test conditions.

9766-15, Session 4
VCSEL-based Flexible Opto-Fluidic Fluorescence Sensors
Dongseok Kang, Boju Gai, Jongseung Yoon, The Univ. of Southern California (United States)

We present a type of compact, mechanically flexible microsystem for opto-fluidic fluorescence sensing based on heterogeneously integrated arrays of microscale vertical cavity surface emitting lasers (micro-VCSELs) and silicon photodiodes (Si-PDs) as a light source for excitation and a detector for fluorescence emission from organic luminophores, respectively. Printable forms of epitaxially grown GaAs-based 850 nm micro-VCSELs and thin film (~3 ?m) single-crystalline Si-PDs separately prepared from respective source wafers (i.e. GaAs and silicon-on-insulator (SOI)) were released by selective wet chemical etching of sacrificial layers and assembled with polydimethylsiloxane (PDMS)-based molded microfluidic channels and a polyethylene terephthalate (PET) substrate by techniques of transfer printing to yield mechanically flexible, opto-fluidic integrated fluorescence sensors. To realize high sensitivity fluorescence sensing in the context of integrated microfluidic VCSEL-PD system, schemes of optical isolation and angle-selective spectral filtering were introduced. First, metal-coated isolation trenches were introduced by photolithography and metal evaporation to eliminate or minimize the absorption of excitation light by a photodiode due to the wave-guided spontaneous emission from co-integrated micro-VCSELs through polymeric encapsulation layer. Secondly, we implemented a specialized design of angle-selective spectral filter based on sputter-deposited multilayers of SiO2 and TiO2 such that the absorption of excitation light reflected by the wall of microfluidic channel and incident back on the Si-PD is suppressed while comparatively enhancing the absorption of fluorescent photons by the infrared-absorbing organic dyes. The resulting VCSEL-based flexible opto-fluidic fluorescence sensor on plastics provided the detection limit of 270 nM (or 2 x 10^-5 wt%) for infrared-absorbing dye solution (IR 145).

9766-16, Session 4
Controlling the parameters of wet lateral oxidation for VCSEL fabrication
Majid Riaziat, Dave Reed, Alex Kor, California Scientific, Inc. (United States)

We present our study of the various parameters that can be controlled during the wet oxidation of VCSELs in order to improve oxidation uniformity and reproducibility. The parameters that need to be controlled are numerous and include: temperature uniformity, vapor flow pattern, wafer bow, epitaxial thickness and composition uniformity, diffusion through adjacent layers, oxidation onset delay, etch skirt, and wafer surface prep. We report the results of our studies on vapor flow rates and patterns, and thermal leveling in the chamber. In our approach, the wet carrier gas is superheated prior to injection into the oxidation chamber, and the flow rate is set at the minimum level required to inhibit the formation of static Benard convection cells. This flow regime minimizes the disturbance to temperature distribution caused by vapor flow in the chamber. We discuss the design of an oxidation system, and the advantage of automatically controlling multiple parameters over time.

9766-17, Session 5
Beam quality study for single-mode oxide-confined and photonic crystal VCSELs (Invited Paper)
Janice T. Blane, William K. North, Jonathan B. Dencker, Peter R. Zeidler, Brian Souhan, U.S. Military Academy (United States); Kirk A. Ingold, Stanford Univ. (United States); James J. Raftery Jr., U.S. Military Academy (United States)

A high-quality single mode beam is desirable for the efficient use of lasers as light sources for optical data communications and interconnects. To this end we conducted a study to analyze the beam quality for a number of vertical-cavity surface-emitting lasers (VCSELs). We constructed an apparatus for measuring the beam quality factor, M2, for on-wafer devices. Along with M2 measurements, we measured spectral content across the device operating range to determine the number of operating modes, with single mode devices (defined as >30dB SMSR) being of primary interest. We determined the device operating range by measuring both voltage and optical output power versus injection current (LIV). Using the spectral measurements, we calculated the root-mean-square (RMS) linewidths as a means to further quantify beam quality. As part of this effort, we characterized the beam quality of devices emitting at 850 nm...
with oxide-confined apertures of the 2.5 \( \mu \)m, 3.0 \( \mu \)m, 3.5 \( \mu \)m, 4.0 \( \mu \)m, and 4.5 \( \mu \)m. In addition to oxide-confined devices, devices with photonic crystal (PhC) confinement to define the optical cavity were studied. Device characterization and beam quality data for each of the studied devices will be presented and discussed.

9766-18, Session 5

Low-dispersion ultra-high-bandwidth vertical-cavity surface-emitting laser arrays

Kent D. Choquette, Stewart T. Frysie, Univ. of Illinois at Urbana-Champaign (United States)

We show a novel design and operation technique for an array of optically coupled vertical cavity surface emitting lasers enabling high-performance optical transmission. Bandwidths up to 37 \( \text{GHz} \) have been obtained under single-mode operation with narrow spectral width and increased output power while the laser array is biased at low current density. Using dynamic coupled mode theory analysis we determine important design parameters to engineer for greater enhancement of modulation response.

9766-19, Session 5

Close to 100Gb/s discrete multitone transmission over 100-m of multimode fibre using a single transverse mode 850nm VCSEL

Bo Wu, Zhou Xian, Ma Yanan, Luo Jun, Huawei Technologies Co., Ltd. (China); Zhong Kangping, The Hong Kong Polytechnic Univ. (China); Shaofeng Qiu, Feng Zhiyong, Huawei Technologies Co., Ltd. (China); Luo Yazhi, The Hong Kong Polytechnic Univ. (China); Joerg Kropp, Vitaly A. Shchukin, Nikolay N. Ledentsov Jr., VI Systems GmbH (Germany); Lu Chao, The Hong Kong Polytechnic Univ. (China)

We study Discrete Multitone Transmission (DMT) over standard multimode fiber (MMF) using high-speed single (SM) and multimode (MM) VCSELs. Transmission speed in the range of 72Gb/s to 82Gb/s over 300m-100m distances of OM4 fiber is realized, respectively, at Bit-Error-Ratio (BER) \(<5 \times 10^{-3}\) and the received optical power of only \((-5 \text{dBm})\). Such BER condition requires only 7% overhead for the conversion to error-free operation using single BCH FEC coding and decoding. We show that SM VCSEL provides a much higher data transmission capacity over multi-mode fiber (MMF). For 100m MMF transmission SM VCSEL allows 82Gb/s as compared to MM VCSEL resulting in only 34Gb/s at the same power \((-5 \text{dBm})\). Furthermore, MM VCSEL link at 0dBm is still restricted at 100m distance by 63Gb/s while SM VCSEL can exceed 100Gb/s at such power levels. We believe that with further improvement in SM VCSELs and fiber coupling 100Gb/s+ data transmission over >300m MMF distances at the BER levels matching the industry standards will become possible.

9766-20, Session 5

Influence of birefringence splitting on ultrafast polarization oscillations in VCSELs

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Spin-VCSELs offer numerous advantages over conventional lasers like reduced threshold, spin-amplification and ultrafast polarization dynamics. The latter have the potential to generate polarization modulation frequencies far above the conventional intensity relaxation oscillation frequency of one and the same device and thus can be an interesting basis for ultrafast optical data transmission. We have shown that fast polarization oscillations can be generated by pulsed spin injection. Furthermore the oscillation frequency can be tuned via modification of the VCSEL’s cavity strain. Using this technique, oscillation frequencies with a tuning range from nearly zero up to 40 \( \text{GHz} \) can be demonstrated. In the device under study, this is more than six times the intensity relaxation oscillation frequency, which is nearly independent of the strain. Now we demonstrate the influence of the strain-induced birefringence splitting on the oscillation frequency. We find that the polarization oscillation frequency is directly corresponding to the birefringence splitting. The reason is that the polarization oscillation has the beating frequency of the two orthogonal linearly polarized cavity modes in the VCSEL. In the case of spin-pumping, those two modes form the circular polarization output of the laser by superposition. Their frequencies are shifted by birefringence manipulation and form the basis of birefringence splitting. The measurement results are compared with simulations employing the spin-flip-model. Our results show that high-frequency polarization oscillations can not only be generated with the help of external strain but with high birefringence splitting in general.

9766-21, Session 5

Monolithic high-index contrast grating VCSEL

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One of the biggest obstacles on the way to high-speed and long-range optical links based on silicon fibers is the lack of cheap and good quality light sources. The best candidate for this role seems to be the Vertical Cavity Surface Emitting Laser (VCSEL) emitting around 1.3 \( \mu \text{m} \) and 1.55 \( \mu \text{m} \) wavelength. Unfortunately, mirrors scheme widely used in shorter wavelength VCSELs – distributed Bragg reflector (DBR), can’t be easily incorporated in 1.3 \( \mu \text{m} \) and 1.55 \( \mu \text{m} \) VCSELs. On the other hand, recent trend in the research focused on short-range optical links is to increase the speed and energy efficiency of the signal sources – the 0.98 \( \mu \text{m} \) VCSELs. This goal is pursued by decreasing of parasitic capacitance of the laser and decreasing the photon lifetime in the laser cavity. We present results of self-consistent 3D, thermal, electrical, gain and optical simulations of a novel, ultra-small VCSEL device of extremely simplified design. The device uses monolithic high contrast grading (MHCG) mirrors instead of the commonly used distributed Bragg reflectors (DBR). We show that very high reflectivity, required to sustain a VCSEL lasing, can be achieved by only a shallow etching of the surface of the laser cavity. Thanks to the extraordinary features of the MHCG mirror, the cavity and the mirror can be made of a single material what opens a way to 1.3 \( \mu \text{m} \) and 1.55 \( \mu \text{m} \) VCSELs. Additionally, the photon lifetime in the laser cavity can be tuned by variation of the design parameters of the mirror in the post-growth process.
9767-1, Session 1

Relative merits and prospects of metal-clad (plasmonic) semiconductor lasers from UV to far IR (Invited Paper)

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

Using metal-clad (or plasmonic) waveguide structures in semiconductor lasers carries a promise of reduced size, threshold, and power consumption. While lasing in metal-clad structure’s has been achieved, the thresholds remain much higher than in conventional semiconductor lasers, except for THz region. We investigate the reasons for it through a rigorous theoretical test, that takes into account increased waveguide loss, Auger recombination, and Purcell enhancement of spontaneous recombination. The conclusion is that purported benefits of metal waveguides are small to nonexistent for all the band-to-band and intersubband lasers operating from UV to Mid-IR range, with a prominent exception of far-IR and THz quantum cascade lasers. For these devices, however, metal waveguides already represent the state of the art, and the guiding mechanism in them has far more in common with a ubiquitous transmission line than with plasmonics.

9767-2, Session 1

Type-I QW cascade diode lasers for spectral region above 3 µm

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It was recently demonstrated that the cascade pumping of type-I quantum well (QW) gain sections can yield edge emitting diode lasers with record performance parameters. For instance, two-stage ~ 3 µm cascade lasers demonstrated twofold reduction of the threshold current density, twofold enhancement of the power conversion efficiencies and threefold increase of the output power level as compared to their parent diode lasers. It is tempting to apply the same laser heterostructure design concept to obtain similarly enhanced performance at longer wavelength, for instance, near technologically important methane absorption band.

In this work we discuss the development of the ~ 3 µm cascade lasers. The experiment showed that the increase of the number of cascades from two to three led to critical enhancement of the differential gain and reduction of the threshold current density. Light p-doping of the AlGaAsSb graded section did not introduce extra optical loss but aided hole transport as required for realization of the efficient multi-stage cascade pumping scheme. Corresponding coated three-stage devices with ~100 µm wide aperture and 3-mm-long cavity demonstrated CW output power of 500 mW near 3.2 µm at 17 OC – more than twofold increase as compared to previous state-of-the-art diode lasers emitting only 200 mW. Peculiarities of the design of the single mode lasers based on multistage cascade heterostructure design will be discussed. Two step etching was applied in effort of simultaneous minimization of both internal optical loss and the lateral current spreading in narrow ridge lasers.

9767-3, Session 1

Electronic control of coherence in a two-dimensional array of photonic crystal surface-emitting lasers

Richard J. E. Taylor, David T. D. Childs, Pavlo I. Ivanov, Ben J. Stevens, Nasser Babazadeh, Guangrui Li, The Univ. of Sheffield (United Kingdom); Gary Ternent, Stephen Thoms, Haiping Zhou, Univ. of Glasgow (United Kingdom); Richard A. Hogg, The Univ. of Sheffield (United Kingdom)

Photonic crystal surface emitting lasers (PCSELs) offer the ultimate in control in semiconductor lasers. PCSELs have been shown to have high single-mode powers, large scale coherent emission, and control of the beam shape and polarization with design of the photonic crystal geometry. Coherently coupled arrays of surface emitting lasers would be useful for a wide range of applications, particularly in achieving high brightness lasers. In this paper we demonstrate 2D coherently coupled PCSEL arrays, where individual PCSELs are separated by a comparatively large distance (1mm) and the region between them is contacted but contains no photonic crystal (referred to as the coupler region). By application of current to the coupler region, we are able to tune between gain and loss in the connecting waveguide. With the coupler in gain we are able to demonstrate that power from one PCSEL can be coupled into an adjacent PCSEL. Secondly we are able to demonstrate that these devices are coherent and the coherence can be electronically tuned over two dimensions by varying the transparency of connecting couplers. By overlaying the nearfield image of adjacent PCSELs we demonstrate that the devices are individually coherent across the device surface, are coherent with each other, and that the coherence is electronically controllable across the 2D array.

9767-4, Session 1

Generation of 7 W nanosecond pulses with 670-nm ridge-waveguide lasers

Andreas Klehr, Thomas Prziwarka, Armin Liero, Thomas Hoffmann, Johannes Pohl, Jörg Fricke, Hans-Jürgen Wünsche, Hans Wenzel, Wolfgang Heinrich, Götz Erbert, Ferdinand-Braun-Institut (Germany)

Short optical pulses with high response speed, high peak power and good beam quality are ideally suited for free-space communication, analytics, material processing and LIDAR. Gain switched diode lasers are very attractive pulse sources for these applications. The aim of this paper is to present detailed experimental and theoretical investigations of the behaviour of ridge-waveguide (RW) lasers emitting at 670 nm under injection of sub-ns current pulses with amplitudes higher than 20 A. The RW lasers are based on strained GainP double quantum wells embedded in an asymmetric AlGainP/AlInP waveguide structure. The widths of the ridges are 7.5 µm and 15 µm and the cavity length is 3 mm. The laser diodes are mounted on an in-house developed high-frequency unit electrically driven by nearly rectangular shaped current pulses with a length of about 700 ps and a repetition frequency of 1 MHz. The emitted optical pulses have a width of about 1 ns. The pulse power reaches a maximum value of 7.2 W for a ridge width of 15 µm and saturates if the applied voltage is further increased. The widths of the optical pulses can be changed between 400 ps to 1.2 ns by a variation of the electrical pulse width from 250 ps to 11 ns.
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At the conference it will be shown on the basis of time-dependent simulations with the drift-diffusion simulator WIAS-TeSCA, that excess electron accumulation under the ridge and leakage currents limit the maximum achievable output power.

9767-5, Session 1

**GaAs-based superluminescent diodes with window-like facet structure for low spectral modulation at high powers**

Omar Ghazal, Danqi Lei, David T. D. Childs, Ben J. Stevens, Nasser Babazadeh, Richard A. Hogg, Kristian M. Groom, The Univ. of Sheffield (United Kingdom)

Superluminescent diodes (SLDs) offer relatively high power over a broad emission spectrum, useful in applications such as fibre-optic gyroscopes and optical coherence tomography. A key parameter defining the coherence properties of the SLD is the spectral modulation depth (SMD), which occurs due to Fabry-Perot modes arising from zero-reflection at the facets of the device.

We present a new scheme for low effective reflectivity (Reff) facets based on the application of a self-aligned stripe process to realise window-like structures in GaAs-based SLDs. We demonstrate low SMD to high output powers without application of anti-reflection coatings, making them naturally broadband. Our self-aligned stripe is formed by regrowth of GaAs/AlGaAs cladding layers upon stripes etched into a GaNP optoelectronic confinement layer. Light is allowed to spread in a laterally unguided window region. However, in contrast to traditional optically transparent window structures, the active region remains intact in the window. Therefore light also undergoes absorption, resulting in further suppression of feedback into the waveguide and lowering Reff further.

We discuss the design criteria for simultaneous achievement of high power and low SMD (e.g. 30mW output power in a narrow bandwidth with only 5% SMD). Furthermore, the Reff of the window is sufficiently low (demonstrated as <10%76) to permit realisation of SLDs processed normal to the cleaved facet, for which output powers >12mW are demonstrated. Such devices offer improved beam quality, ease of packaging in standard mounts compared to the crescent-shape output of tilted facet SLDs, and reduced use of chip real estate.

9767-6, Session 1

**Monolithically integrated laser-detector arrays for chip-based sensing applications**

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Micro-fluidic technologies offer a potential route towards low cost, portable, disposable chip-based sensors. Typical approaches utilise low cost silicon or glass substrates with light emission and detection performed either off-chip using external equipment or incorporated on-chip using ‘pick and place’ diode lasers and photo-detectors. The former approach adds cost and limits portability while the sub-micron alignment tolerances imposed by the application make the latter impractical for all but the simplest of systems. The use of optoelectronic integration coupled to microfluidics and all built on an optically active semiconductor substrate overcomes these limitations by allowing multiple laser/detector arrays to be formed in the substrate itself using high resolution lithographic techniques.

Here we focus on the variety of ways lasers can be used for sensing applications enabled by the flexibility and precision in alignment and the capacity for multiple lasers and detectors on a single chip. We show an example demonstrating parallel measurement for increased throughput and multiple experiments performed sequentially. The fast switching times inherent with semiconductor lasers allows the active sections of the device to be reconfigured on a sub-microsecond time scale providing additional functionality. This is demonstrated here in the capillary fill system using pairs of laser/detectors that are operated in pulsed mode and alternated between lasing and detecting in an interleaved manner. The analyte is interrogated alternately from opposing sides of the microfluidic channel providing information that is used to calculate lateral position, size and instantaneous velocity.

9767-7, Session 2

**Highly strained type-I diode lasers on GaSb (Invited Paper)**

Seth R. Bank, Scott D. Sifferman, Hari P. Nair, Nathaniel T. Sheehan, Rodolfo Salas, Scott J. Maddox, Adam M. Crook, The Univ. of Texas at Austin (United States)

We describe our recent efforts to increase the active layer strain in GaSb-based type-I quantum-well diode lasers via growth at reduced substrate temperatures, with emphasis on extending the emission wavelength. This approach has enabled coherent growth of up to seven 2.8% compressively-strained GaInAsSb/GaSb quantum wells emitting at ~4 µm. We will describe proof-of-concept edge-emitting lasers with improved characteristic temperature and low threshold current densities. Exploratory experiments using bismuth both as a surfactant and lattice constituent to further extend the emission wavelength will be discussed. Both are promising approaches to extend the reach of type-I diode lasers further into the mid-infrared. The authors acknowledge ARO and NSF for support.

9767-8, Session 2

**Microscopic modelling of opto-electronic properties of dilute bismide materials for the mid-IR**

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The introduction of dilute Bismide into InGaAs-based heterostructures strongly reduces the bandgap allowing GaAsBi to reach telecom wavelengths and InAsBi wavelengths in the mid-IR. The interaction between the Bi-states and those of the host matrix is often approximated using the band-anti-crossing (BAC) model.

Integrating the BAC model into fully microscopic many-body models for the optical characteristics of dilute Bismides (absorption/gain, PL), has been shown to yield very good agreement with the experiment. The success of these calculations is in part due to the fact that these properties mostly depend on states close to the bandgap. However, for processes that involve states that are more resonant with the Bi-levels, like Auger processes, the validity of the BAC model becomes questionable. E.g., the clear separation of these calculations is in part due to the fact that these properties mostly depend on states close to the bandgap. However, for processes that involve states that are more resonant with the Bi-levels, like Auger processes, the validity of the BAC model becomes questionable. E.g., the clear separation between bands in the BAC model leads to a pronounced enhancement of Auger losses in GaAsBi for Bi-contents where the bandgap becomes resonant with the BAC hole-band splitting.

First principle DFT calculations show that the introduction of Bi-states leads to much more detailed changes of the bandstructure than captured by the BAC model. Generally, a multitude of anti-crossing features are introduced with gaps that depend on the direction and are not completely free of states. These effects could suppress significantly any sharp features...
predicted by the BAC model.

Here, we use fully microscopic many-body models to calculate important material characteristics of GaAsBi and InAsBi based devices, like absorption/gain, PL and radiative and Auger lifetimes, compare results to experimental data and discuss potential shortcomings of the BAC model.

9767-9, Session 2
First demonstration of orange-yellow light-emitter devices in InGaP/InAlGaP laser structure using strain-induced quantum well intermixing technique

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Recently, there is a strong interest in short-wavelength visible semiconductor laser (VSL), which has important applications in solid-state lighting, medicine, horticulture, displays, and in optical communication. These VSL are available in the violet to green (~405-530nm) and red (635-690nm) spectral range. The wavelength from ~530-635nm is not covered by any commercial VSLs yet. Indium segregation and large strain in the InGaN/GaN system prevents efficient emission from green to yellow-orange range, while insufficient confinement and leakage current prevent the shift from the red to the orange-yellow-green range in the InGaP/InAlGaP system. The only access to VSL from orange -green regime has been achieved through the application of high external pressures and low-temperature. In this paper, a novel strain-induced quantum well intermixing (QWI) technique is employed to promote interdiffusion via application of a thick dielectric encapsulant layer, cycles annealing at elevated temperature. With this QWI technique, we have successfully tuned the bandgap of InGaP/InAlGaP structure from 640nm to 565nm (~250meV), which is the highest degree of intermixing achieved thus far in this material system. Broad area devices fabricated from this novel QWI technique lased at room-temperature (RT) at a wavelength as short as 608nm with a total output power of ~46 mW. This is the shortest-wavelength VSL, and the first report of lasing action in this range. The device performance and output power were achieved through the reinforcement of carriers in cavities. The device performance can be significantly improved with much lower power consumption. The threshold current and voltage were decreased due to the reinforced confinement of carriers in cavities. The device performance can be significantly improved with much lower power consumption.

9767-10, Session 2
Dilute-As GaNAs quantum wells for visible lasers with reduced Auger recombination (Invited Paper)

Chee-Keong Tan, Nelson Tansu, Lehigh Univ. (United States)

Rapid progress in III-Nitride based light emitting diodes has resulted in large-scale implementation in solid state lighting and display technology. Recent works on InGaN emitters have been extended into laser diodes as the future solid state lighting platform. One pressing issue in the development of high efficiency InGaN emitters is the presence of high Auger recombination rates which is a primary source in leading to efficiency droop issue at high operating current density. Recent research on dilute-As GaNAs alloy showed promising findings in suppressing the Auger recombination issue in III-Nitride devices. The strategy pursuit of visible emission using dilute-As GaNAs material as the quantum well (QW) is thus critical for future development of GaN-based laser diodes with reduced Auger recombination.

9767-11, Session 3
Room-temperature continuous-wave operation of BeZnCdSe quantum-well green-to-yellow laser diodes with sub-10 mA threshold current

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Low threshold current waveguide type BeZnCdSe single quantum-well (SQW) laser diodes (LDs) have been developed. The waveguide was formed of a ridge structure with etching away the top p-type BeMgZnSe/ZnSe:N short-period superlattice cladding layer, and then covered with a thick SiO2 layer and planarized with chemical-mechanical polishing and reactive ion etching process. Three type LDs with different SQW thickness and Cd content were developed and compared at varying waveguide width and length. Lasing wavelength of 540, 563, and 567 nm were realized respectively, at room-temperature continuous-wave condition with the laser cavity formed by the cleaved waveguide facets coated with high-reflectivity dielectric films. Compared with our previously developed planar diode structure for a 5-?m-wide, 800-?m-long gain-guided green laser with a threshold current and voltage of 68 mA and 10.4 V, a 540-nm green laser with 7-mm-thick SQW can realize a threshold current and voltage of 7.07 mA and 7.89 V, respectively, for a cavity width of 4 ?m and length of 300 ?m. A 563-nm LD with 4-nm-thick SQW was also developed with 7.4-mA and 8-V threshold current and voltage for a 3-?m-wide, 300-?m-long cavity. A 567-nm yellow LD with 7-mm-thick SQW can achieve a threshold current and voltage of 10.8 mA and 8.4 V, respectively, for a cavity length of 300 ?m and width of 7 ?m. The threshold current and voltage were decreased due to the reinforced confinement of carriers in cavities. The device performance can be significantly improved with much lower power consumption. The threshold current and power consumption is also sufficiently low compared with that of InGaN/GaN green LDs, which will benefit the potential application for ZnSe-based LDs as light sources in full-color display devices installed in consumer products such as pocket projectors.

9767-12, Session 3
CW blue lasing in III-nitride nanobeam cavities on silicon substrate (Invited Paper)

Noelia Vico Triviño, Raphaël Butté, Jean-François Carlin, Nicolas Grandjean, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

III-V nitride semiconductor compounds are nowadays widely used in optoelectronic industry for making blue-and green laser diodes and for fabricating blue light emitting diodes aimed at solid-state lighting. In this
presentation, we will focus on GaN photonic crystal (PhC) cavities to be used in future nanodevices. We will see that GaN semiconductor is closing the gap with its GaAs counterpart, as exemplified by the demonstration of high quality factor (Q) two-dimensional (2D) PhC cavities. Such photonic structures are prepared from self-suspended GaN membranes fabricated with GaN-on-silicon heteroepitaxial layers. Growth of GaN on silicon substrate is very demanding due to the large lattice mismatch and huge thermal expansion coefficient difference. Nevertheless, provided appropriate growth strategy, GaN layers with decent structural properties can be synthesized. Still the density of dislocations is very high but we managed to process GaN PhC structures with excellent optical properties both in the blue-green spectral range and in the near infra-red. For instance, 2D PhC L3 cavities designed at 1.5 micron exhibit Q factors in excess of 20'000. We also fabricated 1D PhC nanobeams featuring a single InGaN/GaN quantum well (QW). In the low absorption part of the QW, Qs in excess of 10'000 are measured. On the other hand, in the blue spectral region, signature of lasing action under continuous wave optical pumping was evidenced at room-temperature.

9767-13, Session 3
Studies on 405 nm blue-violet diode laser with external grating cavity
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Spectroscopy applications of free-running laser diode (LD) are greatly restricted as its broad band spectral emission. And the power of a single blue-violet LD is around several hundred milliwatts by far, it is of great importance to obtain stable and narrow line-width laser diodes with high efficiency. In this paper, a high efficiency external cavity diode laser (ECDL) with high output power and narrow band emission at 405nm is presented. The ECDL is based on a commercially available LD with nominal output power of 100 mW at an injection current of 100mA. The spectral width of the free-running LD is about 1nm full width at half maximum (FWHM). A reflective holographic grating which is installed on a home-made compact adjustable stage is utilized for optical feedback in Littrow configuration. In this configuration, narrow line-width operation is realized and the effects of grating groove density as well as the groove direction related to the beam polarization on the performances of the ECDL are experimentally investigated. In the case of grating with groove density of 3600 g/mm, the threshold is reduced from 22 mA to 18.1 mA or 15.2 mA and the tuning range is 3.95 nm or 6.01 nm respectively when the grating is orientated in TE or TM polarization. And, an output beam with a line-width of 30 pm and output power of 88 mW is achieved in TE polarization. With these narrow line-width and high efficiency, the ECDL is capable to serve as a light source for spectroscopy application such as Raman scattering and laser induced fluorescence.

9767-14, Session 3
Large TE-polarized optical gain from AlInN-delta-GaN quantum well for ultraviolet lasers
Cheng Liu, Yu Kee Ooi, Jing Zhang, Rochester Institute of Technology (United States)

Ultraviolet (UV) lasers with wavelength < 300 nm have important applications in free-space communication, water/air purification, and biochemical agent detection. Conventionally, AlGaN quantum wells (QWs) are widely used as active region for UV lasers. However, high-efficiency electrically injected mid-UV lasers with wavelength - 250-300 nm are still very challenging as the corresponding AlGaN QWs suffer from severe band-mixing effect due to the presence of the valence subband crossover between the heavy-hole (HH) and crystal-field split off (CH) subbands, which would result in very low optical gain in such wavelength regime.

Therefore, in this work, we propose and investigate the use of AlInN material system as an alternative for mid-UV lasers. Nanostructure engineering by the use of AlInN-delta-GaN QW has been performed to enable dominant conduction band – HH subband transition as well as optimized electron-hole wave function overlap. The insertion of the ultra-thin delta-GaN layer, which is lattice-matched to AlInN layer, would localize the wave functions strongly toward the center of the active region, leading to large transverse electric (TE) polarized optical gain for ~250-300 nm. From our finding, the use of AlInN-delta-GaN QW resulted in ~6-times enhancement in TE-polarized optical gain, in comparison to that of conventional AlGaN QW, for gain media emitting at ~255 nm. The peak emission wavelength can be tuned by varying the delta layer thickness while maintaining large TE gain. Specifically, large TE gain was obtained for wavelength - 280 -300 nm, which are very challenging for conventional AlGaN QW UV lasers.

9767-15, Session 3
Electrically injected AlGaN nanowire deep ultraviolet lasers on Si (Invited Paper)
Zetian Mi, Songrui Zhao, Xianhe Liu, McGill Univ. (Canada); Steffi Woo, Gianlugi A. Botton, McMaster Univ. (Canada)

An efficient light source in the ultraviolet (UV)-C band (100-280 nm) is essentially required for a wide range of applications, including water purification, disinfection, and chemical and biological analysis. The current devices are limited to mercury vapor lamps, a few gas lasers, and lasers based on frequency conversion, which require the use of hazardous materials. Here we show that, with the discovery of atomic scale composition modulation in self-organized nearly defect-free AlGaN nanowires and the resulting strong three-dimensional (3D) quantum confinement, electrically injected semiconductor lasers can be achieved, for the first time, in the UV-C band. At room temperature, the laser threshold current density is ~0.6 kA/cm².

In this work, AlGaN nanowire laser structures were grown directly on Si substrate by radio frequency plasma-assisted molecular beam epitaxy. Detailed TEM studies confirm the presence of quantum-dot-like Ga-rich nanoclusters in the nearly defect-free nanowires. The resulting 3D quantum confinement can significantly reduce the transparency carrier density. Our detailed calculation also shows that such vertically aligned randomly distributed sub-wavelength scale nanowires array can provide strong optical confinement in the deep UV spectral range. Electrically injected surface-emitting micron-scale lasers were fabricated using standard photolithography and contact metallization techniques. Electrically injected lasers in the wavelength range of ~260 nm to 315 nm, covering nearly the entire UV-B and UV-C bands were demonstrated, for the first time. The laser threshold is only a few hundred A/cm², which is orders of magnitude lower compared to the conventional AlGaN quantum well lasers.

9767-16, Session 4
Effect of pumping delay on modulation response of double tunneling-injection quantum dot lasers
Levon V. Asryan, Virginia Polytechnic Institute and State Univ. (United States)

The modulation response of double tunneling-injection (DTI) quantum dot
(QD) lasers is studied with a proper account for noninstantaneous pumping of the lasing states in QDs. The active region in DTI QD lasers presents a single layer with QDs clad on each side by a thin barrier layer separating the QD-layer from the injector quantum well (QW) on that side. The electrons (holes) are first captured from the waveguide region (optical confinement layer) into the quantum well on the n- (p-) side of the structure and then tunnel through the corresponding barrier layer into QDs. The barrier layer on the n- (p-) side blocks the further transport of electrons (holes) to that side of the structure thus suppressing bipolar carrier (i.e., both electron and hole) population and parasitic recombination outside QDs. Both the capture and tunneling processes are noninstantaneous and thus cause delay in carrier supply to the lasing states in QDs. Here, the modulation bandwidth of DTI QD lasers is calculated as a decreasing function of the carrier capture time from the waveguide region into QWs and tunneling time from QWs into the QD-ensemble. The approach is based on the use of rate equations for free carriers in the waveguide region, carriers confined in the injector-QWs, carriers confined in QDs, and photons.

9767-17, Session 4

1.5 µm quantum dot laser material with high temperature stability of threshold current density and slope efficiency

Saddam Banyoudeh, Alireza Abdollahinia, Vitalii Sichkovskiy, Johann P. Reithmaier, Univ. Kassel (Germany)

InAs/InGaAs/InP quantum dot (QD) laser material for 1.5 µm emission wavelength was developed. A special emphasis was taken on obtaining high dot densities and small size fluctuations in order to obtain high spectral. Based on growth parameters recently developed (S. Banyoudeh et al., JCG 425, 299 (2015)) a high modal gain of up to 14.5 cm⁻¹ per QD layer or more than 80 cm⁻¹ for a 6 QD layer laser could be obtained, which allow a very robust ground state lasing. Broad area (BA) laser evaluation (pulsed mode) of lasers with different cavity lengths and with and without thermal annealing (RTA) was performed. The impact of RTA on the laser performance will be discussed. After RTA at about 730°C (30 s) the transparency current density went down to 350 A/cm² and the internal absorption down to less than 5 cm⁻¹. BA lasers with a cavity length of 343 µm and as-cleaved can be operated down to 350 A/cm² and the internal absorption down to less than 5 cm⁻¹.

9767-18, Session 4

High-temperature continuous wave operation (up to 100°C) of InAs/InGaAs quantum dot electrically injected microdisk lasers

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Development of lasers with reduced foot-print and high temperature stability of operation parameters is essential for on-chip optical interconnects. Use of self-organized InAs/InGaAs quantum dots (QDs) as an active region of the microlasers offers many advantages owing to their low transparency current density, the spatial localization of carriers within the QDs, and temperature-insensitive behavior. In this work, electrically-injected microdisk lasers with diameter varied from 15 to 31µm based on an InAs/InGaAs QD active region have been fabricated and tested in continuous wave regime. At room temperature lasing is achieved at wavelength around 1.26…1.27 µm with threshold current density about 600 A/cm². Specific series resistance is estimated to be about 10⁻¹⁴ Ohm·cm². The lasers were tested at elevated temperatures. Lasing is achieved up to 100°C with threshold current of 13.8mA and lasing wavelength of 1304nm in device with 31µm diameter. To the best of our knowledge, this is the highest CW lasing temperature and the longest lasing wavelength ever reported for injection QD microdisk/microcoring lasers on GaAs substrates. Emission spectrum demonstrates single-mode lasing with side mode suppression ratio of 24dB and dominant mode linewidth of 35pm. A combination of device characteristics achieved (low threshold, long wavelength, operation at elevated temperatures) makes them suitable for application in future optoelectronic circuits for optical interconnect systems.

9767-19, Session 4

Wavelength tunability of a two-mode semiconductor quantum dot laser in the telecom band

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A two-wavelength emission laser can be used to generate millimeter and terahertz waves by irradiating high-speed photodiodes or nonlinear crystals. Electromagnetic waves at such frequencies have recently become important for high-speed wireless communication and accurate sensing. We have developed a quantum dot (QD) two-mode laser with stable emission. In this study, we investigated the wavelength tunability of a two-mode laser consisting of an InP-based laser diode chip with InAs QDs as the gain medium, and an external cavity in the telecom band. The laser structure with InAs QDs was grown on InP(311)B substrates by solid-source molecular-beam epitaxy. After the growth of the QD laser wafer, the ridge waveguide was fabricated. An external- cavity laser system was constructed using the QD gain chip, an optical band-pass filter, and an etalon filter. The configuration for the two-mode laser was modified from that of a single mode laser. We observed two-mode lasing with a frequency separation of 90 GHz, which is in good agreement with the free spectral range of the etalon filter. Mode hopping and competition were largely suppressed by using QDs as the gain medium because the QDs have a delta-function-like gain profile. Mode hopping observed from 1472.5 nm to 1544 nm. This tunability covers a wide range of wavelengths around the telecom band; therefore, it can be used for high-performance sensing.

9767-20, Session 4

High-speed directly modulated 1.5 µm quantum dot lasers

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In comparison to quantum well (QW) laser material, the density of states
distribution in quantum dot (QD) material is discrete and the carriers are spatially localized. This should lead in an ideal case to a much differential gain and faster response. However, QD material fabricated by self-organized epitaxy suffers for a long time by dot size fluctuations and a limited modal gain. In this work the newest generation of 1.5 µm InAs/InGaAlAs/InP QD material with strongly improved modal gain (70 ~ 80 cm⁻¹ for a 6 QD layer design) and temperature stability (T0 = 131 K) was used to fabricate ridge waveguide lasers. Devices with different cavity lengths down to 190 µm and high reflection coatings on the backside were realized and mounted on a high-frequency submount. For a 266 µm long device a threshold current of 21 mA and nearly 30 mW at thermal rollover were obtained. High-speed measurements were performed with a 65 GHz network analyzer and a pattern generator with variable data rates. At 15 °C record values of about 15 GHz in bandwidth and 34 Gbit/s in digital modulation could be measured. Due to the high temperature stability of the laser performance, a data rate of more than 25 Gbit/s can be still obtained at 50 °C. The impact of different material and device parameters as well as further possible significant improvements in modulation bandwidth will be discussed.

9767-21, Session 5

Non-linear phenomena in quantum-dot lasers (Invited Paper)
Boguslaw Tykalewicz, Cork Institute of Technology (Ireland) and Tyndall National Institute (Ireland); David Goulding, Tyndall National Institute (Ireland) and Cork Institute of Technology (Ireland); Bryan Kelleher, Tyndall National Institute (Ireland) and Univ. College Cork (Ireland); Evgeny A. Viktorov, Univ. Libre de Bruxelles (Belgium) and ITMO Univ. (Russian Federation); Stephen P. Hegarty, Cork Institute of Technology (Ireland) and Tyndall National Institute (Ireland); Guillaume Huyet, Cork Institute of Technology (Ireland) and Tyndall National Institute (Ireland) and ITMO Univ. (Russian Federation)

Quantum dot lasers (QDLs) have been shown to have greatly enhanced stability in both the optical feedback and optical injection configurations due to both a high damping rate of the relaxation oscillations and a relatively low linewidth enhancement factor. QDLs as a result have displayed a significantly different dynamical behaviour in contrast to that observed in conventional semiconductor lasers. This work focuses on describing some recent results on non-linear phenomena observed in single-mode QDLs in both optical feedback and optical injection arrangements.

An unique feature of QDLs is the relative ease with which simultaneous lasing from the ground state (GS) and the excited state (ES) can be achieved. This work demonstrates ultra-fast all-optical switching between the ES and GS via optical injection of the GS, with switching rates on the order of hundreds of picoseconds observed. Hysteric switching between the GS and ES is observed for varying injection strengths and novel two-state dynamics is revealed.

Further more a new mechanism for mode-locking in semiconductor lasers is unveiled using a single-section QDL undergoing external optical feedback. Integer resonances between the relaxation oscillation (RO) frequency and the external cavity repetition rate can promote the synchronisation of many external cavity modes leading to the generation of a mode-locked pulse train at the round trip frequency. High order resonances between the RO frequency and the round trip frequency in QDLs are observed for the first time.

Experimental observations are in excellent agreement with detailed numerical simulations of rate equations appropriate for this laser type.

9767-22, Session 5

Timing jitter performance of mode-locked external cavity multi-quantum-well semiconductor lasers
Benjamin Döpke, Rouven H. Pilny, Heiko Horst kemper, Carsten Brenner, Ruhr-Univ. Bochum (Germany); Andreas Klehr, Götz Erbert, Günther Tränkle, Ferdinand-Braun-Institut (Germany); Martin R. Hofmann, Ruhr-Univ. Bochum (Germany)

A cost-efficient ultrashort pulse source with low timing jitter would have wide-ranging applications, as most popular sources used today, such as mode-locked solid state and fiber lasers possess an amount of complexity that is not easily reduced. One pulse source that is inherently scalable in terms of mass production is the mode-locked edge-emitting semiconductor laser. For applications, such as asynchronous optical sampling terahertz pump-probe spectroscopy, a minimization of the phase noise of the frequency comb components, and thereby timing jitter, is the most important challenge. While monolithic devices have been the source of a lot of recent interest in this regard, jitter reduction schemes are needed to achieve acceptable phase noise performance in these devices. External cavity multi-quantum-well lasers, on the other hand, have received less interest even though material systems have improved in recent years with the availability of super-large optical cavity devices, providing for high beam quality and therefore high potential cavity quality. In this work, we will present a study of the phase noise performance of such devices in an external cavity geometry with varying cavity Q-factor. It is found that the short-term timing jitter performance in free-running operation is lower than in previously published works.

9767-23, Session 5

Interaction of phase and amplitude shaping in an external cavity semiconductor laser
Rouven H. Pilny, Benjamin Döpke, Ruhr-Univ. Bochum (Germany); Jan C. Balzer, Philipps-Univ. Marburg (Germany); Carsten Brenner, Ruhr-Univ. Bochum (Germany); Andreas Klehr, Günther Tränkle, Ferdinand-Braun-Institut (Germany); Martin R. Hofmann, Ruhr-Univ. Bochum (Germany)

Ultrashort pulse generation with semiconductor lasers pose a promising alternative to currently available femtosecond laser sources like solid state and fiber lasers. Semiconductor devices can be produced inexpensively, are energy efficient and their wavelength can be designed by band gap engineering. Furthermore they feature a tunable repetition rate. Yet pulse duration and peak power of those devices limit their potential for applications so far.

However, recent research demonstrated a reduction of the pulse width from 534 fs (full width half maximum) to 216 fs by shaping the spectrally resolved phase and amplitude inside the cavity. The utilized system consisted of a mode-locked edge emitting semiconductor laser diode, a spatial light modulator inside the external cavity to carry out the pulse shaping and an evolutionary algorithm to optimize the phase and amplitude. Consequently we present the results of separate phase and amplitude shaping as well as their interaction if optimized together at the same time. Furthermore we demonstrate the flexibility of the phase and amplitude shaping with respect to each other. Thus we show the capability of our system to adapt to resonator external influences.
9767-24, Session 5

**Mid-IR lasers based on Cr- and Fe-doped ZnSe and ZnS polycrystals (Invited Paper)**

Sergey B. Mirov, Vladimir V. Fedorov, The Univ. of Alabama at Birmingham (United States); Dmitry V. Martyshkin, The Univ. of Alabama at Birmingham (United States) and IPG Photonics - Mid-Infrared Lasers (United States); Igor S. Moskalev, IPG Photonics - Mid-Infrared Lasers (United States); Mikhail S. Mirov, Sergey Vasilyev, IPG Photonics - Mid-Infrared Lasers (United States); Valentin P. Gapontsev, IPG Photonics Corp. (United States)

We report on novel design of tunable mid-IR Fe:ZnSe and Cr:ZnSe solid state lasers which provided significant increase of output power up to 35W@4.1 μm and 57W@2.5 μm and 20W@2.94 μm.

We demonstrate that polycrystalline Cr:ZnS/ZnSe gain media offer unique flexibility in Kerr-Lens-Mode-Locked (KLM) regime as very broad range of parameters (output power, pulse duration, pulse repetition rate) can be accessed using the same laser material and similar laser designs. The pulse duration approaching 3 optical cycles and 950 nm spectral span (3/5 of an octave) were obtained by dispersion management of the resonator within 500 nm bandwidth (1/3 of an octave). We also significantly improved output characteristics of polycrystalline Cr:ZnS:Se lasers in Kerr-Lens-Mode-Locked regime: 1.9 W average power at 41 fs pulse duration, 24 nJ pulse energy and 550 kW peak power with efficiency of 19% with regards to 1567 nm pump power from linearly polarized Er: fiber laser.

High nonlinearity of II-IV semiconductors and random quasi-phase-matching in polycrystalline material in combination with MW-level optical power, which is reached in the gain element of fs laser, offer a number of unique possibilities. The effects of up-conversion of mid-IR fs pulses in the laser medium are observed in current experiments: apart from efficient (10-1 of the main signal) and spectrally broad SHG we detect third and fourth optical harmonics (at about 10-2 and 10-5 level) as well as sum frequency generation between mid-IR fs pulses and a CW pump beam (at about 10-4 level). Implementation of synchronously pumped OPO based on orientation patterned GaAs and random quasi-phase-matching in polycrystalline Cr2+ZnS/ZnSe represents another interesting opportunity, which may lead to ultrafast oscillators with exceptionally broad spectral coverage spanning 2 to 10 μm.

9767-25, Session 6

**Narrow-linewidth 1.5 μm quantum-dot distributed feedback lasers**

Annette Becker, Vitalii Sichkovskyi, Marko Bjelica, Univ. Kassel (Germany); Ori Eyal, Technion-Israel Institute of Technology (Israel); Philipp Baum, Anna Rippien, Florian Schnabel, Bernd Witzigmann, Univ. Kassel (Germany); Gadi Eisenstein, Technion-Israel Institute of Technology (Israel); Johann P. Reithmaier, Univ. Kassel (Germany)

Distributed feedback (DFB) lasers were processed from InP based 1.5 μm quantum dot (QD) material with different numbers of quantum dot layers comprising quite different modal gain values and operation conditions. Stable side-mode suppression ratios of > 40 dB over the whole operation range were obtained with maximum output powers up to more than 15 mW per facet.

Laser material with 2 QD layers (device A) with about a modal gain of 30 cm-1 are compared with 5 QD layers (device B) with about 70 cm-1. Due to the lower modal gain, device A reaches gain saturation at lower current densities and the gain function becomes asymmetric while for device B the ground transition is much stronger keeping the gain function more symmetric.

The intrinsic property of QD laser material is reflected on the different power dependence of the emission linewidth for the different devices in agreement with device simulation results taking into account the quantum dot nature of the material. The impact of the low-dimensional nature and the gain function profile (e.g., role of linewidth enhancement factor) on the emission linewidth will be discussed. A minimum linewidth of 110 kHz was obtained for a 1.2 mm long QD DFB laser, which is about one order of magnitude lower than typical values of QW lasers with similar device geometry.

QD laser material will therefore allow to significantly reduce the linewidth of a laser independent of the device structure, which will be of large interest for coherent communication systems.

9767-26, Session 6

**Pulsed hybrid dual wavelength Y-branch-DFB laser-tapered amplifier system suitable for water vapor detection at 965 nm with 16 W peak power**

Thi Nghiem Vu, Ferdinand-Braun-Institut (Germany) and Vietnam Academy of Science and Technology (Viet Nam); Andreas Klehr, Bernd Sumpf, Thomas Hoffmann, Armin Liero, Günther Tränkle, Ferdinand-Braun-Institut (Germany)

A hybrid dual wavelength Y-Branch-DFB laser-tapered amplifier (TA) system suitable for water vapor differential absorption LIDAR (Light Detection And Ranging) will be presented. The system operates at wavelengths around 965 nm, where one potential spectral region for water vapor detection is located. The system consists of a Y-Branch-DFB laser as master oscillator (MO) and a dual section tapered amplifier as power amplifier. The Y-Branch-DFB laser emits alternatively at two wavelengths which can be finely tuned by current and temperature to a desired pair wavelength for on resonance and off resonance of water vapor absorption lines. The TA consists of a ridge waveguide (RW) section as an optical gate and a flared gain-guided section as an amplifier section. The optical gate converts the CW input beam emitted by MO into a short optical pulse which is subsequently amplified by the tapered section. A pulse of 8 ns width at repetition rate of 25 kHz is generated using the GaN-based pulse driver electronics placed close to the PA. In DIAL application, it responds to a potential spatial resolution of about 1.2 m and a distance of 6 km. A peak power of 16 W is obtained. The spectral properties of the emission of the MO are preserved by the tapered amplifier. The measured spectral line width of 10 μm is limited by spectrum analyzer and a side mode suppression ratio (SMSR) of 37 dB is observed. These values meet the demands for water vapor absorption lines measurement under the atmospheric conditions.

9767-27, Session 6

**Fast difference frequency tuning of multi-section dual-mode lasers with nanoscale surface gratings**

Mihail M. Dumitrescu, Topi Uusitalo, Heikki A. Virtanen, Jukka Viheriälä, Joel Salmi, Antti T. Aho, Tampere Univ. of Technology (Finland)

The conventional buried-grating distributed-feedback (DFB) lasers require complex fabrication with two or more epitaxial growth steps. To avoid the problematic overgrowth we have employed laterally-coupled ridge-waveguide surface gratings, which are applicable to different materials and allow greater flexibility in device structure. Dual-longitudinal-mode multi-section DFB lasers with 3rd order LC-RWG gratings have been fabricated from InP-substrate epiwafers intended for Fabry-Perot lasers, both at 1.3 and 1.55 μm. The process mask imprinting was done by UV nanoimprint lithography. The longitudinal structure of the lasers...
comprised several grating sections to control and stabilize the dual mode emission. The gratings have been apodized and chirped by varying their lateral extension. Grating coupling coefficients in the range of 20 cm-1 were used in sections of several hundred micrometers. Limited overlapping of the modes’ longitudinal envelopes was employed to reduce mode competition. The longitudinal modes were supplementary stabilized and the mode competition was further reduced by applying different bias currents to the sections.

Different frequencies from 15 GHz to 1 THz have been obtained by changing the longitudinal structure of the lasers (mainly varying the lengths and coupling coefficients of the grating sections). The emitted modes have sub-MHz linewidths and are quasi-phase-locked, as indicated by the sharp peak in the RIN at the frequency difference. The frequency difference has been varied by several GHz under bias modulation up to several MHz. Higher frequency difference modulation rates are expected from improved measurement setups and from employing quantum dot active regions for further reduction of mode competition.

9767-28, Session 6
5,000 h reliable operation of 785-nm dual-wavelength DBR-RW diode lasers suitable for Raman spectroscopy and SERDS
Bernd Sumpf, André Müller, Martin Maiwald, Ferdinand-Braun-Institut (Germany)
Shifted excitation Raman difference spectroscopy (SERDS), i.e. exciting the sample alternatingly with two slightly shifted wavelengths, allows to separate Raman signals from sources of interference, e.g. daylight, artificial light sources, and fluorescence. For portable Raman and SERDS sensor systems compact, efficient, robust and reliable light sources are necessary. In this work, reliability investigations of dual-wavelength DBR-ridge waveguide diode lasers at 785 nm will be presented. Wavelength stabilization is made by implementing deeply etched 10th order 500 nm long surface DBR gratings using i-line wafer stepper technology. Diode lasers with a total length of 3 mm and a stripe width of 2.2 μm were realized and characterized. These devices reach maximum output powers up to 215 mW with narrowband emission suitable for Raman spectroscopy. Two DBR gratings were realized in a single chip for the dual-wavelength diode lasers which provide a spectral distance of 0.6 nm (10 cm⁻¹) between both excitation lines for SERDS.

A step reliability test was performed at 50 mW, 75 mW, and 100 mW over altogether 5,000 h. In advance, before each aging step, and after the reliability test, electro-optical characteristics and spectral properties were measured. Here, eight of nine emitters passed the test without failure and no deterioration of output power and spectral performance were observed. The aging rates are smaller than 10⁻⁵ h⁻¹. The threshold currents for all devices remain stable at 37 mA as well as the slope efficiency with 0.78 W/A. Herewith, these devices are well suited for portable Raman and SERDS systems.

9767-29, Session 6
First demonstration of single-mode distributed feedback type-I GaSb-based cascade diode laser emitting near 2.9 μm
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The hydroxyl radical, OH, is a crucial intermediate in the atmospheres of Earth and Mars. For example, in Earth’s atmosphere, the vertical profile of ozone is controlled by catalytic cycles involving OH radicals. Laser-induced fluorescence (LIF) has been used extensively for the measurement of OH in the near ultraviolet. However, semiconductor lasers offer potential breakthroughs in OH detection capabilities in the infrared due to their low mass, high output power (tens of milliwatts), reliability, efficiency, and tunability.

OH radicals possess strong absorption lines around 2.9 μm, but require adequate optical sources for detection using tunable laser absorption spectroscopy. Due to high quantum well (QW) threshold carrier concentration and associated Auger recombination, reaching high output power with GaSb-based type-I QW diode lasers is challenging. To address this, we have fabricated single-mode, narrow-ridge type-I cascade diode lasers using etched laterally coupled distributed feedback (LC-DFB). The improvement of the optical confinement factor by connecting multiple gain stages in series reduces the threshold carrier concentration. This structure makes it possible to minimize the threshold current while the internal efficiency is increased.

These devices produce 13 mW of output power at 20 °C in continuous wave (CW) operation with side-mode suppression greater than 20 dB. The internal waveguide loss was found to be 7.6 cm⁻¹ from sub-threshold Hakki-Paoli measurements for Fabry-Perot devices and increased to 11 cm⁻¹ for LC-DFB devices. Type-I cascade diode lasers are a promising alternative to address the technological gap of available single-mode semiconductor lasers emitting high-power near 3 μm.

9767-30, Session 6
Integrated membrane-based DFB and DR lasers (Invited Paper)
Shigehisa Arai, Nobuhiko Nishiyama, Tomohiro Amemiya, Takuo Hiratani, Daisuke Inoue, Tokyo Institute of Technology (Japan)
Toward on-chip optical interconnection in next generation LSIs, we have been investigating ultra-low-power-consumption lasers as well as a photo-diode (PD) based on a semiconductor membrane structure, which consist of a thin semiconductor core layer sandwiched by low refractive-index claddings with high index-coupling grating structure.

As light sources for this purpose, we realized a membrane distributed-feedback (DFB) laser with a passive waveguide integrated by butt-jointed built-in (BJB) coupling structure. A threshold-current of Ith = 230 μA (for the stripe width W_S = 0.7 μm and L_DFB = 30 μm, L_DBR = 90 μm), an external differential wave (CW) operation with side-mode suppression greater than 20 dB, and an SMSR = 28 dB (at I = 1.2 mA) were achieved. From a small signal response under a direct modulation, a 3dB bandwidth of 9.5 GHz at I = 1 mA, which corresponds to a modulation current efficiency factor of 9.8 GHz/ mA^-0.5, was obtained.

In order to increase a light output from one side of the cavity, we realized a membrane distributed-reflector (DR) laser, which consists of a DFB and a distributed-Bragg-reflector (DBR) sections, and obtained Ith= 250 μA (for W_S = 0.7 um and L_DFB = 30 um, L_DBR = 90 um), an external differential quantum efficiency of 11%, which is around 2 times higher than that of the above mentioned DFB laser, an asymmetric output power ratio of 6.7, and an SMSR of 22 dB at I = 2 I_th.

A monolithic integration of 1/4-phase-shifted membrane DFB laser with a membrane PIN-PD was also demonstrated with a low dark current of 0.8 nA (for W_S = 0.7 um and L_PD = 500 um).

9767-31, Session 7
Road to group IV photonics (Invited Paper)
Detlev Grützmacher, Dan M. Buca, Stephan Wirths, Daniela Stange, Nils von den Driesch, Christian Schulte-Braucks, Siegfried Mantl, Forschungszentrum Jülich GmbH (Germany)
The successful preparation of GeSn alloys with Sn concentrations exceeding...
Performance and reliability of III-V quantum-dot lasers grown directly on Si substrates

Samuel Shufts, Stella N. Elliott, Angela D. Sobiesierski, Peter M. Smowton, Cardiff Univ. (United Kingdom); Jiang Wu, Mingchu Tang, Huiyun Liu, Univ. College London (United Kingdom); Richard Beanland, The Univ. of Warwick (United Kingdom)

The development of photonic integrated circuits, with future CMOS compatibility, forms an essential step in the progression towards energy efficient systems with increased bandwidth and faster inter-chip data transfer speeds. Here, we report on 1.3 µm emitting InAs quantum dot (QD) laser structures grown by solid-source Molecular-Beam-Epitaxy (MBE) directly on silicon (Si) substrates. Direct growth is challenging due to the mismatch of both the lattice parameter and the thermal expansion coefficient between III-Vs and Si. This causes threading dislocations that propagate from the Si interface to the active region of the laser producing non-radiative recombination centres and if severe, increased internal optical mode loss. We address this problem by depositing a GaAs buffer layer onto the substrate, followed by series of dislocation filter layers (DFLs) prior to growth of laser structure. In addition, the use of QDs as active material is chosen over a quantum well structure, since they provide better carrier localisation, keeping the majority of the carriers away from the defects, and may deflect dislocations effectively. As a result we have demonstrated ridge-waveguide lasers with as-cleaved facets emitting in continuous-wave (CW) operation with output powers exceeding 20 mW at room temperature and operation up to 39˚C. Initial reliability measurements show that laser action is maintained beyond 600 hrs over which period the threshold current of a 10 µm 4000 µm laser has increased by ~10%. For the purposes of integration, where cleaving is not possible, we have produced lasers with etched facets and show room-temperature CW operation.

Cavity enhanced 1.5 u?m LED with silicon as hole injector

Dong Liu, Zhenyang Xia, Sang June Cho, Univ. of Wisconsin-Madison (United States); Deyin Zhao, University of Texas at Arlington (United States); Hui-long Zhang, Tzu-hsuan Chang, Xin Yin, University of Wisconsin Madison (United States); Munho Kim, Univ. of Wisconsin-Madison (United States); Jung-Hun Seo, Jaeseong Lee, Xudong Wang, University of Wisconsin Madison (United States); Weidong Zhou, The Univ. of Texas at Arlington (United States); Zhenqiang Ma, Univ. of Wisconsin-Madison (United States)

Hybrid silicon photonics has been widely explored over the past few years. Laser sources are the most critical component in silicon photonics. Up to now, the mainstream in hybrid silicon photonics is wafer or membrane bonding in which the silicon is only used as the passive optical waveguide or reflective mirror. Due to lattice mismatch between silicon and III-V, silicon has never been used as electrical injection material in any III-V optoelectronic devices. Here we report our demonstration of a low cost, high plug-in efficiency Si/InGaAsP/InP PIN edge emitting laser around 1.5 µm by using membrane transfer method. For our devices, the silicon with 200 nm thickness is acting not only as the optical guiding layer but also the hole carrier injection layer, replacing the commonly used thick p-type InGaAs/InP contact/cladding layer. In this hybrid integrated laser, the p type silicon functions as the p ohmic contact, holes injector and cladding layer simultaneously. Since the silicon has the merits of easily doped, high mobility and low optical loss, compared with the conventional p-i-n InGaAsP/InP laser, this structure of p-silicon integrated with i InGaAs/InP rips the advantages of reduced Joule heating due to lowered metal contact resistance, improved injection efficiency and less optical loss resulted from p type InP. To realize high quality Si/InGaAsP interface, an atomic interfacial layer was employed to reduce membrane bonding induced defects. With the silicon hole injection layer, much improved plug-in efficiency has been obtained. The new hybrid integration laser is promising for silicon photonics as a new form of lasing source.
Photonics-crystal lasers on silicon for chip-scale optical interconnects (Invited Paper)

Koji Takeda, Takuro Fujii, NTT Photonics Labs. (Japan); Akihiko Shiya, Eiichi Kuramochi, Masaya Notomi, NTT Basic Research Labs. (Japan); Koichi Hasebe, Takaaki Kakitsuka, Shinji Matsuo, NTT Photonics Labs. (Japan)

Optical interconnects are expected to reduce the power consumption of ICT instruments. To achieve chip-to-chip or chip-scale optical interconnects, it is essential to fabricate semiconductor lasers with a smaller energy cost. In this context, we are developing lambda-scale embedded active-region photonic-crystal (LEAP) lasers as light sources for chip-scale optical interconnects.

We demonstrated the first continuous-wave (CW) operation of LEAP lasers in 2012 and reported a record low threshold current and energy cost of 4.8 uA and 4.4 fJ/bit at 10 Gbit/s in 2013. We have also integrated PhC photodetectors on the same InP chip and demonstrated waveform transfer along 500-um-long waveguides. Although the LEAP lasers have this excellent performance, they have to be integrated on Si wafers to use them as light sources for chip-scale optical interconnects.

In this paper, we report our recent progress in fabricating LEAP lasers on Si. In our previous work in 2014, we bonded InP wafers to Si wafers using oxygen-plasma assisted bonding after almost all fabrication procedures on InP wafers. Because there was difficulty in integrating the output waveguides, we have further worked on fabrication improvement to integrate them. We now bond the MQW-grown InP wafers directly on thermally oxidized Si wafers and perform all process steps on the Si wafer, including high-temperature regrowth. After this process modification, we again achieved CW operation and obtained a threshold current of 57 uA with a maximum output power of more than 3.5 uW at the output waveguides.

Recent progress in interband cascade lasers (Invited Paper)

Rui Q. Yang, The Univ. of Oklahoma (United States)

Interband cascade (IC) lasers are efficient mid-infrared laser source by taking advantage of the broken band-gap alignment in type-II InAs/Ga(In)Sb heterostructures to form cascade stages with interband transitions and low power consumption. GaSb-based type-II IC lasers have been operated successfully in Curiosity Rover on Mars and are already available commercially. In this talk, we will review recent progress in IC lasers along two new directions – InAs-based IC lasers and type-I IC lasers. Both have been recently demonstrated at room temperature and above in cw operation.

Interband cascade laser sources in the mid-infrared for green photonics

Johannes Koeth, Michael von Edlinger, Julian Scheuermann, Steffen Becker, nanoplus GmbH (Germany); Robert Weih, Julius-Maximilians-Universität Würzburg (Germany); Lars Nähle, Marc O. Fischer, nanoplus GmbH (Germany); Martin Kamp, Sven Höfling, Julius-Maximilians-Universität Würzburg (Germany)

Tunable Laser Absorption Spectroscopy (TLAS) has proven to be a versatile tool for gas sensing applications with significant advantages compared to other techniques. These advantages include real time measurement, standoff detection and ruggedness of the sensor. Especially the Mid-Infrared (MIR) wavelength region from 3 to 6 microns is of great interest for industrial process control and the reduction of pollutants. In this contribution we present novel IC devices developed to address the crucial air pollutant sulfur dioxide SO2 at its transition around 4 µm. In general, interband cascade lasers (ICLs) have evolved into important laser sources for the MIR spectral range. Compared to quantum cascade lasers, they offer significant advantages with respect to threshold power density as well as overall power consumption. In contrast to conventional diode lasers, ICLs are able to cover the entire MIR wavelength range of interest.

For application in TLAS, single-mode devices are required. In this work, we fabricated distributed feedback (DFB) ICL devices for addressing SO2 at the wavelength range around 4 µm. A lateral metal grating, defined by electron beam lithography, is used to achieve DFB operation and hence spectrally single-mode emission. Continuous wave (CW) laser operation with power consumption below 500 mW, single-mode suppression ratio of > 30 dB and wavelength tuning range up to 30 nm are demonstrated.

Step-taper active-region quantum cascade lasers for carrier-leakage suppression and high internal differential efficiency

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Tapered-active-region (TA) quantum-cascade lasers (QCLs) [1] have resulted in record-high T0 and T1 values, for 3.9-5.0 µm-emitting devices, and wallplug-efficiency values from 4.9 µm-emitting devices. By stepwise tapering both the barrier heights and quantum-well depths in the active regions (ARs) of 8.80- as well as 8.35 µm-emitting QCLs, virtually complete carrier-leakage suppression is achieved, as evidenced by high T0 values (283 K and 242 K) and high T1 values (561 K and 279 K) for low- and high-doped devices, respectively. These high values are obtained while the threshold-current density is kept low: 1.58 kA/cm2 and 1.88 kA/cm2, respectively. In addition, due to extraction from the lower laser level, high differential transition efficiency values: 89-90 %, are obtained. In turn, the slope-efficiency for 3 mm-long, 35-period high-reflectivity (HR)-coated devices are: 115.1-12.5 W/A; that is, 30-40 % higher than for same-geometry and similar-doping conventional 8-9 µm-emitting QCLs. The values for the internal differential efficiency [1] are found to be in the 85-90% range, by comparison to values in the 58-64 % range, obtained from conventional QCLs emitting in the 7-10 µm wavelength range.

The QCL structures were grown by MOCVD. Within the ARs two shallow barriers are followed by two tall barriers and two deep wells; thus, forming a step-taper TA (STA) structure. Devices were fabricated into ~ 21.5 µm-wide ridges. For HR-coated, low-doped devices (~ 0.7 x10^11cm-2) the maximum single-facet power is ~ 1.2 W, while for HR-coated high-doped devices (~ 1.6 x10^11cm-2) the maximum single-facet power is ~ 3.3 W. [1] D. Botez, J. C. Shin, J. D. Kirch, C.-C. Chang, L. J. Mawst, and T. Earles, “Multidimensional Conduction-Band Engineering for Maxi-Mizing the Continuous-Wave (CW) Wallplug Efficiencies of Mid-Infrared Quantum Cascade Lasers” IEEE J. Sel. Topics Quantum Electron. Vol. 19, No. 4, 1200312, July/August 2013.

Surface-emitting quantum cascade laser with 2nd-order metal-semiconductor gratings for single-lobe emission

Colin Boyle, Chris Sigler, Jeremy D. kirch, Univ. of...
Grating-coupled, surface-emitting (GCSE) quantum-cascade lasers (QCLs) offer a pathway towards realizing watt-range output powers in the mid-infrared spectral region with high beam quality. We have demonstrated single-lobed surface emission from a GCSE QCL, which employs metal-semiconductor, 2nd-order distributed feedback (DFB) gratings and distributed Bragg reflector (DBR) terminations [1]. Initial devices demonstrate -0.4 W single-lobed, single-mode power at 4.75 μm. The QCL structure was grown using MOVPE and the grating was defined using a combination of e-beam lithography patterning and wet-chemical etching. The DBF and DBR regions result in a total grating length of 5.1 mm. The electrical isolation between the DBR and DBF regions was achieved by an AlOx isolation process. Due to resonant coupling of the guided light to the antisymmetric surface-plasmon modes of the 2nd-order grating, the antisymmetric (A) modes are strongly absorbed [1]; thus, allowing for the symmetric (S) mode to be favored to lase over the 36-41% range in grating duty cycle (?). Initial devices employed Au as the metal layer comprising the metal/semiconductor grating. Maximum pulse output powers were in the range: 392-460 mW, emitted from ~21.5 μm-wide ridges. The threshold-current densities are in the range: 30-41 kA/cm2, depending on the phase shifts at the device ends. The longitudinal far-field beam pattern is measured at 108 cm, and shows a central single-lobed beam. A single-spatial-mode spectrum together with the single-lobed beam pattern indicate that the lasing mode is the symmetric one.

surrounded by two symmetrically detuned weak sidebands, separated from the strong central mode by an angular frequency on the order of one THz. This is a clear signature of a coherent instability resulting from the dynamic Stark effect, and leads to the emission of a harmonically mode-locked amplitude-modulated waveform.

9767-46, Session 10

Terahertz pulse generation from quantum cascade lasers (Invited Paper)

Sukhdeep S. Dhillon, Feihu Wang, Kenneth Maussang, Juliette Mangeney, Jérôme Tignon, Lab. Pierre Aigrain (France)

We demonstrate the generation of ultrashort pulses from broadband THz QCLs in a metal-metal waveguide, permitting new insights into the limits of mode-locking these devices. In particular and contrary to belief that a long gain recovery time is required, we demonstrate that the dominant factor for active pulse generation in QCLs is in fact a “THz-gigahertz phase matching” i.e. the synchronization between the propagating electronic microwave modulation and the generated THz pulses in the QCL. This allows the THz pulse to propagate in phase with the microwave modulation along the gain medium, permitting short pulse generation.

9767-44, Session 9

External cavity quantum cascade lasers operating under resonant pumping modulation (Invited Paper)

Dmitry G. Revin, Michael Hemingway, John W. Cockburn, The Univ. of Sheffield (United Kingdom); Yongrui Wang, Alexey A. Belyanin, Texas A&M Univ. (United States)

Recent demonstration of the mid-infrared quantum cascade laser (QCL) operating in the free-space external ring cavity resonator in continuous wave regime at room temperature represented a significant step towards the development of the active mode locking in such QCLs. The absence of the spatial hole burning in a ring resonator with the light travelling only in one direction, should provide superior stability for the short pulse generation in the active mode locking regime. The comprehensive study has been carried out on the performance characteristics of 5.3μm wavelength QCL in both ring and linear (for the comparison) external cavities when the laser was pumped with the short current pulses at the repetition rate close to the round trip time for the light in these cavities. The length of the ring cavity of 1.2 - 3.8m (~80 – 250MHz) allows direct, very detailed study of the emission pulses. Above the laser threshold conditions, very stable, periodic, ~3ns long emission pulses, with the observed duration mainly limited by the detector response, have been demonstrated for both fundamental and up to the fifth harmonic frequencies. The laser emits up to ~3mW of the averaged out-coupled optical power and has emission spectra which are narrow near the resonant pumping frequencies and broad for slightly off-resonance conditions. Introduction of the diffraction grating inside the cavity provides additional emission wavelength tuning. The theoretical modelling of the QCL dynamics in the external cavity under the resonant modulation supports experimental observations and indicates active mode locking regime.

9767-45, Session 10

Frequency comb operation of long-cavity terahertz quantum-cascade lasers (Invited Paper)

Martin Wienold, Humboldt-Univ. zu Berlin (Germany) and Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Benjamin Röben, Lutz Schrottk, Holger T. Grahn, Paul-Drude-Institut für Festkörperelektronik (Germany)

Multimode quantum-cascade lasers (QCLs), operating in a coherent frequency comb regime, have recently gained large attention due to their versatile potential for spectroscopic applications. However, fundamental physical aspects of multimode operation of terahertz QCLs are still lacking a sufficient understanding. We discuss our experimental findings for lasers with Fabry-Pérot cavities, combining high-resolution Fourier-transform spectroscopy with the spectroscopy of the radiofrequency beat note signal. We found a complex dynamical behavior of the lasers with sharp transitions between different multimode regimes and a striking sensitivity to external optical feedback for frequency comb regimes, which can be exploited for coherent, detector-less probing techniques.

9767-47, Session 10

Active mode-locking in quantum cascade lasers with monolithic and external cavities

Yongrui Wang, Alexey A. Belyanin, Texas A&M Univ. (United States)

We report theoretical studies of the dynamics of mid-infrared quantum cascade lasers (QCLs) and study the active modulation in QCLs with a monolithic cavity, external Fabry-Perot cavity, and external ring cavity. For a monolithic cavity laser, modulation in a short section can lead to picosecond output pulses for QCLs with a short gain recovery time ~1 ps, and frequency combs can be generated when the modulation period is fine tuned. In external cavity lasers, a variety of dynamical regimes, pulse shapes, and spectra can be produced by varying the current pulse amplitudes, duration, and repetition rate.

9767-48, Session 11

Superradiant emission from electronic excitations in semiconductors (Invited Paper)

Carlo Sirtori, Angela Vasanelli, Yanko Todorov, Simon Huppert, Thibault Laurent, Giulia Pegolotti, Univ. Paris 7-Denis Diderot (France)

Efficient generation of light has always been a major issue in condensed matter physics and semiconductor technology in particular. Material science has permitted the realization of quantum structures with emission over a wide spectral range. Moreover, by exploiting advanced fabrication processing researchers have realised optical cavities confining the electromagnetic radiation in extremely small volumes. This has enhanced light-matter interaction and allowed extraordinary performances in the optical-electrical conversion.

This presentation illustrates how light-matter interaction, usually considered only as a weak probe, becomes the dominant energy relaxation mechanism for collective excitations in a two-dimensional electron gas. Indeed, when the electron concentration is sufficiently high, electrons respond to the solicitation of photons as a whole, with an absorption spectrum presenting a unique resonance at a completely different energy with respect to that of the electronic transitions. This optical resonance corresponds to a many-body excitation of the system that ties together all the intersubband dipoles, thus presenting a phenomenal interaction with light. This results in a spontaneous emission rate of the collective excitation depending on the electronic density, a phenomenon known as superradiance.

By conducting thermal emission experiments, we have observed a strong
An optimized bi-functional material for integrated mid-infrared quantum cascade based sensors

Andreas Harrer, Benedikt Schwarz, Peter Reininger, Rolf Szedlik, Tobias Zederbauer, Hermann Detz, Donald MacFarland, Aaron M. Andrews, Werner Schrenk, Gottfried Strasser, Technische Univ. Wien (Austria)

We present an improved bi-functional quantum cascade laser detector (QCLD) design with 0.47W output power and 4.5% wall-plug efficiency in pulsed operation. In a ridge detector configuration a responsivity of 40mA/W is demonstrated. The design is based on a two region extractor starting with thick barriers followed by a region with thin barriers. The first part with the thick barriers maintains the wavelength overlap and extracts horizontally. The second part with thin barriers extracts vertically and prevents thermal backfilling. In addition the active transition is slightly more diagonal than in our previous designs which results in a higher detector extraction efficiency. All significant laser parameters were be improved by a factor of two while the detector performance and noise figure was improved too. The threshold current was reduced from 8kA/cm2 respectively 6kA/cm2 to 3kA/cm2 at room temperature.

A bi-functional surface emitting and detecting sensor was processed from the presented material. A distributed feedback ring quantum cascade laser is integrated with a detector element. The surface emitted light is collimated, back reflected by a flat mirror, focused and detected by the detector element of the same device. The surface operation mode enables for comparable long interaction lengths as needed for gas absorption measurements. By placing a single gas-cell into the beam path gas concentrations from 0% up to 95% of butane and 0% up to 60% of propane in nitrogen were measured with a sensitivity in the low percent range.

Theoretical analysis of quantum-dot quantum cascade lasers: design considerations and current requirements

Stephan Michael, Technische Univ. Kaiserslautern (Germany); Weng W. Chow, Sandia National Labs. (United States); Hans Christian Schneider, Technische Univ. Kaiserslautern (Germany)

The present contribution investigates a microscopic model for electrically pumped quantum dots (QDs) as active material for quantum cascade lasers. We consider an AlGaAs heterostructure composed of self-organized InGaAs dots-in-a-well sandwiched between source and drain quantum wells. We compute the injection current and modal gain for the case of electrical pumping using a microscopic model that includes electron-electron and electron-phonon scattering. We find that, in order to achieve a steady-state modal gain at room temperature, an efficient extraction process is required to avoid accumulation of electrons in the continuum states of the QDs. For a model design that implements this requirement, we investigate the influence of the inhomogeneous broadening and OD density on the modal gain.

9767-51, Session 11
Continuous-wave terahertz lasing in graphene

Alexey A. Belyanin, Yongrui Wang, Texas A&M Univ. (United States); Mikhail Tokman, Institute of Applied Physics of the RAS (Russian Federation)

We prove the general feasibility and demonstrate the design of the continuous-wave THz laser operating between Landau levels in graphene placed on a polar substrate [1]. Steady state population inversion under a continuous wave optical pumping becomes possible due to surface-phonon mediated relaxation of carriers. Our microscopic kinetics simulations including all relevant scattering processes show the existence of the steady state gain of magnitude up to 5% per monolayer. The laser concept is scalable to other materials with massless Dirac fermions, e.g. surface states in 3D topological insulators Bi2Se3 or Bi2Te3.


9767-67, Poster Session
Simulation of broad spectral bandwidth emitters at 1060nm for retinal optical coherence tomography

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Optical coherence tomographic (OCT) ophthalmic imaging using 1060nm sources is of considerable recent interest. Broad spectral bandwidth super-luminescent diodes (SLDs) or gain blocks (GBs), with broad spectral coverage (>100nm) are required.

Here we simulate InGaAs/GaAs single, and double quantum well (QW) SLDs and GBs, which have different requirements in terms of gain and amplified spontaneous emission (ASE) spectra. For SLDs the ASE spectrum modulation must be <3dB. For GBs integrated in a swept laser source, some modulation of the gain spectrum is tolerable, leading to different designs for the QWs.

Utilising higher-order states is a well-known strategy for realising broadband SLDs. For broad spectral coverage two In0.30Ga0.70As QWs with widths of 10nm and 4nm are optimal. The thinner QW fills a dip in the ASE, and epitaxy is simplified by maintaining a constant indium composition in the QWs. We show that whilst the SLD spectrum is more appropriate for OCT, the total bandwidth of the device is truncated due to the combined density-of-states.

Therefore, to obtain a broader gain spectrum (with some spectral modulation), the roles of the QWs should be reversed. Here, different indium compositions are utilised in the QWs. A narrow, deep QW provides long wavelength gain, whilst a wider, shallower QW delivers the shorter wavelength gain. An enhancement in the gain band-width is predicted.

We additionally discuss the role of QW position and GaAsP carrier blocking layers. Experimental results where the limits to indium composition and QW thickness for long wavelength emission are also explored.
Characterization of bending loss in tunable Y-junction lasers for gas sensing applications

Nam T. Tran, Saroj K. Patra, Kjetil Haddeland, Bjørn-Ove Finland, Norwegian Univ. of Science and Technology (Norway)

GaSb-based semiconductor diode lasers are promising candidates for mid-infrared lasers in the wavelength region of 2-5 μm, whose applications include the light sources needed for trace-gas sensing systems based on tunable diode-laser absorption spectroscopy (TDLAS). Among edge-emitting laser structures, Y-junction structure is an interesting alternative, thanks to its wide tunable range and simple fabrication process. Most of widely tunable monolithic laser structures benefit from passive gratings and phase sections, requiring regrowth of the laser structures. The regrowth, however, is difficult due to the reactive nature of AlGaAsSb which is used for cladding layers in GaSb-based laser diodes. In addition to not requiring regrowth, the Y-junction lasers offer easier processing, but have a complex waveguide junction structure and reduced side mode suppression ratio (SMSR). The SMSR can be improved by adding gratings or a third waveguide to the structure.

The Y-junction structure consists of a straight and an S-bend cavity, in which the bent section creates the length difference between two cavities for mode beating. The bending loss in the bent section, however, limits the performance of the device. In this work, we have characterized the bending loss of the S-bend waveguide lasers with different configurations. The L-I characteristics of those lasers show that the loss in the bent section decreases with the increase of bend radius. The results then will be used for the optimization of Y-junction laser characteristics, in terms of tunable range and SMSR.

Optimisation of photonic crystal coupling through waveguide design

Richard J. E. Taylor, Pavlo I. Ivanov, Guangru Li, Tim S. Roberts, David T. D. Childs, Richard A. Hogg, The Univ. of Sheffield (United Kingdom)

Photonic crystal surface emitting lasers (PCSELs) offer ultimate control in semiconductor lasers; high single-mode powers, large scale coherent emission, and control of beam shape and polarization. Previous PCSELs utilised the high refractive index contrast between semiconductor and voids. However, the presence of voids presents possible issues in device reliability, and reproducibility, and the low refractive index of the photonic crystal (PC) layer results in difficulties in the design of the lateral waveguide. Utilising all-semiconductor PCs (through re-growth) allows several advantages including comparative freedom in waveguide design.

We consider device design strategies for obtaining high coupling to the PC in order to obtain high power/unit area emission for high brightness applications. We initially consider an InGaAs/InGaN/AlGaAs/PCSEL structure, and discuss how this waveguide structure can be optimised to give high coupling to the PC for both all-semiconductor and void/semiconductor structures. We generally find that all-semiconductor structures enjoy higher coupling coefficients than void/semiconductor structures. The beneficial role of an additional waveguide layer above the PC region is highlighted. We go on to analyse a range of possible PCSEL designs in various materials (GaN, GaAs, InP) at wavelengths ranging from 400nm to 10um. We show that in general, the all-semiconductor design has higher coupling coefficients. We highlight how the PCSEL structure may in future allow any present edge-emitting laser structure to be redesigned to be a high performance surface emitter. We highlight the need for the development of epitaxial process on complex 3D surfaces to realise such devices in future.

TEM Study of the effect of ex-situ and in-situ rapid thermal annealing on threading dislocations in GaAs monolithically grown on Si by MBE

Wei Li, The Univ. of Sheffield (United Kingdom); Siming Chen, Jiang Wu, Huiyun Liu, Univ. College London (United Kingdom); Richard A. Hogg, Ian M. Ross, The Univ. of Sheffield (United Kingdom)

The epitaxy of III-V semiconductor materials upon Si has attracted significant recent interest with a view to full scalability in the monolithic integration of III-V and Si devices and optoelectronic integrated circuits. The major research challenges include the minimization of threading dislocations (TDs) due to the large lattice mismatch, and difference in thermal expansion coefficients, between III-V compounds and Si.

We report on the influence of post-growth rapid thermal annealing (RTA) and in-situ thermal cycle annealing (TCA) on the threading dislocation (TD) density in InAs/GaAs self-assembled QD structures monolithically grown on Si. We go on to show how in-situ TCA results in the realization of CW operation of an InGaAs/GaAs QD laser grown by MBE on Si (100) substrate with a 4° offset towards [011] operating at 1510nm up to 32°C. The InGaAs/GaAs self-assembled QD structures were monolithically grown on Si (100) substrate with a 4° offset towards [011] utilizing double Si atom steps. The effect of post-growth RTA between 650-800°C on the TD density was investigated by applying bright-field scanning TEM. The TD density was deduced from TEM images acquired from regions of known thickness, determined using electron energy loss spectroscopy. The TD density in annealed samples is shown to be markedly reduced and the continuous threading dislocations become discontinuous after annealing. This leads to the concept of in-situ TCA and the deposition of a strained-layer superlattice and buffer layers. As a consequence, InAs/GaAs self-assembled QD Fabry-Perot ridge laser devices are demonstrated with continuous-wave operation up to 32°C.

High-performance room temperature InGaAs/AlGaAs/GaAs quantum cascade lasers

Dorota Piercińska, Kamil Pierscinski, Piotr Gutowski, Magdalena Morawiec, Maciej Bogański, Institute of Electron Technology (Poland)

The main issue that limits high temperature performance of GaAs-based devices is low conduction band-offset, causing the electrons to escape to 3D continuum of states at elevated temperatures of active region. In this paper, we demonstrate, that incorporation of 3% indium to both active QWs and the injectors improve QCL performance and main optical parameters.

In this work we report on the design, fabrication and characterization of a mid-IR QCLs based on strained InGaAs/AlGaAs/GaAs grown by molecular beam epitaxy on GaAs substrate. Structures were grown with indium content of 3% in QWs and 45% of Al in AlGaAs barrier layers. The design results in strained heterostructure, however, no strain relaxation was observed as documented by X-ray diffraction measurements. Devices exhibit performance largely improved over GaAs/AlGaAs/GaAs QCLs. More than 2 times reduction of threshold current density was observed. Lasing at -9.5 μm was achieved in pulsed mode up to T = 50°C with characteristic temperature T0 < 120 K. Additionally, InGaAs based QCLs are characterised by two times larger activation energy, which reduces the electron escape current, what, in turn, is advantageous for QCLs performance.

Various experimental techniques were employed, in order to gain insight into the performance of investigated devices. In order to determine
main device parameters (such as WPE, waveguide losses, T0 and T1) measurements of temperature dependent Light-Current-Voltage (LIV) characteristics were performed. Additionally, devices were characterized in terms of temperature behavior by means of thermoreflectance spectroscopy, thermal imaging and time resolved spectral measurements.

9767-72, Poster Session

Three-dimensional finite-difference time-domain modelling of photonic crystal surface-emitting lasers

Pavlo I. Ivanov, Richard J. E. Taylor, Guangru Li, David T. D. Childs, Salam Khamas, Jayanta Sarma, Robertusr Erdelyi, Richard A. Hogg, The Univ. of Sheffield (United Kingdom)

Photonic crystal surface emitting lasers (PCSELS) offer the ultimate control of the emission properties, with the beam shape, divergence, and polarisation being governed by the design of the photonic crystal (PC). However, such complex devices provide significant difficulties in their simulation, and therefore in their engineering. Present techniques rely upon analytical solutions to coupled-mode theory, which include a number of simplifications and assumptions (e.g. an average refractive index model). Two dimensional finite-difference time-domain (FDTD) modelling similarly regards e.g. the active element and waveguide. Here we present a three-dimensional (3d) finite-difference time-domain model of PCSELS, which allows the investigation of the beam divergence in far-field region, diffraction loss and optical confinement factors of these lasers. In a full 3d model, the device geometry is included in the simulation. We focus on GaAs based PCSEL structures (AlGaAs waveguide and 3xInGaAs/GaAs QW) with either InGaP/GaAs or InGaP/air photonic PCs, which we refer to as all-semiconductor and void-semiconductor PCSELS. The void-semiconductor devices are presently the most widely discussed form of PCSEL.

We explore the impact of changing the PC hole shape, size, and lattice structure in addition to the choice of all-semiconductor or void-semiconductor designs. The beam divergence and the diffraction loss are shown to be dependent on the number of holes, with an increase in the number of holes, the narrower the beam and higher diffraction loss. We discuss the determination of the threshold gain from the diffraction losses, and explore limitations to direct modulation of the PCSEL.

9767-52, Session 12

Design and simulation of high-brightness diode lasers for operation in the presence of external feedback (Invited Paper)

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High power, high brightness laser diodes are of great interest for kW-class direct diode laser systems, where power scaling is achieved with a combination of incoherent and spectral beam combining and advances in coherent beam combining are being targeted for future systems. Optical feedback is important for these systems, since the output facet reflectivity of the lasers is low and small external feedback can be significant. Some applications benefit from external feedback (e.g. wavelength / phase locking), but feedback can also degrade the beam quality and diode reliability. As the power and brightness of these systems grows, so does our need to understand and control the impact of optical feedback.

We report on the design and simulation of high-brightness laser diodes for operation with external feedback. These diodes need large optical cavities for low fast-axis divergence and wide near field, but these support many vertical modes. Thus, large modal discrimination is needed to suppress the propagation of the unwanted modes. Finally, high power conversion efficiency is required. Next, we investigate the impact of the external feedback on the operation of 980nm tapered and single-mode lasers using our laser simulation tools, which have been modified to include multiple vertical modes and coupling with conventional optical design tools. We study the impact of feedback on beam quality and power conversion efficiency. We also report on the back coupling to parasitic vertical modes as a function of vertical misalignment (e.g. bar “smile”) and assess the impact of the light coupled into them.

9767-53, Session 12

DBR tapered diode laser at 1030 nm with nearly diffraction-limited narrowband emission and 12.7 W of optical output power

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Within biomedical imaging titanium:sapphire lasers are of special interest. They require optical pumping by high-power, diffraction-limited emission in the blue-green spectral range. Using diode lasers has the advantage that the pump wavelengths can be selected with respect to the largest absorption of the laser crystal. This may help to increase pump efficiencies or output power, beneficial for a widespread application of titanium:sapphire lasers. Promising results were demonstrated for optical pumping at 515 nm. Considering all pump source requirements, non-linear frequency conversion of near-infrared diode lasers currently remains the method of choice towards efficient diode-pumped titanium:sapphire lasers. In this context new tapered diode lasers at 1030 nm were developed.

In this work we present our results for a 1030 nm distributed Bragg reflector (DBR) tapered diode laser. The laser is based on an InGaAs triple quantum well within an asymmetric super large optical cavity. The design of the vertical structure results in a low vertical far field angle of 14° (FWHM). Intrinsic wavelength stabilization at 1030 nm is realized by a 3rd order DBR grating, manufactured using electron beam lithography. Up to 12.7 W of optical output power and an electro-optical efficiency > 40% are obtained. Narrowband emission with spectral widths of 17 pm is measured over the whole power range. At 10.5 W a beam propagation ratio of 1.1 (1/e2) is obtained. With a central lobe power content of 8 W the laser is well suited for non-linear frequency conversion towards 515 nm for efficient pumping of titanium:sapphire lasers.

9767-54, Session 12

High performances of very long (13.5mm) tapered laser emitting at 975 nm

Patrick Resneau, Michel Garcia, Michel Lecomte, Yannick Robert, Eric Vinet, Olivier Parillaud, Michel Krakowski, III-V Lab. (France); Dmitri L. Boiko, Ctr. Suisse d’Electronique et de Microtechnique SA (Switzerland)

The technology of Mode-Locked Semi-Conductor Lasers is a promising candidate considered by ESA for optical metrology systems for various space applications in the context of high-precision optical metrology, in particular for High Accuracy Absolute Long Distance Measurement. The following very challenging target performance requirements should be met: pulse duration<1ps, pulse energy > 200pJ, high spatial beam quality (M2=2.5). For pulse repetition frequency of 3GHz and pulse energy of 200pJ (resp.500pJ), the average optical power should be 600mW (resp.1.5W). We intend also to get compactness, integration of gain and absorber on the same chip, high wall plug efficiency and possibility to operate in hybrid mode-locking regime. Therefore, we have decided to address these targets...
Three-section master oscillator power amplifier at 1.57 µm for LIDAR measurements of atmospheric carbon dioxide

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High brightness laser sources are required for the detection of greenhouse gases in future space missions. We present experimental results on a Three-Section Master Oscillator Power Amplifier at 1.57 µm to be applied in an Integrated Path Differential Absorption (IPDA) LIDAR system for column-averaged atmospheric CO2 measurements. The application requires high power and high beam quality together with spectral purity and modulation capacity to be used in Random Modulation CW LIDAR system. The device consists of distributed feedback laser acting as master oscillator, a bent modulator section and a tapered optical amplifier section with a tilted front facet to avoid coupled cavity effects. The modulator section acts as an absorber or amplifier when driven at zero or positive bias.

Devices with different geometries and epitaxial structures were fabricated and characterized, presenting CW output powers higher than 500 mW and stable single mode emission. A high Optical Modulation Amplitude and Extinction Ratio were achieved by modulating at 25 Mbps the modulator section. The spectral and modulation characteristics are presented and analyzed.

Coherent imaging and sensing using the self-mixing effect in THz quantum cascade lasers (Invited Paper)

Paul Dean, Edmund H. Linfield, Giles Davies, Univ. of Leeds (United Kingdom)

In recent years self-mixing (SM) interferometry has emerged as a powerful technique for coherent imaging and sensing using terahertz (THz) frequency quantum cascade laser (QCL) sources. SM occurs when radiation from a laser is partially reflected from an external object and injected back into the laser cavity. The reflected radiation interferes (‘mixes’) with the inter-cavity field, producing variations in the emitted power and terminal voltage. Thus, by combining the local oscillator, mixer, and the detector all in a single laser, this technique allows the development of simple, self-aligned systems that can sense both the phase and amplitude of the THz field reflected from samples.

In this paper we present recent advancements in SM techniques using THz QCLs, with particular focus on three distinct imaging methodologies. Firstly we describe three dimensional THz imaging using swept-frequency SM interferometry, and demonstrate that depth resolutions down to ~0.1 µm can be achieved. Secondly we demonstrate an imaging scheme applied to materials analysis of samples including explosives and biological materials. Finally we present apertureless scanning near-field optical microscopy (SNOM) at THz frequencies, and demonstrate transverse resolutions down to ~1 µm. We summarise by discussing the outlook for this field.
**Microwave self-modulation of THz quantum cascade lasers**

Fabrizio Castellano, Consiglio Nazionale delle Ricerche (Italy); Lianhe H. Li, Edmund H. Linfield, Giles Davies, Univ. of Leeds (United Kingdom); Miriam S. Vitiello, Consiglio Nazionale delle Ricerche (Italy)

Quantum cascade lasers (QCL) have recently been demonstrated as a promising platform for the generation of optical combs in the infrared and terahertz frequency ranges via mode-locking of the laser cavity.

Optical gain modulation at the round-trip frequency of the laser cavity via injection of microwave signals is the most effective technique to achieve mode-locking, but frequency combs have also been demonstrated by implementing group-velocity dispersion compensation in a laterally corrugated waveguide.

We here report on the observation of a novel physical effect that could provide a mechanism for self-mode-locking of THz QCLs. The samples are standard double-metal THz QCLs with an active region characterized by a thin injection contact. The latter induces the depletion region of the Schottky contact used to bias the laser to extend into the GaAs/AlGaAs active region, producing a conduction band profile similar to that of an IMPATT diode, a well-known type of microwave oscillator. Current flow through QC active region is thus governed by the avalanche dynamics of the IMPATT injector, which behaves as a microwave oscillator and thus induces a modulation of the THz emission. We achieve multimode laser emission centered around 3 THz, with distinctive sidebands 10 GHz away from the Fabry-Perot QCL modes, a clear signature of the modulation of the THz emission. Microwave measurements confirm that the devices are also emitting 10 GHz radiation, due to the oscillation of the IMPATT injector. The observed microwave self-modulation of THz QCLs can be interestingly exploited to engineer self-mode-locked THz QCLs.

**Monolithic integration of a quantum cascade laser array and an echelle grating multiplexer for widely-tunable mid-infrared sources**

Clément Gille, mirSense (France) and III-V Lab. (France); Luis Jorge Orbe Nava, Guillermo Carpentero del Barrio, Univ. Carlos III de Madrid (Spain); Johan Abaultre, Gregory Maisons, Mathieu Carras, mirSense (France)

In the mid-infrared (Mid-IR), arrays of Distributed Feedback Quantum Cascade Lasers (DFB-QCL) have been developed to extend the wavelength operation range of laser-based gas sensing systems. Narrow-linewidth, single mode operation and wide tunability are then gathered together on a single chip with high mechanical stability and compactness. In order to benefit from this extended wavelength range in a single output beam we have developed a platform for InP-based photonics. After the validation of all required building blocks such as straight waveguides, adiabatic couplers between QCL and passive waveguides, and echelle grating multiplexers, we are tackling the integration into a single monolithic device.

We present the design, fabrication and performances of a tunable source, fully monolithic based on the echelle grating approach. Advantages are design flexibility, relatively simple processing and the need for only a single epitaxial growth for the entire structure. The gain medium of the laser array is based on three distinct cascade designs, with respective gain at 7.3, 8.5 and 9.4 μm wavelengths. The evanescent coupler has been designed to transfer all light adiabatically from the active region to a low loss passive waveguide, while taking advantage of the high gain available in the quantum wells. The multiplexer is based on an etched diffraction grating, covering the whole range of the 30 lasers of the array while keeping a very compact size. These results show the first realization of a monolithic, widely tunable source in the Mid-IR and would therefore benefit to the development of fully integrated spectroscopic sensor systems.
power consumption below 1 W and output power greater than 10 mW at operating temperatures up to 50 °C. In particular, we describe optimized devices emitting at 4.7 μm for low-level detection of CO, 4.8 μm for OCS isotopologue measurements, and 7.4 μm for detection of SO2.

9767-64, Session 14

Spectroscopic benzene detection using a broadband monolithic DFB-QCL array

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Quantitative laser spectroscopic measurements of complex molecules that have a broad absorption spectra require broadly tunable laser sources operating preferably in the mid-infrared region, where many molecules have their strongest fundamental ro-vibrational transitions. In this paper a novel broadly tunable mid-infrared laser source comprising of an array of distributed feedback quantum cascade lasers (DFB-QCLs) was used to target a broadband absorption feature of benzene (C6H6), which is one of the highly toxic (carcinogenic) atmospheric pollutants.

In contrary to conventional broadly tunable external cavity QCLs, the DFB-QCLs array is a monolithic semiconductor device with no movable opto-mechanical components, which eliminates issues with beam misalignment or mode-hopping caused by mechanical vibrations. The DFB-QCLs array used in this work provides broadband spectral coverage from 1022.5 to 1053.3 cm⁻¹, which is sufficient to resolve the absorption feature of benzene at 1037 cm⁻¹ (9.64 μm). To effectively inject all DFB-QCLs array beams into a 76 m multipass cell (AMAC-76LW, Aerodyne Research), a dispersive beam combiner based on a ZnSe transform lens and a reflective diffraction grating was designed and implemented.

A multi-component spectral measurement utilizing a linear least square fitting algorithm and reference absorbance spectra from the PNNL spectroscopic database, were used to retrieve benzene concentration levels. The Allan deviation analysis of the benzene concentration data yields a short-term precision of 100 ppbv/Hz¹/₂ and a minimum detectable concentration of 12 ppbv for 200 s averaging time. A sensor prototype was also tested by sampling atmospheric air as well as vapors of different chemical products that contained traces of benzene.

9767-65, Session 14

Cascade laser applications: trends and challenges

Eric Margoto, Yves Fazilleau, Arcliès (France); Benoît d’Humières, TEMATYS (France)

The first quantum cascade laser was invented 20 years ago and demonstrated at Bell Labs in 1994 by Faist et al. When analyses need rapid measurements, cost effective monitoring and miniaturization, tunable semiconductor lasers are perfect sources, thanks to their outstanding characteristics. Indeed, application fields like environmental gas analysis or industrial process control are now taking advantage of tunable semiconductor lasers for leaving the laboratory and enabling on-field testing.

Today, advances in cascade lasers (CL) are revolutionizing infrared spectroscopy and OEMs can count on two mature alternatives: interband cascade lasers (ICLs) that are expected to be a cost killer in the 3-6μm spectrum and quantum cascade lasers (QCLs), with more power and a continuous wider spectral resolution from 3 to 300μm. New CL-based applications are launched every day. The market is getting mature with strong players for driving applications like: industry (Vertex70 from Bruker), environment, life science (Spero from Daylight Solutions) or transports (Mesa-1400QL-NX from Horiba).

Our study is a qualitative and quantitative market analysis of the CL technologies and applications. It shows that the improvements of components performance, like micro-spectrometers, along with the progress of infrared laser spectroscopy will drive the CL market growth. We compare the different CL technologies, we identify the specific detectors of each spectral domain and their use either as continuous or pulsed sources. In addition, CL technologies allow today to be extended to new applications such as active or passive imaging applied to microscopy for example.

9767-66, Session 14

Single-mode enhancement in coupled-cavity quantum cascade lasers

Maciej Kuc, Robert P. Sarzala, Tomasz G. Czyszanowski, Lodz Univ. of Technology (Poland); Maciej Bugajski, Institute of Electron Technology (Poland)

We perform numerical analysis of single mode operation of coupled-cavity (CC) quantum cascade laser (QCL) being attractive cost-effective alternative to distributed feedback (DFB) QCLs. CC QCLs can be realized by cutting slot or multiple slots across their cavity, dividing the laser into unequal, electrically separated sections, which can be driven independently. Coupled cavities share the longitudinal modes favoring only those which meet the resonance condition in separate cavities and can be efficiently enhanced by the gain spectrum. In comparison to DFB QCLs, fabrication of CC QCLs involve less fabrication effort. The price which must be paid is lower SMSR with respect to DFB QCLs and more laborious current tuning which paradoxically allows for single mode emission in the case of the imprecisely fabricated structures increasing their fabrication yield.

We report on numerical analysis of longitudinal mode discrimination in coupled-cavity AlInAs/InGaAs/InP quantum cascade lasers. Using a three dimensional, self-consistent model of physical phenomena in edge emitting laser we performed exhaustive analysis of geometrical parameters of CC QCL on spectral characteristics. We discuss the enhancement of the single mode operation in multi-section designs concerning variable dimensions of sections and air gaps between sections and provide designing guidelines assuring single-mode operation. We also show impact of independent current tuning of laser sections inducing Stark effect and heating as additional elements enhancing single mode operation. To support our analysis we confront one with experiment verifying effects observed in simulations.
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9768-1, Session 1

Novel III-nitride-based nanostructure LEDs: nano-scale correlation of the optical, structural, and chemical properties (Invited Paper)

Jürgen H. Christen, Otto-von-Guericke-Univ. Magdeburg (Germany)

The controlled growth of core-shell nanorod heterostructures offers a potential benefit for the fabrication of high efficient III-nitride based optoelectronic devices. Since the active region is wrapped around the three-dimensional core, the active layer scales with the rod's aspect ratio. Therefore, by controlling the density, diameter and height of the three-dimensional nano LEDs, a significant increase of the optically active surface in comparison to planar heterostructures can be achieved.

For a detailed understanding of these complex nanostructures and the physics based on them, a systematic determination and correlation of the structural, chemical, electronic, and optical properties is essential. However, due to the small dimensions of such selectively grown nanostructures highly spatially resolved techniques are required for the characterization of individual nanostructures. Using nanometer-scale spatially resolved cathodoluminescence spectroscopy performed in a scanning transmission electron microscope (STEM-CL) we present a direct correlation of the optical properties with the actual crystalline real structure of single nanorod heterostructures. The CL system combines low temperatures, and an overall spatial resolution of $7 \times 5 \text{ nm}$ with high spectral resolution.

Typical results which will be presented include nano-scale cathodoluminescence microscopy of InGaN/GaN nanowire LEDs. We demonstrate the direct correlation of the luminescence and structural properties of the individual core-shell layers. In particular, we will discuss the crystalline quality, local indium incorporation, n- and p-layer quality of the nanostructure LED. The impact of extended defects on the emission is directly visualized using the capability of addressing individual basal plane faults and threading dislocations.

9768-2, Session 1

Estimation of free carrier concentrations in high-quality heavily doped GaN:Si micro-rods

Matin Mohajerani, Technische Univ. Braunschweig (Germany); Sevak Khachadorian, Christian Nenstiel, Technische Univ. Berlin (Germany); Jana Hartmann, Hao Zhou, Hergo-Heinrich Wehmann, Technische Univ. Braunschweig (Germany); Tilman Schimpke, Martin Strassburg, OSRAM Opto Semiconductors GmbH (Germany); Axel Hoffmann, Technische Univ. Berlin (Germany); Andreas Waag, Technische Univ. Braunschweig (Germany)

The controlled growth of highly n-doped GaN micro rods is one of the major challenges during fabrication of recently developed three-dimensional (3D) core-shell light emitting diodes. Since with the larger active area, higher electrical conductivity is needed to achieve higher current density in micro-rods. Generally, silicon is used as an n-type dopant in GaN and causes deterioration of a crystalline quality in heavily-doped planar samples. Nevertheless, in our GaN:Si micro-rods, it promotes 3D growth with a high crystalline quality in spite of heavy doping above $10^{20} \text{ cm}^{-3}$.

We report on the investigation on highly-doped GaN:Si micro-rods grown by metal-organic vapor phase epitaxy using a selective area growth technique on GaN buffer layer/sapphire templates. The doping concentration is gradually varied to realize a high aspect ratio and a good interface quality for subsequent shell growth. Utilizing spatially-resolved micro-Raman spectroscopy, a direct and accurate estimation of free carrier concentrations and doping profile is obtained on both m- and c-planes along the height of individual micro-rods. The lower frequency branch of LO-phonon-plasmon coupled modes in the Raman spectra is fitted and the free-carrier concentration is determined up to $-2 \times 10^{20} \text{ cm}^{-3}$ in the highest doped region. We also observed a negligible shift and broadening of the E$^\text{2}$high Raman mode compared to the ones of a strain-free GaN revealing no doping-induced strain and a high crystalline quality in our micro structures. Additionally, carrier concentrations are estimated from a fitting of near band edge photoluminescence emission at low temperature. A good agreement is found between the results from the both methods.

9768-3, Session 1

GaN-based devices for new gas sensor technologies (Invited Paper)

J. Daniel Prades, Univ. de Barcelona (Spain)

Low power consumption, long-term stability and high specificity are some of the most sought after requirements for future gas sensors technologies. In this contribution, the potential of GaN-based devices to contribute to this field will be discussed.

On the one hand, new optically-driven sensor device concepts featuring zero power consumption have shown that this is an open field for optically active materials [1]. Specifically, light emitters and absorbers active in the visible range, such as InGaN, are required to operate these new technologies in ambient light.

On the other hand, the traditional strategy to maximize the sensor response by choosing chemically and thermally unstable materials leads to well know long-term stability issues. Additionally, this choice produces vigorous and highly unspecific responses to gases. Following recent finding [2], an alternative strategy could be relying on highly stable gas-immune materials to build up the fundamental elements of the sensor platform in combination with highly specific functionalizations. The well-established microelectronic methods to process GaN would provide the necessary fine control over the electrical and optical properties of the device platform. The flexibility of molecular chemistry would deliver sufficient flexibility to tailor the specific response of the sensor almost at will.

The first attempts to implement this strategy in new devices will be presented.


9768-4, Session 1

Single-crystal phosphors for high-brightness white LEDs/LDs (Invited Paper)

Encarnación G. Villora, Stelian Arjoca, National Institute
for Materials Science (Japan); Daisuke Inomata, Tamura Corp. (Japan); Kiyoshi Shimamura, National Institute for Materials Science (Japan)

White LEDs are rapidly replacing traditional light sources for general lighting. Typical white LEDs consist of ceramic powder phosphors (CPPs) embedded in binders on top of blue LEDs. Although their luminance has improved notably over the years, their performance is compromised when used in white high-brightness (HB) configurations, due to overheating and encapsulants’ degradation under high irradiation fluxes. Both compromise the efficiency, color quality and lifetime of white LEDs and require the use of complicated cooling techniques especially in the case of LDs.

Recently we have proposed the use of single-crystal phosphors (SCPs) as an alternative to conventional CPPs. These are based on the garnet phosphor Ce:Y3Al5O12 (Ce:YAG) and the solid solutions Ce:(Y1-xLux)3Al5O12 (Ce:YLAG). These SCPs overcome all the critical issues encountered with HB-applications. SCPs can realize binder-free packaging, they exhibit superior conversion efficiencies and thermal stability thanks to their single-crystal nature (almost free from impurities and defects), and they possess a comparatively high thermal conductivity (2 orders of magnitude larger than conventional encapsulants). Ce:YLAG SCPs present an internal quantum-efficiency over 95%, which remains stable up to 300°C, thus minimizing the generation of phosphor heat by optical losses and Stokes shift. In conjunction with a blue LED/LD, Ce:YAG SCPs lead to white light with color temperatures $T_c$ about 6000 K and color rendering indices $Ra$ around 70. Lower $T_c$ and higher $Ra$ (>90) can be realized by Ce:YLAG plus an additional red phosphor. Furthermore, we have found that the temperature of SCPs remains low even under high irradiances. Therefore, SCPs are especially promising for upcoming HB LD-headlights and projection-mapping.


9768-5, Session 2
Development of AlGaN-based UVC emitters (Invited Paper)
Zlatko Sitar, Ramon Collazo, Zachary Bryan, Isaac S. Bryan, Ronny Kirste, North Carolina State Univ. (United States)

Invited: Despite the rapid progress in III-nitride-based laser diodes, sub-300 nm UV semiconductors lasers have not been realized. UV optoelectronic devices have a variety of applications such as sterilization, water purification, spectroscopy, high density optical data storage, and biological sensing. Technical and scientific barriers arise from the lack of proper crystalline substrates and a poor understanding of defect control in the wide bandgap semiconductors. AlGaN-based technology developed on single crystalline AlN substrates and impurity control in the active region offers a pathway to address all these challenges.

In addition to low dislocation density, reduction in non-radiative centers and compensating point defects in the active region are required to achieve high IQE. In order to understand the influence of point defects on radiative lifetime and ultimately achieve high IQE, we have carried out an extensive study of vacancy and carbon control via Fermi level and supersaturation management for various MQW structures grown on bulk AlN substrates. The use of bulk AlN substrates enabled us to undoubtedly distinguish the effect of growth condition, such as $V/III$ ratio, on optical quality from the influence of dislocation density. At a high $V/III$ ratio, a record high IQE of -80% at a carrier density of 1018 cm$^{-3}$ was achieved at ~258 nm.

Using this technology, we achieved lasing at room temperature in AlGaN-based MQW structures with a threshold below 60 kW/cm$^2$ and lasing wavelength from 237 to 281 nm. All samples had a lasing FWHM less than 0.8 nm, the narrowest reported to date.

9768-6, Session 2
Status of DUV LED on sapphire (Invited Paper)
Cyril Pernet, Tetsushiko Inazumi, Tetsumi Ochi, Hiroyasu Ichinokura, Hideki Asano, Hidemasa Tomozawa, Nikkiso Co., Ltd. (Japan); Hiroshi Amano, Nagoya Univ. (Japan); Isamu Akasaki, Meijo Univ. (Japan)

With output power of several tens of mW and long life time, DUV LED are already able to address a large range of markets in disinfection, curing and medical applications.

In this presentation we will present the present status of 255-355nm AlGaN-based DUV-LEDs grown on sapphire in term of output power, efficiencies and reliability, and discuss about the potential improvements in design and fabrication to reach better performance.

9768-7, Session 2
UV LEDs: the next solid-state revolution
Robert C. Walker, RayVio (United States)

Pathogens in our air, water, and on surfaces are a major health problem for billions of consumers across the globe. Water borne illnesses are responsible for 3.4 million deaths every year, primarily affecting children, and cost billions of dollars in lost opportunities. Infectious diseases, such as Ebola, SARS/MARS, avian flu, measles etc., are major concerns, with the possibility of becoming global pandemics. Ultraviolet light has been long established as one of the leading methods of disinfection, but its applications have been limited due to inherent constraints of the mercury bulb technology. Ultraviolet light emitting diodes (UV-LEDs) hold the promise to bring superior UV disinfection products to markets, just as visible LEDs are revolutionizing the way the world does its lighting. If UV LED technology can achieve significant breakthroughs in price and performance vs. existing products that are available on the market today, they can enable a host of products that can be directly used by consumers, giving people a level of safety that governments’ central infrastructure has not been able to achieve.

We will explore potential consumer applications for this technology, and the path to achieve the enabling price and performance requirements.

9768-8, Session 2
Enhancement of light emission-localized surface plasmon using Pt nanorings in deep UV-emitting AlGaN quantum wells
KyungRock Son, HeeWoong Shin, Kyeong Heon Kim, Tae Hoon Park, Byeong Ryong Lee, Tae Geun Kim, Korea Univ. (Korea, Republic of)

AlGaN-based deep-ultraviolet light-emitting diodes (DUV LEDs) have attracted considerable interest for a wide range of applications, such as in biological detection and water/air purification systems. However, AlGaN-based DUV LEDs are still far from practical application because of their extremely low external quantum efficiency (EQE) of approximately 5–14%. One important limitation for the EQE in DUV LEDs is related to the existence of high threading dislocation densities in AlGaN epilayers due to the significant crystal lattice and thermal mismatches between the sapphire and the III-nitride materials, leading to poor material quality and thus to a low internal quantum efficiency.

In this study, we demonstrate that the light emission from AlGaN-based multiple quantum wells (MQWs) can be significantly enhanced when the light waves generated in the MQWs are coupled to energy-matched localized surface plasmon (LSP) from Pt nanorings structures. The LSP coupling effect of hybrid nanostructures can be controlled across a wide
range from deep UV to visible regions by optimizing the diameter of Pt nanorings. In particular, we discovered that deep UV emission ranging from 276 nm to 284 nm in the MQWs was enhanced for AlGaN MQWs using the Pt nanoring array with a diameter of 325 nm, with which an emission enhancement ratio of 304% was achieved in PL peak intensity at a wavelength of 279 nm, as compared to bare AlGaN MQWs. More details on the experimental and simulation results will be presented at the conference.

9768-9, Session 2
Investigation of light output uniformity and performance using a UV transmitting glass optic for a multi-UV LED array
Brian S. Jasenak, Adam Willssey, James Forish, Rachel Willsey, Kopp Glass, Inc. (United States)

Ultraviolet light-emitting diode (UV LED) adoption is accelerating; they are being used in new applications such as UV curing, germicidal irradiation, and forensic analysis. In many of these applications, it is critically important to produce a uniform light distribution and consistent surface irradiance. Flat panes of fused quartz, silica, or glass are commonly used to cover and protect multi-UV LED arrays. However, they don’t offer the advantages of an optical lens design. An investigation was conducted to determine the effect of a secondary glass optic on the uniformity of the light distribution and irradiance. Glass optics capable of transmitting UV-A, UV-B, and UV-C wavelengths can improve light distribution and intensity.

In this study, a UV transmitting glass formulation and secondary linear optic were designed and manufactured to demonstrate their effects on achievable irradiance uniformity and performance. Prismatic patterning on the light source surface of the lens was used to minimize reflection losses on the incident surface of the glass. Fresnel optics were molded into the opposite side of the UV transmitting glass to control the refraction of the light and to gain the desired light distribution from two multi-UV LED arrays. A 20% increase in relative irradiance was observed while maintaining the same coverage area. This talk will discuss the optical design and the resulting benefits of controlled light output on UV LED systems, which include reduced driving current, decreased thermal deterioration, improved energy efficiency, and longer LED lifetime.

9768-10, Session 3
Radiative and non-radiative processes in InGaN quantum well LEDs (Invited Paper)
Axel Hoffmann, Felix Nippert, Technische Univ. Berlin (Germany); Ines Pietzonka, OSRAM Opto Semiconductors GmbH (Germany); Sergey Y. Karpov, STR Group-Soft Impact Ltd. (Russian Federation); Bastian Galler, Alexander Wilm, Martin Strassburg, OSRAM Opto Semiconductors GmbH (Germany)

We have investigated a series of state-of-the-art InGaN/GaN single and multi-quantum well light emitting diodes by means of differential carrier lifetime measurements. Combined with basic electroluminescence characterization this allows us to extract the A, B and C recombination coefficients of the ABC-model as a function of quantum well number in the active region and temperature giving insight into the radiative and non-radiative processes within the active region, as well as allowing to identify the actively pumped volume in the active region.

Differential carrier lifetime measurements are usually (e.g. in VCSELs) performed by modulating the electric pumping of the device and monitoring the optical or electrical response. We have found that for LEDs this may lead to misleading results since the measurement then includes parasitic effects like the modulation of the space charge zones in the p-n-junction. Instead we inject the additional carriers by resonant optical pumping of the electrically driven device.

9768-11, Session 3
LEDs for solid-state lighting: searching room for improvements (Invited Paper)
Sergey Y. Karpov, STR Group-Soft Impact Ltd. (Russian Federation)

The paper reviews state-of-the-art light-emitting diodes (LEDs) developed for solid-state lighting with the focus on their efficiency and ways for its further improvement. Advantages and disadvantages of various schemes of color mixing for white light generation are discussed and benchmarked using recent data on the efficiency of state-of-the-art LEDs. Optimal parameters of individual emitters are estimated to provide desirable characteristics of white-light sources, i.e. correlated color temperature, color rendering index, and efficacy. Based on these guidelines, requirements to the efficiency of various III-N and III-P LEDs are derived aimed at improving the overall efficacy and color rendition of the white-light sources. In view of the above requirements, the mechanisms of the LED efficiency losses are considered on the heterostructure, chip, and device levels. In particular, such phenomena, as non-radiative efficiency droop, “green gap” in the LED efficiency, current crowding, Stokes losses at light conversion, various channels of recombination losses, etc. are addressed. The underlying physics and solutions promising to overcome the existing problems are discussed and illustrated by simulations. Among the factors leading to the efficiency reduction, those related to intrinsic properties of the materials used for LED fabrication and their growth technology are of special importance. The paper considers phase separation in InGaN alloys and plastic relaxation in highly strained LED structures as the factors that may be responsible for the efficiency degradation in LEDs emitting in the green/yellow spectral range. Finally, a possible room for the efficiency improvement is discussed for both III-N and III-P LEDs.

9768-12, Session 3
Thermal droop in InGaN-based LEDs: physical origin and dependence on material properties
Carlo De Santi, Matteo Meneghini, Marco La Grassa, Univ. degli Studi di Padova (Italy); Bastian Galler, Roland Zeisel, Berthold Hahn, OSRAM Opto Semiconductors GmbH (Germany); Michele Goano, Francesco Bertazzi, Politecnico di Torino (Italy); Stefano Dominici, Politecnico di Torino (Italy) and Univ. degli Studi di Padova (Italy); Gaudenzio Meneghesso, Enrico Zanoni, Univ. degli Studi di Padova (Italy); Nicola Trivellini, Univ. degli Studi di Padova (Italy)

Over the last few years, the scientific community has extensively investigated the efficiency droop, i.e. the drop of the efficiency of InGaN LEDs at high current densities. However, an even stronger decrease in quantum efficiency takes place when the LEDs are operated at high temperature levels: state-of-the-art LEDs can show 15-40 % drop in optical power (thermal droop) when the temperature is increased from 25 °C to 150 °C. This temperature range is relevant for real-life applications, since most of the high power LEDs on the market are rated for a maximum temperature of 125-175 °C.

This paper reports an extensive analysis of the physical origin of the thermal droop in InGaN-based Light-Emitting Diodes. The study is aimed at separately investigating the impact of defect density and of indium content in limiting the efficiency of the devices in the high temperature range. The analysis was carried out by combined electroluminescence vs temperature, deep-level transient spectroscopy, and differential carrier lifetime measurements. The individual contributions of Shockley-Read-Hall (SRH) recombination, thermionic escape from the quantum wells and trap/phonon assisted tunneling have been evaluated by experimental measurements and numerical simulations.
The results of this analysis demonstrate that the thermal stability of the output signal is strongly determined by the defectiveness of the material in the low current regime, due to SRH recombination and defect-related carrier escape processes; on the other hand, in the high current regime thermal droop can be strongly influenced by the thermionic escape of electrons out of the quantum wells.

9768-13, Session 3

Improvement of internal quantum efficiency and efficiency droop in GaN-based flip-chip light-emitting diode structures via the Purcell effect

Han-Youl Ryu, Inha Univ. (Korea, Republic of)

Spontaneous emission (SE) rate of a semiconductor quantum well (QW) can be modified significantly depending on the local density of states. When the SE rate is enhanced, the radiative lifetime of carriers in QWs is reduced, which leads to an increase in the internal quantum efficiency (IQE) of LEDs. This Purcell enhancement effect is also expected in a flip-chip (FC) or vertical light-emitting diode (LED) structures where a high reflectance mirror exists near QWs. In this study, the Purcell effect in blue FC LED structures is investigated using numerical simulations based on the finite-difference time-domain method. Depending on the thickness of the p-GaN layer in FC LEDs, the variation of the Purcell factor is obtained to be as high as 20%, which results in the relative IQE enhancement as large as 8% and 2.5% for the unmodified IQE of 0.4 and 0.8, respectively. Since the influence of the Purcell effect becomes more conspicuous as IQE decreases, the Purcell enhancement can be advantageously used to mitigate the efficiency droop problem to some extent. When the Purcell enhancement effect is to the blue LED with the peak IQE of 0.8 and the droop ratio of 29.1%, the peak IQE and the droop ratio are found to be improved to 0.82 and 26.3%, respectively. Unlike surface-plasmon coupled LED structures, the FC LED structures exhibit high light extraction efficiency as well as the improved IQE characteristics. The Purcell effect in FC LED structures is expected to be importantly adopted for industry development of high efficiency LEDs.

9768-14, Session 3

3D numerical modeling of the carrier transport and radiative efficiency for InGaN/GaN light-emitting diodes with V-shaped pits

Chi-Kang Li, Li-Shuo Lu, Chen-Kuo Wu, Chung-Cheng Hsu, Yuh-Renn Wu, National Taiwan Univ. (Taiwan)

In this paper, a V-pit embedded inside the multiple quantum wells (MQWs) LED was studied. A three-dimensional (3-D) stress-strain solver and Poisson, drift-diffusion solver are employed to study the current path, where the quantum efficiency and turn-on voltage will be discussed. The model will be calibrated by PL measurements especially for the parameters of threading dislocation. As we know, in planar LEDs, the hole current is hard to flow through MQWs due to lower mobility of holes, which makes the radiative recombination non-uniform. However, in V-pit LEDs, our results show that the current is flowing through shallow sidewall quantum wells (QWs) and then injecting into the deeper lateral QWs, where the V-pit geometry provides more percolation length for holes to make the hole distribution uniform along lateral QWs. Theoretically, the variation of the internal quantum efficiency (IQE) for different V-pit sizes is due to the trap-assisted potential and QW areas. According to the experimental PL efficiency measurement, there is a switch behavior for IQE as the V-pit diameter decreases. This is explained by the diameter-dependent energy barrier and lateral QW ratio from experiments. In our simulation, we found the carriers trapped by TDs is another key factor to explain such switch behaviors. In addition, the V-pit structure would not only enhance the hole percolation length but act as a potential barrier to prevent nonradiative recombination from TD. Finally, we implemented the indium fluctuation model into the V-pit structure and we found the turn-on voltage is earlier compared with the planar LED with indium fluctuations, because the V-pit structure provide more percolation length through sidewall QWs for both the electron and hole. By using indium fluctuation model and V-pit structure, the simulated turn-on voltage can be pushed earlier to well explain the experimental data.

9768-65, Session 3

3D modeling of intrinsic disorder in InGaN/GaN heterostructures (Invited Paper)

Claude Weisbuch, Ecole Polytechnique (France) and Univ. of California, Santa Barbara (United States); Marco Piccardo, Marcel Filoche, Ecole Polytechnique (France); Chi-Kang Li, Yuh-Renn Wu, National Taiwan Univ. (Taiwan); Lucio Martinelli, Ecole Polytechnique (France); J. Perretti, Ecole Polytechnique (France); James S. Speck, Univ. of California, Santa Barbara (United States)

It emerges now that the operation of LEDs might be very different from their theoretical designs, as real world materials and structures have intrinsic and essential disorder. It was recently shown in a simplified model that disorder can account for a turn on voltage of LEDs smaller by 1V compared to simulations. We will present novel theoretical and modeling tools of disorder aimed at a deep understanding of the various effects of disorder in LEDs. As a first application of these new tools we model our detailed measurements of the absorption edge of InGaN/GaN multi quantum wells with varying in composition.

9768-15, Session 4

Recent advances in pulsed sputtering techniques for fabrication of nitride LEDs (Invited Paper)

Hiroshi Fujioka, The Univ. of Tokyo (Japan) and JST-ACCEL (Japan); Kohei Ueno, Astushi Kobayashi, Jitsuo Ohta, The Univ. of Tokyo (Japan)

It is well known that group III nitride devices exhibit high performance but their applications are limited in small area devices because their fabrication process involves low throughput high temperature epitaxial growth by MOCVD. It is quite natural to expect that group III nitride devices prevail widely among various new application fields once low cost fabrication process is established. Large area nitride displays are among these applications. For this purpose, we have proposed the use of a new low cost growth technique named PSD (pulsed sputtering deposition). PSD has already attracted much attention of industry engineers because its productivity is much higher than that of MOCVD. In this technique, pulse operation enhances surface migration of the film precursors and, therefore, the temperature for epitaxial growth is dramatically reduced. This reduction allows us to utilize large area low cost substrates such as glass that were not used for growth of semiconductors so far due to their low softening temperatures. The other advantage of PSD lies in the fact that growth system is carbon/hydrogen free. This nature gives us as-grown p-type materials and pure ud-materials, which are attractive for device applications. In this presentation, we will discuss recent advances in PSD techniques for fabrication of nitride based LEDs.
3-pad LED flip chip COB: novel approach in lowering thermal resistance to enable smaller heat sink on super high-power LEDs

Pao Chen, Dongwook Noh, Flip Chip Opto Inc. (United States)

3-Pad LED flip chip on Board (COB) is an invention that exhibits extremely lower thermal resistance compared to conventional 2-Pad LED flip chip COB and wire-bond LED COB. This exclusive characteristic enhances the thermal dissipation and delivers the performance benefits such as lower thermal decay, lower junction temperature, flexibility in heatsink grade and the feasibility to increase brightness via higher driving current for the best lumen-per-dollar value.

Besides N- and P- electrode pads, the 3-Pad LED flip chip consists of an additional thermal pad designed to couple the heat directly from the LED junction to a copper pillar extending from the copper substrate of a metal core printed circuit board (MCPB) while both N- and P- electrode pads are bonded to the MCPB circuitry. Since the path of thermal dissipation between the 3-Pad LED flip chip and the MCPB copper substrate is highly thermal conductive, a 3-Pad LED flip chip COB is able to exhibit extremely low thermal resistance, e.g., a 900W 3-Pad LED flip chip COB has a thermal resistance of 0.007°C/W with a light emitting surface (LES) of D=85mm.

Other than the feasibility of applying higher current, lower thermal resistance also facilitates the applications that coordinate with economical heatsink of higher thermal resistance. For instance, a 150W 3-Pad flip chip COB is able to maintain the same LED junction temperature as a 150W wire-bond COB while coordinating with a heatsink of 30%-40% less volume.

General principles of light out-coupling from trapped modes and the application for GaN LED using dynamic nano-inscribing patterning technique

Long Chen, Ashwin Panday, Shengjun Zhou, Chad Huard, Xi Chen, L. Jay Guo, Univ. of Michigan (United States)

Trapped modes of light are very general, which intrinsically limit the performance and applications of many photonic/plasmonic systems such as Hyperbolic Metamaterials (HMM) and LED. Here in this work we develop a general model to describe the light-out coupling from trapped modes by using gratings in the language of photon population distribution and photon momentum transforming. Based on this model, we discovered the general efficiency enhancing conditions and the design principles to optimize the out-coupling efficiency by engineering both the nanoscale grating structures and the photonic density of states in the systems. One of the key conditions we find out is that in order to optimize the out-coupling efficiency, one should channel the regions of highest photonic density of states in both the light-trapping media and the outside. As an application of these principles, we experimentally studied the light extraction problem of a flip-chip GaN LED initially with microscale patterned sapphire substrates (PSS) at the sapphire/n-GaN interface. By using nanoscale gratings fabricated by the mask-free, large-area dynamic nanoinscribing (DNI) patterning technique, we verified that the out-coupling efficiency sensitivity depends on the out-coupling conditions. And with our optimized design, we obtained a further enhancement of 10% of the total radiative power and a 20% peak enhancement in addition to the PSS structures.

Emission characteristics of light-emitting diodes by confocal microscopy

Wing Shing Cheung, Hoi Wai Choi, The Univ. of Hong Kong (Hong Kong, China)

The emission profiles of light-emitting diodes have typically been measured by goniophotometry. However this technique suffers from several drawbacks, including the ability to generate three-dimensional emission profiles as well as poor spatial resolution. This limitations are particularly pronounced when the technique is used to compared devices whose emission patterns have been modified through surface texturing at the micrometer and nanometer scales, as well as LED chips which have been geometrically shaped.

In view of such limitations, confocal microscopy has been adopted for the study of emission characteristics of LEDs. A laser-scanning confocal microscope is used for the work, although the laser is turned off and the microscope is operated in reflection mode to collect point-by-point plane-by-plane emission from devices. This enables three-dimensional emission maps to be collected, from which two-dimensional cross-sectional emission profiles can be generated. Various measurement conditions have to be fulfilled before the technique can be employed for this purpose, including the measurement range and the numerical aperture of the objective. These conditions are explored in this work and will be reported in the full paper. As an illustration, the technique has been adopted to compare the emission profiles of LEDs with and without microstructures. The effects of microstructuring becomes evident, since technique enables probing of light at the locations of the microstructures.

Increased light extraction efficiency of flip-chip light-emitting diode using anodic aluminum oxide

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Highly optical performances of flip-chip light-emitting diodes, employing anodic aluminum oxide patterned sapphire substrates with various pitch (50-130 nm) of textures on the surfaces of the substrates, are evaluated. At 350 mA, the chip (280 nm) delivers higher power of 420 mW in comparison to the characteristics in the cases of bare samples (410 mW) and without hole expansion samples (415 mW). We speculate that this result should be subjected to a surface roughening and surface plasma waves enhancements, and then we will examine this part of its relevance.

P-doped (Al)GaN layers by MBE: applications to long-wavelength lasers and tunnel junctions (Invited Paper)

Marco Malinverni, Denis Martin, Nicolas Grandjean, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

The technology of III-V nitride based light emitting diodes (LEDs) and laser diodes (LD) is nowadays well established in the blue range with impressive performance. However, there is still room for improvement at longer wavelengths for which high-in content InGaN quantum wells are required. In-rich InGaN alloy is subject to thermal degradation, which may occur during growth of p-type cladding layers. There is thus a need to
reduce as much as possible the thermal budget induced by layer growth on top of the InGaN based active region. Along these lines, molecular beam epitaxy (MBE) appears as a suitable growth technique. Mg doped (Al) GaN layers were thus deposited by NH3-MBE at low-temperature (750°C). Their electrical properties compare well with those grown by metal organic vapour phase epitaxy. Compensation is shown to be very low even for (Mg) larger than 5x10¹⁹ cm⁻³. p-type AlGaN cladding layers were then used to fabricate LEDs emitting at 500 nm and with state-of-the-art I-V curves. Furthermore, the high net acceptor concentration together with low diffusion of the doping species across the p-n junction interface allowed us to achieve GaN tunnel junction (TJ) with excellent characteristics. Eventually, we fabricated micro-LEDs featuring buried GaN TJ for current confinement with specific resistance of 3.7?10⁻⁴ ? cm² for the whole device.

9768-21, Session 5

Correlation between p-GaN growth environment with electrical and optical properties of blue LEDs
Modestas Zulonas, Ilya E. Titkiv, Amit Yadav, Ksenia A. Fedorova, Edik U. Rafailov, Aston Univ. (United Kingdom); Andrei F. Tsatsulnikov, W. V. Lundin, Alexey V. Sakharov, Ioffe Physical-Technical Institute (Russian Federation); Thomas J. Slight, Wyn Meredith, Compound Semiconductor Technologies Global Ltd. (United Kingdom)

Two blue emitting (450nm) LEDs with the growth condition variations in the top p-GaN epi-layer were investigated. One of the blue color LEDs' p-GaN layer were grown in the N₂/H₂ gas mixture environment and the another one - in the pure N₂ environment. The light output, voltage-current-capacitance, contact resistance, electroluminescence and photoluminescence measurements were done to compare the impact of metal-organic chemical vapor deposition (MOCVD) technique influence on the p-GaN layer growth environment. It was observed that the LED which had the top p-GaN epi-layer grown in the pure N₂ gas environment had better characteristics than the LED with the top p-GaN epi-layer grown in the N₂/H₂ gas mixture environment. The following qualitative explanation was given: the main difference between growing environments is the incorporation rate of Magnesium. In theory, Mg incorporates in GaN layer as shallow or deep level (in Mg⁺H2 complex) acceptor, resulting in p-GaN conductivity compensation. The hydrogen environment improves the Mg incorporation rate, but Mg activation in H2 (annealing) strongly affects free hole concentration. So, the growth of p-GaN in the N₂/H₂ atmosphere increases deep levels concentrations acting as hall traps (increasing resistance) and non-radiative centres (decreasing EL and PL).

9768-22, Session 5

Practical issues of surface plasmon coupled light-emitting diodes
Chun-Han Lin, Hao-Tsung Chen, Charng-Gan Tu, Chieh Hsieh, Chia-Ying Su, Yu-Feng Yao, Yang Kuo, Yean-Woei Kiang, Chih-Chung Yang, National Taiwan Univ. (Taiwan)

Surface plasmon (SP) coupling with the quantum wells (QWs) of a light-emitting diode (LED) can lead to the following advantages, including the enhancement of the internal quantum efficiency (IQE) of an LED of a low intrinsic IQE, the reduction of the efficiency droop effect, and the increase of modulation bandwidth. However, the critical condition for effective SP coupling with the QWs of an LED is that the thickness of the p-type layer cannot be larger than 100 nm. Nevertheless, based on the currently low p-type conductivity, such a thin p-type layer will lead to poor current spreading and hence high device resistance. To solve this problem, the conductivity of the p-type layer needs to be enhanced such that the p-type layer thickness can be reduced for shortening the distance between the fabricated surface metal nanostructures and the QWs. In this paper, we report our recent progress in increasing the p-type conductivity by growing an alternating-layer structure of p-GaN and u-GaN. In such a structure, the highly Mg-doped p-GaN layers provide high-concentration holes. Holes diffuse into the neighboring u-GaN layers for high-mobility migration. Because of the low impurity concentration in a u-GaN layer, hole mobility in such a layer is expected to be high. By using the high mobility, the overall conductivity can be increased. We demonstrate the growth results of high-conductivity p-type layers and evaluate their impacts on the development of an SP-coupled LED.

9768-23, Session 5

Blue resonant-cavity light-emitting diode with half milliwatt output power
Pinghui S. Yeh, Chi-Chieh Chang, Yu-Ting Chen, National Taiwan Univ. of Science and Technology (Taiwan); Da-Wei Lin, Chun Chia Wu, Jhao Hang He, Hao-Chung Kuo, National Chiao Tung Univ. (Taiwan)

GaN-based blue resonant-cavity light-emitting diodes (RCLED) featuring a Si-diffusion-defined confinement structure were fabricated and characterized. The epitaxial structure grown on a c-plane sapphire substrate consisted of 25 pairs of AlΝ/GaN distributed Bragg reflector (DBR), an n-GaN layer, 10 pairs of InGaN/GaN multiple quantum wells, a p-AlGaN electron blocking layer, and a p-GaN layer. After processing, a 2-pair TiO2/SiO2 dielectric reflector of designed thickness was deposited on top of the devices to provide approximately 50% reflectance at the peak wavelength. An output power of 0.5 mW before packaging at an injection current of 25 mA from 20-7m-diameter RCLED was achieved under room-temperature continuous-wave operation. And the slope efficiency was increased by approximately 50% after deposition of the top reflector. Charge-coupled-device (CCD) images exhibited bright spots of sizes corresponding to the diffusion-defined aperture sizes. The full width at half maximum (FWHM) of the emission spectrum was reduced from more than 16 nm to approximately 4 nm after depositing the top reflector, and remained stable at various current densities up to 12.7 kA/cm² and at various ambient temperatures up to 60°C. The peak wavelength was around 428 nm with a wavelength shift coefficient of less than 0.03nm/K. The far-field patterns exhibited half-power angles of approximately 45° indicating superior directionality than conventional LEDs.

9768-24, Session 5

Fabrication and characterization of superluminescent diodes for 2-3 um wavelength range
Nouman Zia, Jukka Viheriälä, Riku Koskinen, Mervi Koskinen, Soile Suomalainen, Mircea Guina, Tampere Univ. of Technology (Finland)

A Superluminescent light-emitting diode (SLD) offers a good compromise between the brightness and beam directionality of a laser diode (LD) and the broad emission spectrum of an LED. The operation is based on the amplification of spontaneous emission via stimulated emission process, preserving a relatively broad emission spectrum compared to LDs. The development of SLDs at long-infrared wavelengths (2-3 μm) has until recently received little attention. This is due to the fact that one would need to employ a less developed and not so widely available optoelectronic (GaSb-based) technology. There are only a few reports of SLDs at this wavelength range, yet such sources would find many needs in spectroscopic and sensing application, in particular for the environmental monitoring. In this paper we report on the fabrication of GaSb-based SLDs operating at 2 μm at above 5mW ASE power in CW. The emission spectrum of SLD was
GaN-nanowire-based light-emitting diodes

(Linvited Paper)

Lars Samuelson, Lund Univ. (Sweden) and Glo AB (Sweden); Bo Monemar, Lund Univ. (Sweden); Jonas B. Ohlsson, Lund Univ. (Sweden) and QuNano AB (Sweden); Nathan F. Gardner, GLO-USA, Inc. (United States)

GaN semiconductor nanowires are highly interesting since they offer routes to dislocation-free materials, and the possibility to reach higher concentrations and to design optimal cavities and arrays for optimal control of the out-coupling of light. Today, highly efficient blue and green NW-LEDs in the GaN-InGaN materials system can be fabricated. We expect also to very soon realize efficient yellow and red GaN-based nanowire-based LEDs, which will complete the ideal system for color rendering optimization of tri-color R-G-B or four-color R-Y-G-B individually addressable NW-LEDs. This will offer significant avenues towards application areas within advanced display applications as well as in lighting.

Illumination systems that do not use phosphors are expected to be highly superior in comparison with today’s UV/Blue-Led-pumped phosphors, with respect to long-time color stability and in terms of conversion efficiency from electrical input power to light.

In addition, the high quantum efficiency of the nanowire devices at low current densities make them especially suitable for display architectures where each nanowire or group of nanowires may form a pixel, operating at ultra-low current densities. A great and challenging opportunity, quite unique to NW-LEDs, would be the implementation of a monolithic RGB, direct-view display technology that would be exceedingly bright and power efficient in comparison with any display technologies available today.


9768-26, Session 6

Broad emission spectra of multi-section core-shell InGaN/GaN quantum-well nanorod light-emitting diode arrays

(Invited Paper)

Chang-Gan Tu, Yu-Feng Yao, Chia-Ying Su, Chieh Hsieh, Chi-Ming Weng, Chun-Han Lin, Hao-Tsung Chen, Yean-Woei Kiang, Chih-Chung Yang, National Taiwan Univ. (Taiwan)

First, the comparison of emission spectrum between single-, two-, and three-section GaN nanorods (NRs) with sidewall InGaN/GaN quantum wells (QWs), which are grown with metalorganic chemical vapor deposition based on the pulsed growth technique, indicates that a multi-section NR can lead to a significantly broader sidewall emission spectrum. Then, the growth of a two-section, core-shell, InGaN/GaN MQW NR-array light-emitting diode device based on the similar technique is demonstrated. A two-section n-GaN NR is grown through a tapering process for forming two uniform NR sections of different cross-sectional sizes. The cathodoluminescence (CL), photoluminescence (PL), and electroluminescence (EL) characterization results of the two-section NR structure are compared with those of a single-section NR sample, which is prepared under the similar condition to that for the first uniform NR section of the two-section sample. All the CL, PL, and EL spectra of the two-section sample are red-shifted from those of the single-section sample. Also, the emitted spectral widths of the two-section sample become significantly larger than their counterparts of the single-section sample. Such variations are attributed to the higher indium incorporation in the sidewall QWs of the two-section sample due to the stronger strain relaxation in an NR section of a smaller cross-sectional size and the more constituent atom supply from the larger gap volume between neighboring NRs.

9768-27, Session 6

Position-controlled MOVPE growth and electroluminescent characterization of core-shell InGaN/GaN microrod LEDs

(Invited Paper)

Tilman Schimpke, Hans-Jürgen Lugauer, Adrian Avramescu, Tansen Varghese, Andreas Koller, QOSRAM Opto Semiconductors GmbH (Germany); Jana Hartmann, Technische Univ. Braunschweig (Germany); Johannes Ledig, Institut für Halbleitertechnik, TU Braunschweig (Germany); Andreas Waag, Technische Univ. Braunschweig (Germany); Martin Strassburg, QOSRAM Opto Semiconductors GmbH (Germany)

Today’s InGaN-based white LEDs still suffer from a significant efficiency reduction at elevated current densities, the so-called “Drop”. Core-shell microrods, with quantum wells (QWs) covering their entire surface, enable a tremendous increase in active area scaling with the rod’s aspect ratio. Enlarging the active area on a given footprint area is a viable and cost effective route to mitigate the drop by effectively reducing the local current density.

Microrods were grown in a large volume metal-organic vapour phase epitaxy (MOVPE) reactor on GaN-on-sapphire substrates with a thin, patterned SiO2 mask for position control. Out of the mask openings, pencil-shaped n-doped GaN microrod cores were grown under conditions favouring 3D growth. In a second growth step, these cores are covered with a shell containing a quantum well and a p-n junction to form LED structures. The emission from the QWs on the different facets was studied using resonant temperature-dependent photoluminescence (PL) and cathodoluminescence (CL) measurements. The crystal quality of the structures was investigated by transmission electron microscopy (TEM) showing the absence of extended defects like threading dislocations in the 3D core.

In order to fabricate LED chips, dedicated processes were developed to accommodate for the special requirements of the 3D geometry. The electrical and optical properties of ensembles of tens of thousands microrods connected in parallel are discussed.

9768-28, Session 6

Nitride nanowires for new functionalities: from single wire properties to flexible light-emitting diodes

(Invited Paper)

Maria Tchernycheva, Dai Xing, Hezhi Zhang, Agnès Messanvi, Vladimir Neplokh, Pierre Lavenus, Nan Guan, Jianchang Yan, François H. Julien, Univ. Paris-Sud 11 (France); Lorenzo Rigutti, Institut d’Astrophysique Spatiale
We will present our recent work on nitride nanowire based light emitters. These nanomaterials have the potential to boost the device performance and to bring new functionalities. We will first discuss single nanowire properties, namely the fabrication and characterization of single nanowire light emitting diodes with graphene transparent contacts [1], the structural characterization of these nanowires using charge collection microscopy [2], the possibility to control the LED color by a post-growth treatment [3] as well as the coupling of single nanowire emitters with waveguides in order to form a functional photonic platform [4]. Then we will focus on our recent progress toward flexible nitride nanowire devices. We will discuss our method to combine high flexibility of polymer films with high quantum efficiency provided by nitride nanowires to achieve flexible inorganic light emitting diodes with a tunable color [5].

References


Advances in solid-state lighting (Invited Paper)

John Edmond, Cree, Inc. (United States); Sten Heikman, Cree Santa Barbara Technology Ctr. (United States)

With the advances in LED efficiency over the last several years, solid state lighting in the marketplace has grown significantly. This includes outdoor full color displays, street and parking deck lighting, indoor lighting and hand held devices. In each application, there is an optimization between the LED chips, the components they are encapsulated into and the lighting systems made from these components. In this presentation, several aspects of the lighting system will be considered. This will include chip design, the chip interaction with phosphors and their incorporation in various component types. System optimization with respect to electrical and optical characteristics such as voltage, color temperature, color rendering index and luminous efficiency will also be discussed. Other key aspects of what matters for the growth of the solid state lighting market going forward (lm/W/$) will be presented as well.
be addressed. This will lead us to the conception of a monolithic spatially controlled white light source.

9768-32, Session 7
High-brightness low-power consumption microLED arrays
James R. Bonar, Gareth J. Valentine, Zheng Gong, James Small, Steve Gorton, mLED Ltd. (United Kingdom)
mLED will provide a review of some of their latest results pertaining to microLED arrays. The inherent technology provides salient advantages to traditional display technologies but requires the development of high performing small LED pixels, fine pitch bonding, backplane integration and colour conversion. A number of challenges relating to the formation of sub 10 um LEDs and the ability to form arrays with fine pitch and full colour capabilities will be discussed. The characterisation and performance of small pixels will be detailed with luminance, efficiency droop, recombination effects, thermal dependency, etc. discussed. Bonding requirements and constraints posed will be reviewed and the routes to providing pixel pitch of sub 20 um discussed alongside the backplane control integration. The development of colour conversion for fine pitch LED pixel will be shared and the steps to full colour integration discussed. The technology also lends itself to a range of applications. As well as micro-displays for Wearables, time will be taken to overview other market sectors which would benefit from this high brightness array of micro-pixelated sources.

9766-33, Session 7
Fabrication of white flip-chip light-emitting diodes by substrate transferring technique
Ray-Hua Horng, Ching-Ho Tien, Kuo-Wei Ho, Dong-Sing Wu, National Chung Hsing Univ. (Taiwan)
A phosphor template produced by spin-coating method is introduced to improve the angular color uniformity of the white FC-LED. It was shown that the luminous flux of thin film LEDs epilayer with rough n-GaN transferred to glass substrate and then bonded to phosphor (FRGW-LED) was increased by 75.4%, compared to a FGWB-LED. The angular CCT deviation of a FRGW-LED reaches 1278 K in the range of -80° to +80°. According to the mentioned results, the FRGW-LED, which fabricated on the glass substrate with the roughened u-GaN surface and the structure of phosphor layer on the u-GaN, both has a better light extraction characteristic and a higher CCT stability.

9768-63, Session 7
LED light engine concept with ultra-high scalable luminance
Christoph Hoelen, Philips Lighting B.V. (Netherlands)
Although LEDs have been introduced successfully in many general lighting applications during the past decade, high brightness light source applications are still suffering from the limited luminance of the LEDs. High power LEDs are generally limited to 100 Mnit (108 lm/m²sr) or significantly less, while dedicated devices for projection may achieve luminance values up to ca 200 Mnit with phosphor converted green emitters. In particular for high luminous flux applications with limited etendue, like front projection systems, only very modest luminance values in the beam can be achieved with LEDs compared to systems based on discharge lamps. In this paper we introduce a light engine concept based on a light converter rod pumped with short wavelength blue LEDs that breaks through the etendue and brightness limits of LEDs for these applications, enabling LED light source luminance values that are several factors higher than what could be achieved with LEDs so far. In LED front projection systems, green LEDs are the main limiting factor. With our green modules, peak luminance values in the range of 1-1.5 Gnit have been achieved, enabling doubling of the screen brightness of LED based DLP projection systems, and even more when this technology is applied as well to the other colors. This light source concept, introduced as the ColorSpark High Lumen Density LED technology, enables a breakthrough in the performance of LED-based light engines not only for projection systems, but for a wide variety of high brightness applications.
The most potential lighting sources are InGaN/GaN light emitting diodes (LEDs), which are widely used in solid-state lighting, because of their high luminance efficiency and wide tuning range of the light emitting wavelength from ultraviolet to near infrared. However, one key issue for light emission strength of GaN-based LEDs is the high local defect density and strain in multiple quantum wells (MQWs) causing the electric polarization fields.

In this work, we construct 3D confocal microspectroscopy to clarify strain distribution and the relationship between the threading dislocation and the shape of pattern sapphire substrates (PSS). From the 3D reconstruction of axial E2high Raman intensity mapping, the origin of the V-shaped pits in MQW can be traced back to the tip of protruded patterns in PSS through threading dislocation. In order to analyze strain distribution above PSS, the depth resolved Raman spectrum measurement is also done at flat area, cone area and cone tip of PSS, separately. The difference in E2high Raman shift between substrate and surface at the PSS cone is twice as high as that at the flat area. The formation of threading dislocation and V-shaped pits is consistent with strain distribution. The ability to identify the strain evolution in 3D structure nondestructively makes the 3D confocal micro-Raman spectroscopy a potential technique to give a favor to optimize PSS structure and explore many important structural problems associated with GaN-based optoelectronic devices.

9768-37, Session 8

Progress in characterizing the multidimensional color quality properties of white LED light sources

Kees Teunissen, Christoph Hoelen, Philips Research (Netherlands)

With the introduction of solid state light sources, the variety in emission spectra is almost unlimited. However, the set of standardized parameters to characterize a white LED light source, such as CCT, CRI and LER, is limited and insufficient for describing perceived differences between light sources. Several characterization methods have been proposed over the past decades, but their applicability has not always been validated. To gain more insight in the relevant characteristics of the emission spectra for specific applications, we have conducted a perception experiment to rate the attractiveness of three sets of objects, including fresh food, packaging materials and skin tones. The objects were illuminated with seven different combinations of Red, Green, Blue, Amber and White LEDs, all with the same CCT and illumination level, but with differences in color fidelity (CRI) and color saturation. The results show that, on average, object attractiveness increases with increasing saturation for two out of three applications. However, there is no clear relation between saturation and skin tones attractiveness, partly due to differences in preference between males and females. A simple gamut area index, based on the CRI computation methodology, shows a high correlation with object attractiveness. A complementary color saturation index shows the direction and magnitude of the color differences for the eight CRI test-color samples. Together they provide useful information for designing preferred emission spectra. These measures have been proposed in CIE TCI-91 to be used for white LED light sources in conjunction with the general color rendering index (CRI).

9768-38, Session 8

Adaptive multi-wavelength LED star simulator for space life studies

Nicola Trivelin, LightCube SRL (Italy); Diego Barbisan, Univ. degli Studi di Padova (Italy); Marco S. Ercuriani, INAF - Osservatorio Astronomico di Padova (Italy) and Univ. degli Studi di Padova (Italy); Marco Ferretti, Univ. degli Studi di Padova (Italy); Riccardo U. Claudi, Enrico Giro, INAF - Osservatorio Astronomico di Padova (Italy); Matteo Bonato, Tufts Univ. (United States); Lorenzo Coccola, Luca Poletto, IFN-CNR LUXOR Lab. (Italy); Bernardo Salasnich, INAF - Osservatorio Astronomico di Padova (Italy); Matteo Meneghini, Gaudenzo Meneghesso, Enrico Zanoni, Univ. degli Studi di Padova (Italy) and Univ. degli Studi di Padova (Italy) and Univ. degli Studi di Padova (Italy); Marco S. Erculiani, INAF - Osservatorio Astronomico di Padova (Italy); Nicola Trivelin, LightCube SRL (Italy)

With this work we report on the design of an LED based star simulator which is the result of a cooperation between the Italian National Astrophysics Institute and LightCube SRL, a Padova University R&D spin-off. One of the most interesting open question in the extraterrestrial biological search for life is the study of the possible environmental conditions able to sustain bacterial activity: i) temperature, ii) atmosphere and iii) light. The light is the key in several biological mechanisms and depends on the spectrum and the distance from a star. The idea at basis of this design is the development of a system capable not only to match the emission spectrum of several standardized stars but to accurately generate a custom spectrum, for example as resulting from a partial absorption from the atmosphere. The simulator is designed to achieve a luminous output customizable both in spectrum and in intensity. The core of the system is a 24 channel independent LED illuminator specifically designed to replicate the spectral emission of the desired star. The spectral emission ranges from 365 nm to 940 nm and is able to simulate stars from B type (20000 K) to M type (3200 K). The simulated star light intensity can also be carefully tuned to achieve the correct illuminance at a specific distance from the star. An adaptive software has been designed to automatically duplicate the spectrum and intensity of a target star, while a calibrated micro-spectrometer provides an optical feedback to guarantee the emission accuracy.

9768-39, Session 9

InGaN-based orderly-arranged-nanocolumn light-emitters (Invited Paper)

Katsumi Kishino, Koji Yamano, Tatsuya Kano, Shunsuke Ishizawa, Kai Motoyama, Hiroaki Hayashi, Daishi Fukushima, Dajiro Shiba, Takao Otto, Sophia Univ. (Japan)

InGaN-based orderly arranged nanocolumns were fabricated on GaN/ sapphire and GaN/Si templates by Ti-mask selective area growth (SAG) by rf-MBE [1, 2]. In this talk, the recent activities on the orderly arranged nanocolumn system are described. That is, uniform arrays of GaN nanocolumns with the diameter less than 50 nm was prepared by Ti-mask SAG. Then the dislocation filtering effect as a function of nanocolumn diameter was systematically investigated. The Ti-mask SAG was employed to prepare InGaN/GaN nanocolumn arrays on Si using a thin sputter-deposited AlN nucleation layer to fabricate flip-chip type nanocolumn LEDs bonding on a supportive conductive CuW carrier. At the same time, a recently developed nano-template SAG technique [3] was utilized to grow InGaN/GaN nanocolumn arrays on the AlN/Si substrate patterned with a nanoimprint technology. The ordered arrangement of the nanocolumns leads the photonic crystal effect [4], based on which yellow-emitting nanocolumn LEDs with a directional radiation beam profile were prepared, followed by fabrications of blue, green, red and yellow (RGBY) photonic crystal nanocolumn LEDs. The monolithic integration of different emission color nanocolumn LEDs with directional radiation beams was demonstrated. This research was supported by JSPS KAKENHI Grant Number 24000013.

References:
Lateral thin-film photonic crystal phosphor structure for enhanced color-conversion efficiency

Kyungtaek Min, Hyunho Jung, Heonsu Jeon, Seoul National Univ. (Korea, Republic of)

The importance of color-converting phosphors has revived lately, as we witness it from the phosphor-capped white light-emitting diodes that had opened up the solid-state lighting business. Considerable efforts have been devoted to improve the luminous efficiency of phosphors, although most developmental works have focused on materials aspect. On the contrary, we have proposed structurally engineered phosphor?photonic crystal (PC) phosphors, to be more specific?as an alternative but new approach to improve the phosphor efficiency. Differing from our initial approach where a vertically stacked PC was employed, here we propose a thin-film lateral PC phosphor structure. Numerical simulations based on finite-difference time-domain method show that the absorbance of pump photons by the lateral PC phosphor can be greatly enhanced when pump photon energy is tuned to a 7-point band-edge mode where the lateral photon momentum becomes zero. A one-dimensional lateral PC backbone structure is fabricated first into a high index Si3N4 thin film deposited on top of quartz substrate, which is followed by spin-coating of phosphor material to infiltrate the void regions of the PC backbone. Laser interference lithography technique is used to generate large-area lateral PC patterns, while CdSe/ZnS-based colloidal quantum dots serve as phosphor material. Photoluminescence excitation experiments are performed to characterize the properties of the fabricated PC phosphor as a function of pump wavelength. We have observed that, when the pump photon energy is resonant to the 7-point band-edge mode, phosphor emission intensity is enhanced 4 times that of the reference phosphor having no internal structure.

Plasmon-coupled CdSe quantum dots for solid-state lighting

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The optical properties of plasmon-coupled CdSe quantum dots (QDs) were revisited for solid-state lighting application of white light-emitting-diodes (LEDs). It is well known that CdSe QDs with sizes near the bulk Bohr radius have wide optical tunability, high color purity, and strong blue-shift of bandgap due to the quantum confinement. The CdSe QDs with sizes less than 2 nm displayed both emission spectra from bandedge and surface-trapped states. The bandedge PL has high color purity and size-dependent optical spectrum. The PL from the surface-trapped state is due to the crystal irregularity and dangling atoms on the surface and has the broad spectral distribution. The plasmon-exciton coupling through Coulomb interaction and the strong local field enhance the spontaneous emissions from the bandedge and surface-trapped state of QDs. The temperature-dependent PL studies revealed 18-fold and 7-fold PL enhancements at bandedge and surface-trapped states of uncoupled QDs at 6 K in comparison with the PLs at 300 K. It indicates the large reduction of thermal transition from the surface-trapped states to the bandedge and additional reduction of non-radiative decays at low temperature. The large PL enhancement through plasmon-exciton coupling with strong local field, and the spectral combination of blue LED excitation, intermediate spectrum from bandedge transition, and broad spectral distribution of surface trapped state enable the high-quality solid-state lighting for hybrid white LEDs.

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Near-infrared light source composed of nitride-based light-emitting diode and Pr3+-doped glass phosphor

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Currently, a GaAs-based near-infrared light-emitting diode (LED) is used as a light source of a mobile saccharimeter, which measures a sugar content in farm products based on the near-infrared spectroscopy. However, due to its narrow spectral bandwidth, measurement accuracy of the existing saccharimeter is not sufficient. Broad spectrum near-infrared light sources are greatly demanded in the application. The light source composed of a nitride-based LED and Pr3+-doped glass phosphor, can provide such spectrum with an emission wavelength ranging from 900 nm to 1100 nm, so that it is attractive for accurate saccharimeter application. In this paper, performance of the near-infrared light source is presented. We initially fabricated a near-infrared light source composed of a nitride-based 480 nm LED with a die size of 1.09 mm2 and glass phosphor rod with a radius and length of 3 mm and 10 mm, respectively. The device exhibited a near-infrared output power of 100 µW at a forward current of 350 mA, and a broad emission spectrum ranging from 840 nm to 930 nm. Further investigations such as shapes of the glass phosphor and coagulating conditions will be discussed in the presentation.

State of the art process control of MOCVD growth for LEDs and other devices (Invited Paper)

Kolja Haberland, LayTec AG (Germany)

Developing and manufacturing of LED structures is still driven by the need of production cost reduction and performance improvements. Therefore in-situ monitoring during the epitaxial process plays a key role in the constant process of yield improvement and process optimization. With the continuing trend towards larger wafers (up to 300mm) stronger bow and increased aspherical curvatures are additional challenges the growers have to face. As the industry starts to look at new LED wavelengths ranges such as UV, new challenges arise as new substrate materials (nano-PSS or AI) and different buffer layers (AlGaN) are used. In this talk we will review the current status of in-situ monitoring for visible and UV LEDs and present new and improved in-situ monitoring techniques, providing solution for the challenges mentioned above. This includes multiple-head curvature monitoring systems, improved pyrometers, as well as in-situ photoluminescence measurements. In addition the industry clearly moves towards feed-back loops for control of the wafer temperature and other measured parameters. So the in-situ metrology must be prepared to take the step from in-situ monitoring to in-situ control. Therefore during-run data analysis and real-time connectivity with fab-wide used advanced process control (APC) systems and statistical process control (SPC) systems is a new demand. In his talk we will show examples how closed-loop control can be realized.
and how data are provided into manufacturing execution (MES) and equipment engineering (EES) systems. We will also introduce LayTec’s “open analysis concept” that allows to use identical but user-specific analysis schemes for different types of growth systems within an LED fab.

9768-44, Session 10

Blue LED manufacturing optimization based on a MOCVD growth parameter sensitivity study
E. Sakalauskas, X. Chen, O. Feron, H. Behmenburg, R. Leiers, Markus Luenenbuerger, P. Lauffer, A. R. Boyd, J. Lindner, Michael Heuken, AIXTRON SE (Germany)

A growth parameter sensitivity study enabled recent developments and improvements in the Close Coupled Showerhead® MOCVD tool design to facilitate further reduction of the LED production costs. Based on a sensitivity study of key parameters the uniformity of LED structures is improved. The most important dependencies such as LED wavelength dependence on surface temperature, ammonia flow, group II molar flow, total flow and total pressure was experimentally determined for a state of the art production reactor. These data serve as input to simulate, understand and finally improve the uniformity and performance of LED produced. The measured dependencies and the equipment optimizations result in wavelength uniformity of full susceptor load consisting of 4” DPSS wafers of 91.8% for a 6”m bin yield centred at 443nm.

In a multi growth campaign utilizing 5 runs with 4 inch DPSS wafer loaded the run to run wavelength stability was assessed. The temperature was controlled using LayTec Inside TCT measuring on the graphite between the wafers for all 4 heater zones and automatically correcting the setpoint for the QWs using LayTec P400 400nm pyrometry. RZR wavelength std dev. of 0.23 nm was observed in AIXTRON lab for this series indicating <0.2°C std dev. in average QW temperature. Details and physical background of MOCVD equipment improvements as well as LED process optimizations will be reported and discussed.

9768-45, Session 10

Enhanced optical layers for LED manufacturing using pulsed laser deposition production equipment
Matthijn Dekkers, SolMatS B.V. (Netherlands)

Pulsed Laser Deposition (PLD) is a flexible and versatile technique allowing fast optimization of thin film materials. PLD is superior above other technologies for the deposition of ultra-dense or highly porous oxide films. Because of this unique feature PLD allows for the density control of optical layers. The refractive index of materials can therefore be tuned, or a refractive index grading in the optical layers can be applied. In combination with low temperature processing and damage-free deposition, it makes the technique highly suitable to be used for LED manufacturing. Mainly because of the sample size in conventional PLD tools the technology is considered to be useful only for research. In order for PLD processes to make it into commercial applications, next generation PLD equipment is needed. With the SIP platform Solmates demonstrates that PLD has now reached the maturity level of High Volume Manufacturing. This next generation deposition system is suitable for development and (pilot-) production purposes Equipped with automated wafer handling it offers high run-to-run consistency at commercial throughput and yield in the LED segment.

In this contribution the performance and specifications of the PLD production platform are addressed. Data on stability and reproducibility of wafer level deposition of optical layers with excellent properties will be presented. Furthermore application examples, of which some are close to pilot-production, will be discussed:

• ITO damage free deposition enabling fully transparent OLEDs
• High quality ITO processed at low temperatures, without annealing
• Refractive index tuning and grading for LED efficiency enhancement

9768-46, Session 10

Significant Improvement of GaN crystal quality with ex-situ Sputtered AlN nucleation layers
Shuo-Wei Chen, National Chiao Tung Univ. (Taiwan) and Epistar Corp. (Taiwan); Young Yang, Wei-Chih Wen, Epistar Corp. (Taiwan); Heng Li, Department of Photonics & Institute of Electro-Optical Engineering, National Chiao Tung University (Taiwan); Tien-Chang Lu, National Chiao Tung Univ. (Taiwan)

We have investigated the crystal structural and electro-optical characteristics of GaN based LEDs with an ex-situ sputtered AlN nucleation layer on pattern sapphire substrates (PSS). The AlN nucleation layer was firstly deposited on PSS by sputtering followed by the normal GaN template growth using metal-organic chemical vapour deposition (MOCVD). In comparison to the conventional in-situ low-temperature (LT) GaN nucleation layer, crystal quality of GaN templates has been significantly improved by growing on AlN nucleation layer. The X-ray (102) FWHM was improved from 240 to 110 arcsec and (002) FWHM was improved from 230 to 101 arcsec, respectively. Lower threading dislocation density can be observed through transmission electron microscopy (TEM) cross section images. In addition, TEM plane view images also revealed that screw defect density was dramatically reduced compared with GaN layers growing on LT-GaN nucleation layers. Moreover, the increase of reverse-bias voltage was more than 17%–45%, indicating that leakage current was also reduced around 30% due to the better crystal quality. Most important of all, GaN based LEDs with ex-situ sputtered AlN nucleation layer possessed higher output power with 6.5% enhancement than LEDs with conventional LT-GaN nucleation layer. In terms of cost-effective mass production, we can expect that the ex-situ sputtered AlN nucleation layer would be a novel technology that would revolutionize excellent nitride-based device development.

9768-64, Session 10

Aging behavior, reliability and failure physics of GaN-based opto-electronic components (Invited Paper)
Enrico Zanoni, Matteo Meneghini, Gaudenzio Meneghesso, Univ. degli Studi di Padova (Italy)

GaN-based LEDs are finding wide application in several fields, including general and industrial lighting, automotive, and biomedical lighting. These applications require high reliability (lifetime > 50000 h), and long-term stability of the luminous output. Several reports indicated that high power LEDs may suffer from premature degradation, either due to gradual or sudden failure mechanisms. This paper reviews the physical mechanisms responsible for the degradation of GaN-based high efficiency LEDs, by reporting our latest results. More specifically, we will discuss in detail the following: (i) Degradation of the active layer of the devices, due to the generation of non-radiative defects and to the creation of shunt paths through the junction; (ii) Degradation of the phosphor-package system, with consequent worsening of the chromatic properties of the LEDs; (iii) Sudden failure due to electrostatic discharges and electrical overstress. The presented results are critically compared with the most recent literature on GaN LED reliability, with the aim of providing a clear understanding of the topic.
Semipolar GaN on patterned-sapphire substrates: towards exploitable LED substrates (Invited Paper)

Jesus Zuniga-Perez, Lars Kappei, Philippe De Miery, Florian Tendille, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France); Maxim Korytov, Nikolay Cherkashin, Ctr. d'Elaboration de Matériaux et d'Etudes Structurales (France); Philippe Vennéguès, Mathieu Leroux, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France)

While semipolar GaN bulk substrates exist and display structural properties as good as those of polar substrates (indeed they are often sliced from large GaN boules grown along the c-axis), their current small size and relatively-high prices limit their use to fundamental research. Thus, to move semipolar orientations a step forward and bring them closer to industrial applications, heteroepitaxial growth of semipolar GaN templates seems to be necessary. In this contribution we will address the fabrication of heteroepitaxial semipolar GaN templates on patterned sapphire substrates and their subsequent use as templates for the growth of InGaN/GaN LEDs. First we will describe the general fabrication strategy: this consists in patterning the sapphire substrate of the appropriate orientation and revealing c-planes on which the GaN growth will occur along the c direction. Subsequently, the c-oriented crystals are brought to coalescence leading to a compact semipolar layer. Several growth strategies enabling to reduce the overall defect density have been implemented resulting in semipolar GaN templates with dislocation densities in the high 10^7 cm^-2 and basal stacking faults in the order of 100 cm^-1. The defect-reduction mechanisms will be illustrated by means of CL and TEM studies. Finally, MQWs and LEDs structures spanning the emission range from about 450 nm up to 550 nm have been grown. Their structural and optical properties will be described and compared to other semipolar or polar devices emitting at the same wavelengths.

Development of semipolar (11-22) LEDs on GaN templates (Invited Paper)

Brian Corbett, Zhiheng Quan, Duc V. Dinh, Donagh O’Mahony, Tyndall National Institute (Ireland) and Univ. College Cork (Ireland); GregorZ Kozlowski, Mahbub Akhter, Peter Parbrook, Tyndall National Institute, University College Cork (Ireland); Pleun Maaskant, Tyndall National Institute (Ireland) and Univ. College Cork (Ireland); Marian Caliebe, Univ. Ulm (Germany); Stefan Schulz, Tyndall National Institute, University College Cork (Ireland); Matthias Hacker, Institute of Optoelectronics, Ulm University (Germany); Yisong Han, Univ. of Cambridge (United Kingdom); Klaus Thonke, Univ. Ulm (Germany); Ferdinand Scholz, Univ. Ulm (Germany); Markus Pristovsek, Colin J. Humphreys, Univ. of Cambridge (United Kingdom); Frank Brunner, Markus Weyers, Ferdinand-Braun-Institut (Germany); Tobias M. Meyer, OSRAM Opto Semiconductors GmbH (Germany); Liverios Lymerakis, Max-Planck-Institut für Eisenforschung GmbH (Germany)

We report on blue and green-emitting LEDs on (11-22) templates created by overgrowth of GaN on structured r-plane sapphire substrates under the European Union funded ALIGHT project. Low defect density, 100 mm diameter GaN templates were obtained by MOVPE and HVPE techniques. Chemical-Mechanical polishing was used to obtain smooth surfaces for the subsequent growth of LED structures. Excellent ohmic contacts to the p-type GaN were obtained. The LEDs show excellent output power in addition to polarized emission and faster dynamics than c-plane LEDs. Freestanding LEDs have been obtained by use of laser-lift-off.

Semipolar GaN on patterned-sapphire substrates: towards exploitable LED substrates (Invited Paper)

Sarah Schlichting, Christian Nenstiel, Felix Nippert, Technische Univ. Berlin (Germany); Nikolay N. Ledentsov, Vitaly A. Shchukin, VI Systems GmbH (Germany); Jari Lytytikäinen, Oleg G. Okhotnikov, Tampere Univ. of Technology (Finland); Yuri M. Sherenyakov, Alexey S. Payusov, Nikita Y. Gordeev, Mikhail V. Maximov, Ioffe Physical-Technical Institute (Russian Federation); Axel Hoffmann, Technische Univ. Berlin (Germany)

\[ (Al0.5Ga0.5)0.5In0.5P-(Al0.8Ga0.2)0.5In0.5P layers and light-emitting diodes (LED) with GaP barriers were investigated by means of electroluminescence (EL), photoluminescence (PL) and photoluminescence excitation (PLE) spectroscopy. The structures were grown by molecular beam epitaxy side-by-side on (100), (211)A and (311)A GaAs substrates. PL and EL studies were performed at low temperature to understand the reason of significantly higher electroluminescence efficiency for the structures grown on surfaces strongly tilted towards the <111> direction. We observe that PL at low temperatures is dominated by the indirect gap transitions between the holes at the point of the Brillouin zone for the valence band and electrons at the X point of the conduction band, which are allowed at low temperature due to the alloy disorder. We see that structures grown on surfaces inclined towards the <111> direction show a significant shift of the bandgap energy towards higher energies as compared to (100) surface. The point transition energies are revealed as 2.355 eV for (100); 2.355 eV for (311) and 2.360 eV for (211) substrate orientations. Even more important, the Stokes shift between the X PL maximum and the? exciton-like enhancement in the PLE spectrum of the structures diminishes for higher substrate tilt angles as compared to the (100) surface: 58 meV (100); 50 meV (311) and 45 meV for the (211) substrate orientations. This brings the? point into the resonance with the X minimum for high-index surfaces.

Room temperature green to red electroluminescence from (Al,Ga)As/GaP QDs and QWs

Christian Golz, Shabnam Dadgostar, W. Ted Masselink, Fariba Hatami, Humboldt-Univers. zu Berlin (Germany)

Monolithic integration of III-V light emitters with silicon is an ambitious goal for decades. Among the III-V compounds, GaP has the smallest lattice mismatch to Si. GaP is used conventionally in manufacturing low-cost green to orange LEDs. GaP has however similar to Si, an indirect bandgap and useful light emission from it is possible by doping which results in low efficiency. The challenge of high efficiency light emitters has recently been approached by exploring the use of epitaxial quantum structures embedded in GaP. Here we present the growth, fabrication, and characterization of the LEDs based on (Al,Ga)As QWs and QDs embedded in a p-n GaP structure. The structures were grown on Sulphur-doped GaP(001) substrate using gas-source MBE. The nominal coverage of the (Al,Ga)As was varied between 1.2 and 5.4 monolayers (ML). For structures with (Al,Ga)As layer thicker than the critical 2D-3D transition (1.7 ML), the 3.6% lattice mismatch in the materials system results in formation of defect-free QDs via Stranski-Krastanow growth mode. The optical emission was characterized using...
photoluminescence, cathodoluminescence and electroluminescence spectroscopy. In order to carry out the electroluminescence measurements the mesa-structures of 300 and 500 µm diameter were fabricated by photolithography and wet etching. The structures based on GaAs/GaP QDs show optical emission between 1.8 eV and 2 eV, whereas the (Al,Ga)As quantum structures emit light in the range between 2 eV and 2.2 eV. The structures containing GaAs layer thicker than 2.7 ML and (Al,Ga)As emit light up to room temperature.

9768-51, Session 11

Red InGaP light-emitting diodes epitaxially grown on engineered Ge-on-Si substrates

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The integration of light emitting functions on silicon substrates has attracted intensive research in recent years. In contrast to the InGaP light emitting diodes (LEDs) whose epitaxy technology on Si substrates is robust and mature, the epitaxy of other compound semiconductor light emitting materials covering the visible wavelength range on Si is still challenging. We have studied epitaxial growth of InGaP materials on engineered Si substrates covering red and yellow-green colors. Two kinds of substrates have been evaluated: Ge-on-Si (GOS) and compositional-graded SiGe alloys on Si. The GOS was grown on 8° Si substrate in a metal organic chemical vapour deposition (MOCVD) reactor using two-step growth and cycling annealing. Threading dislocation density (TDD) was as low as 10^6/cm². GaAs buffer layer and lattice-matched InGaP red LEDs were then grown on GOS sequentially in the same MOCVD process. Reference samples were grown on Ge and GaAs substrates. The LED grown on GOS has comparable performance with the LED on GaAs substrate and slightly better than the LED on Ge substrate. The SiGe/Si substrate whose final SiGe composition is 71% Ge was obtained via two separated compositional grading growths on 6° Si substrate followed by two chemical mechanical polishing (CMP) processing. Lattice matched GaAsP buffer layer was grown on the SiGe buffer followed by n-InAlP, undoped InGaP, and p-InAlP layers. The fabricated LED has light emission at 592 nm. The current-voltage curve shows the device is series resistance limited and improvements are on the way.

9768-52, Session 11

AlGaInP red-emitting light emitting diode under extremely high pulsed pumping

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Efficiency of commercial 620 nm InAlGaP Golden Dragon-cased high-power LEDs has been studied under extremely high pump current density up to 4.5 kA/cm² and pulse duration from microsecond to nanosecond range. At short-pulsed pumping of 1 ns and duty cycles well below 1%, no efficiency decrease in the whole range of drive currents and a very low, < 1.45 kA/cm² and pulse duration from microsecond down to sub-nanosecond range. At short-pulsed pumping of 1 ns and duty cycles well below 1%, no efficiency decrease in the whole range of drive currents and a very low, < 1
passive techniques decrease the amplitude of the reflected laser pulses and decreasing signal to noise ratio (SNR). Active jamming techniques deceive and puzzle laser receivers. A phase shifted high energy pulse is transmitted with each reflected pulse that distort or change the signal information. Active jammers need higher energy pulses to provide high jammer to signal ratio (JSR). High power pulsed laser source operating at 1064 nm, energy per pulse of 80 mJ, pulse width of 200 μs and repetition rate ranges from 10-20 Hz has been used. The amplitude of the scattered laser pulse is reduced by a factor of 90% compared to the incident pulses using an absorptive material, at the same time an electronic circuit receives the laser pulses to trigger high-power LEDs operating at the same wavelength that make phase shift and signal distortion to the received pulses. The transmitted and reflected signals are measured and processed using matching filter and compared using cross-correlation algorithm in cases of: passive, active and passive-active techniques. The results show that the passive-active technique is best and optimum to solve the disadvantages of passive and active techniques have been used individually. Due to the decrease of SNR, higher JSR can be obtained with lower power sources and increases the complexity for the digital signal processing (DSP) based systems.

9768-55, Poster Session

Do we need to re-calibrate our strategy in InGaN-on-SiC LED technology given its low efficiency?

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Although performance of LEDs has been raised dramatically, the achievements are not as significant as they could be. Wall-plug efficiency of commercial large-area (> 1 mm²) high-power LEDs operating at 1 > 1A hardly surpasses 20%. Big efforts have been on increasing optical efficiency, which suffers from nonradiative recombination processes and appears as one of two components of WPE. In sharp contrast to that advance, we put forward an alternative approach to make high-power LEDs more efficient. We are concerned about electrical efficiency (second WPE component) by considering inevitable electrical losses paid for carrying electrons over a device with finite series resistance into the active region prior to their recombination. We show experimentally that due to the inherent limitation imposed by the current crowding effect, the figures of merit to give attention to should be series resistance, ideality factor, current spreading length, chip size, and threshold voltage. We introduce the rule of thumb for ad hoc estimating LED performance. Looking forward, this information could help low-voltage high-current single chip LEDs hold ground in their competition against high-voltage low-current multiple chip LEDs.

Theoretical simulations of GaN-based tunnel-junction light-emitting diodes

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For wide-bandgap III-nitride material systems, the interband tunneling is originally believed to be inefficient due mainly to the high potential barrier heights. However, the great polarization effect in wurtzite III-nitride materials provides a new design approach for tunneling structures. With the supplement of polarization-induced electrostatic field, the insufficient band-bending from doping-induced normal built-in field can be largely strengthened supposing that the two fields are designed to be with the same direction. In solar cells, efficient tunnel junction for electrically connecting p-n junction sub-cells is fundamentally required. As for the nitride light-emitting diodes (LEDs), the employment of tunnel junctions can further extend the LED applications and/or provide the alternative ways to enhance the device performance, e.g., the InGaN tunnel-junction LEDs have been proposed to avoid driving LEDs under degraded efficiency in high current density [1-3]. In this study, the GaN-based tunnel junctions and GaN-based tunnel-junction LEDs are investigated theoretically in a finite element approach. Specifically, the tunnel-junction LED structures for various applications will be explored and suggested by energy band engineering. Furthermore, detailed characterization of the designed structures will be performed systematically.


Improved performance of AlGaN-based ultraviolet light-emitting diodes with conducting filament-embedded AlN/ITO hybrid electrodes

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Ultraviolet light-emitting diodes (UV-LEDs) are promising candidates for conventional UV lamp replacements and sanitary light sources for sterilization. However, its external quantum efficiency should be increased by developing UV-transparent/reflective ohmic electrodes as well as improving the quality of AlGaN-based epitaxial layers for UV emission. However, it is difficult to find such electrodes because UV-LEDs requires highly resistive p-AlGaN layers with a large work function value. As a possible solution, we have developed conducting filament (CF)-embedded wide-bandgap transparent conductive electrodes (TCEs) using electrical breakdown (EBD).

In this study, we applied this method to four different types of (Al)GaN LEDs (450 nm, 385 nm with p-GaN/p-AlGaN terminated surfaces, 365 nm with p-AlGaN terminated surface) using AlN, and compared each LED with reference ITO-LED to confirm the validity of the method in the lateral structures. To reduce the electrical shock at the p-(Al)GaN surface during the EBD process, metal dot array was fabricated in 10-nm-thick AlN rods to form localized CFs, and then 60-nm-thick ITO overlay was deposited before metal-pad deposition to improve the current spreading effect. Consequently, the light-output powers were increased by 12%, 65%, 78%, and 75% and the forward voltages were reduced by 3%, 6%, 10%, and 8% for 450 nm, 385 nm p-GaN terminated, 385 nm p-AlGaN terminated, 365 nm p-AlGaN terminated LEDs with AlN TCEs when compared to that of the reference ITO-LED in each case.

Growth and photoluminescence properties of Au- or N-doped iron disilicide

Kensuke Akiyama, Kanagawa Industrial Technology Ctr. (Japan); Hiroshi Funakubo, Tokyo Institute of Technology (Japan)

Semiconducting iron disilicide (FeSi2) has attracted much attention over the past ten years as one of the promising materials for fabricating infrared optoelectronic devices. It emits light of about 1.55 μm suitable for silica optical fiber communications. This is because FeSi2 has a band gap of approximately 0.80 eV and ability of epitaxially growth on Si substrates.
These properties of this semiconducting material have been expected for a development of emitting device on Si substrates. Moreover, this material is considered to be an environmentally friendly semiconductor since both Si and Fe are nontoxic and occurs abundantly in the Earth’s crust. Light-emitting diodes (LED) using ?-FeSi2 active-layer showed the emission efficiency of about 0.1%. It is suggested that the control of the transition type in energy band gap is essential for the improvement of its emission efficiency.

In this study, we report a pronounced enhancement in intensity of photoluminescence (PL) spectrum and observation of PL at room temperature by doping gold (Au) or nitrogen (N) atoms in ?-FeSi2 films grown on Si wafers by metal-organic chemical vapor deposition (MOCVD) method.

A clear PL spectrum for ?-FeSi2 was observed by Au-coating on the surface of Si. High-crystal-quality ?-FeSi2 with a low-level non-radiative center was formed on the treated Si by Au. Moreover, it is considered that the Au or N atoms in ?-FeSi2 modulate the transition type in energy band gap. This high quality ?-FeSi2 opens the door for the real applications of the LED using ?-FeSi2 active-layer.

9768-60, Poster Session

Modeling of novel hybrid photonic crystal structures involving cured hydrogen silsesquioxane pillars for improving the light extraction in light-emitting diodes

Anand Kadiyala, Jeremy M. Dawson, West Virginia Univ. (United States)

The Solid-State Lighting (SSL) industry utilizes semiconductor based light emitting diodes (LEDs) as core elements of light sources. LED lighting has several advantages over conventional incandescent bulbs, however, device-level issues such as material quality, low quantum efficiencies, and low light extraction efficiencies etc. still exist. Many techniques have been explored to provide improvement in the area of LED light extraction. Improvement in light extraction efficiency, through the use of integrated optical components such as photonic crystals, is critical for the improvement in the overall efficiency of the device. Fabrication and integration of PhCs into LEDs with little or no degradation in device’s electrical characteristics is an important accomplishment to be considered. Use of electron beam lithography and novel electron beam resists like hydrogen silsesquioxane will allow advancements towards achieving this goal. The unique chemical properties of HSQ allows transformation of the patterned resist into silicon dioxide. This leads to a hybrid PhC structures that contain the cured form of HSQ and other materials of interest in an LED. In this work, novel hybrid PhC structures in square and triangular lattice configurations will be modeled to improve light extraction in blue InGaN/GaN based LEDs (?=465 nm) and attain an optimal structure. Feature sizes from 100 nm to 465 nm will be modeled and the effect of the patterned structure (band gap and/or diffraction) on the light extraction will be studied and analyzed. Simulation data from frequency domain and time domain engines in MPB and OptiFDTD respectively will be analyzed and presented.

9768-61, Poster Session

Defect-mediated Purcell enhancement of plasmon-coupled CuInS2 and CuInS2/ZnS

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Plasmon-coupled CuInS2 (CIS) and CuInS2/ZnS (CIS/ZnS) quantum dots (QDs) are of great interest in developing hybrid white light-emitting-diodes (LEDs) because of the large enhancement of spontaneous emission and the spectral combination of the blue LED excitation and the broad photoluminescence of CIS and CIS/ZnS. The broad spectral distribution of CIS and CIS/ZnS is due to the energy transitions from the surface-/interface-, shallow-, and deep-trapped states and the morphology distribution of QDs. The large enhancement of spontaneous emission of CIS and CIS/ZnS is attributable to the strong local field and Purcell enhancement. The optical studies of plasmon-coupled excitons at the surface-/interface-, shallow-, and deep-trapped states of CIS with and without ZnS shell revealed defect-mediated Purcell enhancement. The Purcell enhancement of plasmon-coupled CIS QDs were two to three-fold compared to the decay rates of CIS, and those of plasmon-coupled CIS/ZnS QDs were twenty to thirty-fold compared to the decay rates of CIS/ZnS at shorter, intermediate, and longer spectral regions. The temperature-resolved PL enhancements of plasmon-coupled CIS at room temperature and 6 K were two-fold and three-fold compared to the integrated CIS PLs while the PL enhancements of plasmon-coupled CIS/ZnS at room temperature and 6 K were five-fold and eight-fold compared to the integrated CIS/ZnS PLs. The larger PL enhancement of plasmon-coupled CIS/ZnS compared to that of plasmon-coupled CIS is accredited to the larger Purcell enhancement. The large enhancement of spontaneous emission and the spectral combination of the blue LED excitation and the broad PLs from CIS and CIS/ZnS lead to the realization of hybrid white LEDs. Acknowledgement: This work at HU is supported by NSF HRD-1137747 and ARO W911NF-11-1-0177.

9768-62, Poster Session

Interfacial coatings and glass modification for highly luminescent phosphor glass composite plates in white LEDs

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Much attention has been focused on the color conversion phosphor plates based on phosphor particles and glass matrices due to their superior stability against temperature and better thermal conductivity derived from the glass over phosphor-resin composites in white LEDs. The phosphor-in-glass (PiG) plates are typically prepared by sintering the mixture of phosphor particles and glass frits at the moderate temperature (<1000°). Sometimes, reaction between phosphors and glass matrix during sintering stage can degrade the luminescence of PiG. In particular, a non-oxide phosphor shows a significant instability. In this study, we developed a surface passivation route to prevent interfacial reaction between phosphors and glass frits. Via surface-induced coating of inert oxide layers, a successful passivation of phosphor particles and resultant enhanced luminescence of color converting PiG plates are demonstrated as a result of surface modification of refractive indices. Also, we presents enhanced inhomogeneity of glass and resultant increase in light emission properties. Incorporating macroscopic oxide particles during preparation of PiG enhanced the compositional inhomogeneity of glass and the color conversion efficiency was greatly improved.
9769-1, Session 1

**Fast and ultrafast all-optical control of light in nematic and smectic-A liquid crystals (Keynote Presentation)**

Igor Mu?evi?, Marusa Vitek, Jo?ef Stefan Institute (Slovenia); Laura Cattaneo, Matteo Savoini, Alexey Kimel, Theo Rasing, Radboud University (Netherlands)

Liquid crystals are superior optical materials for large area displays, but it is considered that their collective and slow-millisecond response makes them useless for ultrafast optical applications. In contrast to that, we propose and demonstrate two different strategies to push the optical response of a nematic liquid crystal in the gigahertz and terahertz range. The first approach is based on the optical Kerr effect in the nematic liquid crystal, which is induced by an intense femtosecond optical impulse. We show that the refractive index of the nematic liquid crystal pentyl-cyanobiphenyl can be modulated at a time scale as fast as 500 fs via a coherently excited optical Kerr effect. The change in the refractive index is in the order of 10⁻⁴ at a fluence of 4 mJ/cm² and is strongly polarization dependent. The second approach is based on Stimulated Emission Depletion (STED) from dye molecules, which are collectively ordered in a host liquid crystal. We demonstrate by temporal tuning of STED that it is possible to generate an arbitrary sequence of nanosecond fluorescent pulses with variable width and variable delay in a nematic liquid crystal. Our results show that the optical Kerr effect and STED mechanism in principle allows for very fast (THz and GHz) and efficient control of light by light, which could in the future be used for all-optical control of the flow of light in photonic microdevices based on liquid crystals.

9769-2, Session 1

**Smart optical vortex coronagraphy from liquid crystal defects (Invited Paper)**

Etienne Brasselet, Artur Aleksanyan, Univ. Bordeaux 1 (France)

During the last few years, liquid crystal topological defects have been unveiled as very effective optical elements that enable topological shaping of the light. In contrast to artificially structured singular optical elements produced for instance by liquid crystal photo-alignment or lithographic techniques, the use of natural liquid crystal defects does not require any machining step. We propose to use such self-engineered topological phase masks for optical vortex coronagraphy. Optical vortex coronagraphy allows the observation of dim objects nearby a bright source of light by use of an appropriately chosen vortex phase mask acting as an efficient angular filter. Since its introduction, its successful experimental implementation has been reported both in laboratory and real conditions. Here we report on the first-time experimental demonstration of optical vortex coronagraphy based on liquid crystal topological defects. The figure of merits of our approach will be reviewed and discussed.

9769-3, Session 1

**Plasmonic color tuning (Invited Paper)**

Byoungho Lee, Hansik Yun, Seung-Yeol Lee, Seoul National Univ. (Korea, Republic of); Hwi Kim, Korea Univ. Sejong Campus (Korea, Republic of)

In general, color filter is an optical component to permit the transmission of a specific color in cameras, displays, and microscopes. Each filter has its own unchangeable color because it is made by chemical materials, such as dyes and pigments. Therefore, in order to express various colorful images in a display, one pixel should have three sub-pixels of red, green, and blue colors. Here, we suggest new plasmonic structure and method to change the color in a single pixel. It is comprised of a cavity and a metal nanoparticle. The optical cavity generally supports standing waves inside it, and various standing waves having different wavelengths can be confined together in one cavity. On the other hands, although light cannot transmit sub-wavelength sized aperture, surface plasmons can propagate through the metal nanoparticle with high intensity due to the extraordinary transmission. If we combine the two structures, we can organize the spatial distribution of amplitudes according to wavelength of various standing waves using the cavity, and we can extract a light with specific wavelength and amplitude using the nanoparticle. Therefore, this cavity-aperture structure can simultaneously tune the color and intensity of the transmitted light through the single nanoparticle. We expect that the cavity-apertures have a potential for dynamic color pixels, micro-imaging system, and multiplexed sensors.

9769-4, Session 1

**Application of resonant soft x-ray scattering at carbon edge in liquid crystals**

Chenhui Zhu, Anthony Young, Cheng Wang, Alexander Hexemer, Lawrence Berkeley National Lab. (United States); David Walba, Noel Clark, Univ. of Colorado at Boulder (United States); Quan Li, Oleg D. Lavrentovich, Liquid Crystal Institute (United States)

Liquid crystals (LCs) form many interesting nano-scale structures, many of which can be probed with X-ray scattering techniques, such as layering in smectics, hexagonal packing of cylinders in discotics, and layer modulation/undulation in bent-core smectics (e.g. B7 phase [1], SmAPFmod phase[2]). Typically hard X-rays are used due to its high penetrating power. However, in the hard X-ray regime, the scattering contrast of some LC nanostructures can be extremely low due to their weak electron density modulation. Here we present several case studies where the scattering contrast can be dramatically improved by tuning the x-ray energy to carbon K-edge (~ 284 eV). At resonance, the scattering cross section increases by orders of magnitude. More importantly, bond orientation sensitivity can be achieved with linearly polarized soft X-rays, thus enabling the visualization of novel structures, which may be purely from orientation variation, such as the helical nanofilament phase [3] in the bent-core B4, the twist grain boundary (TGB) smectic phase, and the newly discovered twist bend nematic phase [4,5]. The technique has a great potential in characterizing liquid crystal structures in both nano- and meso-scale, e.g. blue phase, clock phases [6], etc.

phase I and II have been performed by means of transmission electron microscopy applied to sub-micron structures not limited to BPs. Real-space observation of the structures of cholesteric blue phases (BPs) by optical means is a challenge because typical lattice constants of BPs are of the order of or smaller than the wavelength of visible light. Nevertheless, Kikuchi and co-workers succeeded in obtaining real-space images of bulk BPs using confocal microscopy that are consistent with the symmetries of the underlying structures of bulk BPs. Their observations did not rely on fluorescent dye but the structural color of BPs. However, theoretical interpretation of the experimental confocal microscope images (for example, understanding the relation between the intensity distribution in the images and the ordering of BPs) remains challenging; geometrical optics commonly used to explain the principle of confocal microscopy is entirely useless in our problem. In this work, we present our numerical approach to calculate the confocal images of BPs by solving the Maxwell equations for the propagation and reflection of light. To be more specific, we calculate the responses of a thick (but not infinitely thick) sample of BPs to incident light with different incident directions, and from the reflecting light we construct the confocal images with given focal depths. We present the calculated two-dimensional confocal microscope images for different orientations of bulk BPs, and also the intensity variations along the depth directions. Many of the calculation results are consistent with the experimental observations. Our approach will facilitate the understanding of the principle of confocal microscopy applied to sub-micron structures not limited to BPs.

Blue phase liquid crystals (BPLCs) are self-assembled 3D photonic crystals that are based on the periodic variation of physical properties within the periodic superstructures. Complex birefringent liquid crystalline fluids allow for creation or self-assembly of photonic crystals that are based on the periodic variation of physical properties within the periodic superstructures. Photonic band-gap manipulation of blue phase liquid crystal (Invited Paper)

Tsung-Hsien Lin, National Sun Yat-Sen Univ. (Taiwan)

Blue phase liquid crystals (BPLCs) are self-assembled 3D photonic crystals exhibiting high susceptibility to external stimuli. Two approaches for the photonic bandgap tuning of BPs were developed. Introducing a chiral azobenzene into a cholesteric liquid crystal could formulate a photosresponsive BPLC. Ultrawide tuning of the BP photonic bandgap from ultraviolet to near infrared has been achieved. The tuning is reversible and nonvolatile. We will then report on the electric field-induced bandgap tuning in polymer-stabilized BPLCs. Under different film conditions, both red-shift and broadening of the photonic bandgaps have been achieved respectively. The stop band can be shifted over 100 nm. The bandwidth can be expanded from ~30 nm to ~250 nm covering nearly the full visible range. It is believed that the developed approaches could strongly promote the use of BPLC in photonic applications.

Visualization of topological defects in wide-temperature amorphous blue phase enabled by polymer molding

Min Su Kim, Liang-Chy Chien, Liquid Crystal Institute (United States)

Direct visualization of three-dimensional topological defects in amorphous liquid crystalline blue phase by confocal laser scanning microscopy and scanning electron microscopy is demonstrated. Tracing of topological defects in amorphous blue phase with wide temperature range (> 800K) and inducing chirality are enabled by polymer molding. The polymer molding straightforwardly positions the location of disclinations, memorizes the anchoring information at nano-scale, and reveals the difference in correlation length of different blue phases. It can be expected that defect tracing not only unveils the structural mystery in blue phase III, but also potentially opens up new device applications. A liquid crystal electro-optical device showing the capacity of fast field-induced birefringence and high optical contrast based on an achromatic dark state will be presented.

Light-modulated patterns of plasmonic, upconversion, and graphene nanoparticles in liquid crystals (Keynote Presentation)

Ivan I. Smalyukh, Univ. of Colorado at Boulder (United States)

Graphene materials and structures have become an essential part of modern electronics and photovoltaics. However, despite many production methods, applications of graphene-based structures are hindered by high costs, lack of scalability and limitations in spatial patterning. Here we fabricate three-dimensional functional solid microstructures of reduced graphene oxide in a lyotropic nematic liquid crystal of graphene oxide flakes using a pulsed near infrared laser. This reliable, scalable approach is mask-free, does not require special chemical reduction agents, and can be implemented at ambient conditions starting from aqueous graphene oxide flakes. Orientational ordering of graphene oxide flakes in self-assembled liquid-crystalline phases enables laser patterning of complex, three-dimensional reduced graphene oxide structures and colloidal particles, such as trefoil knots, with ‘frozen’ orientational order of flakes. These structures and particles are mechanically rigid and range from hundreds of nanometres to millimetres in size, as needed for applications in colloids, electronics, photonics and displays.
the materials birefringence. Notable examples include liquid crystalline blue phases and cholesteric liquid crystals. Here, we show selected examples of liquid crystalline photonic crystals from regular nematic superstructures, including colloidal crystals, blue phase colloids andcolloidal structures, and discuss their photonic properties. Methodologically, we use numerical modelling based on custom adapted interactive solving of Maxwell’s equations. Specifically, we demonstrate the role of topological defects in the photonic band structure and discuss the material tunability. Three-dimensional profiles of selected eigenmodes in the birefringent background are visualized, and their spatial profile is linked to the emergence of photonic band gaps. Finally, we discuss the role of the symmetries of multiple material components in the over-all photonic band structure of the material.

9769-11, Session 3
Nematic liquid crystals used to control photo-thermal effects in gold nanoparticles (Invited Paper)
Cesare Umeton, Univ. della Calabria (Italy)

We have characterized and modeled photo-thermal effects observed in gold nanoparticles (GNPs) dispersed in Nematic Liquid Crystals (NLCs). Under a suitable optical radiation, GNPs exhibit a strong light absorption/scattering; the effect depends on the refractive index of the medium surrounding the nanoparticles, which can be electrically or optically controlled. In this way, the system represents an ideal nano-source of heat, remotely controllable by light to adjust the temperature at the nanoscale. Photo-induced temperature variations in GNPs dispersed in NLCs have been investigated by implementing a theoretical model based on the thermal heating equation applied to an anisotropic medium; theoretical predictions have been successfully compared with results of experiments carried out in a NLC medium hosting a small amount of GNPs. Both theory and experiments represent a step forward to understand the physics of heat production at the nanoscale, with applications that range from photonics to nanomedicine.

9769-12, Session 3
Nanoscale imaging of defects in layered liquid crystals (Invited Paper)
Antal I. Jákli, Liquid Crystal Institute (United States); Cuiyu Zhang, Kent State Univ. (United States); Oleg D. Lavrentovich, Liquid Crystal Institute (United States)

Defects determine many static and dynamic properties of materials. They are mainly studied by optical microscopy, which cannot reveal the detailed structure of the defect core, where the deformations are too strong to sustain the usual type of order. The size of the core in most liquid crystals is in the range of 1-10 nanometers, which calls for imaging techniques with resolution much higher than the optical one. Here we summarize and discuss results of Transmission Electron Microscopy (TEM) nanoscale imaging of defects in various layered liquid crystals built of rod and bent-shaped molecules. [1–7] We will present and analyze structures of edge and screw dislocations, twist and tilt grain boundaries of smectic layers, layer modulations, nanofilaments and pseudo-layers of the materials birefringence. Notable examples include liquid crystalline blue phases and cholesteric liquid crystals. Here, we show selected examples of liquid crystalline photonic crystals from regular nematic superstructures, including colloidal crystals, blue phase colloids and colloidal structures, and discuss their photonic properties. Methodologically, we use numerical modelling based on custom adapted interactive solving of Maxwell’s equations. Specifically, we demonstrate the role of topological defects in the photonic band structure and discuss the material tunability. Three-dimensional profiles of selected eigenmodes in the birefringent background are visualized, and their spatial profile is linked to the emergence of photonic band gaps. Finally, we discuss the role of the symmetries of multiple material components in the over-all photonic band structure of the material.

9769-13, Session 4
Liquid crystals enable adaptive imaging with miniature cameras (Invited Paper)
Tigran Galstian, Univ. Laval (Canada)

Liquid crystals have been proven as excellent materials for displays and other pixelated spatial light modulators. However, their use in imaging applications was long time considered as not appropriate or not competitive. Cost, tuning speed and light scatter being the key drawbacks. I will describe the evolution of liquid crystal lens technology over the last 40 years. I will also describe the challenges and accomplishments that brought us to the excellent image quality, obtained today by using commercial miniature cell phone cameras, that leaves no more doubt for the potential that those materials represent in the mobile imaging.

9769-14, Session 4
LC-lens array with light field algorithm for 3D biomedical applications (Invited Paper)
Yi-Pai Huang, Po-Yuan Hsieh, Amir Hassanfirooz, National Chiao Tung Univ. (Taiwan); Manuel Martinez, Univ. de València (Spain); Bahram Javidi, Univ. of Connecticut (United States); Chao-Yu Chu, Yun Hsuan, Wen-Chun Chu, National Chiao Tung Univ (Taiwan)

Liquid crystal lens (LC-lens) array was utilized in 3D bio-medical applications including 3D endoscope and light field microscope. Comparing with conventional plastic lens array, which was usually placed in 3D endoscope or light field microscope system to record image disparity, our LC-lens array has higher flexibility of electrically changing its focal length. By using LC-lens array, the working distance and image quality of 3D endoscope and microscope could be enhanced. Furthermore, the 2D/3D switching ability could be achieved if we turn off/on the electrical power on LC-lens array. In 3D endoscope case, a hexagonal micro LC-lens array with 350um diameter was placed at the front end of a 1mm diameter endoscope. With applying electric field on LC-lens array, the 3D specimen would be recorded as from seven micro-cameras with different disparity. We could calculate 3D construction of specimen with those micro images. In the other hand, if we turn off the electric field on LC-lens array, the conventional high resolution 2D endoscope image would be recorded.

In light field microscope case, the LC-lens array was placed in front of the CMOS sensor. The main purpose of LC-lens array is to extend the refocusing distance of light field microscope, which is usually very narrow in focused light field microscope system, by montaging many light field images sequentially focusing on different depth. With adjusting focal length of LC-lens array from 2.4mm to 2.9mm, the refocusing distance was extended from 1mm to 11.3mm. Moreover, we could use a LC wedge to electrically shift the optics axis and increase the resolution of light field.

9769-15, Session 4
Superlens in the skies: Liquid crystal polymer telescope technology development (Invited Paper)
Nelson V. Tabiryan, Svetlana V. Serak, David Roberts, Zhi Liao, BEAM Engineering For Advanced Measurements Co. (United States); Eugene Serabyn, Jet Propulsion Lab. (United States); Diane M. Steeves, Brian R. Kimball, U.S. Army Natick Soldier Research, Development and Engineering Ctr. (United States)
We present a new and complex electrically switchable diffraction grating device, based on an interdigitated electrode structure and vertical alignment (VA) in liquid crystal (LC) device, which has advantages of fast switching, high diffraction efficiency and almost non-diffraction at off state.

A liquid crystal cell was assembled using one Indium Tin Oxide (ITO) coated glass substrate and one plain glass substrate. The patterned substrates, which act as in-plane switching electrodes for addressing the LC layer sandwiched between them, are consisted of an interrogated pattern of two ITO electrodes.

When an electric field is applied on the two electrodes, the LC molecules with positive dielectric anisotropy are orientated to tilt toward the electric field direction. The LC molecules in the regions near the electrodes edges experience a horizontal electric field and aligned along the electric field lines. Thus, this in-plane switching of liquid crystal molecules induces a periodic refractive index modulation for the light passing through them. The magnitude of this refractive index modulation depends on the liquid crystal director distribution. The average refractive index profile has a periodic oscillation, which acts as a diffraction grating.

The diffraction efficiency of the proposed liquid crystal grating is varied by voltage applied to the interdigitated electrodes, and the zero-order diffraction efficiency of the device measured can reach 70%. Dynamic response of diffraction grating is improved by surface localized polymer structure.

### References

Morphing dynamics in light-triggered liquid crystal network coatings (Invited Paper)
Dirk J. Broer, Danqing Liu, Technische Univ. Eindhoven (Netherlands)

Polymers that can change shape or can change their surface topography in response to a trigger have a wide application potential varying from micro-robotics to avionics. Preferably this morphing proceeds fast and reversibly. We developed new morphing principles based on in-situ photo-polymerized liquid crystal networks. Commonly the triggers are temperature, light, pH or the presence of chemicals or other moisture. In the lecture we will focus on UV actuation and demonstrate that by accurate positioning of molecules in the space of a thin film or coating the deformation figures can be predetermined and can vary between simple gratings or can be made very complex such as fingerprints that can be switched between off (flat surface) and on (corrugated surface) by light. The underlying principles are based on photo-induced changes in the degree of order of liquid crystal polymer networks and the accompanying changes in density by the formation of free volume. The surfaces can be switched with frequencies of the order of 0.1 Hz. In the lecture we will discuss several methods to fabricate the responsive layers as well as some of the most eye-catching properties.

References:
D. Liu, L. Liu, P. Onck, D.J. Broer, PNAS 2015, 112, 3880-3885

New architectures of liquid crystal-based lenticular lenses in index matching approach for display applications (Invited Paper)
Sin-Doo Lee, Jiyoon Kim, Hyungjin Kim, Chiwoo Kim, Seoul National Univ. (Korea, Republic of); Chiwoo Kim, Seoul National University (Korea, Republic of)

We describe two types of liquid crystal (LC)-based lenticular lenses in the index matching approach with the help of the polymer lens structures constructed through a simple imprinting process. The first type shows a polarization-dependent focusing effect which arises primarily from the index matching scheme between the polymer lenticular lens and the LC on it. It exhibits excellent 2 dimensional (2D) viewing properties irrespective of the viewing angle and allows the focusing effect for 3 dimensional (3D) imaging which depends on the radius of curvature of the static polymer lens as well as the refractive indices of the LC. The focusing and non-focusing properties depending on the input polarization are useful for realizing autostereoscopic 2D-3D convertible displays combined with polarization-selection elements. The second one is capable of laterally shifting the focusing effect in a complementary geometry with an offset between the center of the convex lens in the bottom substrate and that of the concave lens in the top substrate. Depending on the index matching between each of two different polymer lenses and the LC, either the focusing effect from the convex lens-LC interface or that from the LC-concave lens interface is achieved. The lateral shift of the focusing properties is dictated by the amount of the offset between the convex lens and the concave lens whereas the focal length depends on the amount of the index mismatching. For the input beam polarized linearly along the direction of the lenticular lens array, according to an applied voltage, the ordinary and extraordinary indices of the LC coincide with the index of the convex lens and that of the concave lens made of two different polymers, respectively. Distinct 3D viewing characteristics with laterally shifting zones are demonstrated.

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Transiently separable high-speed response component in cholesteric liquid crystals (Invited Paper)
Yo Inoue, Hiroshi Moritake, National Defense Academy (Japan)

In this study, we present an undiscovered high-speed response component separable only in the transient state in cholesteric liquid crystals with a uniform lying helix, in which the helix axis lies in the cell-plane direction. When an electric field is applied perpendicularly to the helix axis, it is well known that two physical phenomena are induced: (i) the flexoelectric effect and (ii) the elongation of the helical structure. So far, their mechanisms have been clarified both experimentally and theoretically, at least in the stationary state. However, we revealed the existence of a third component with a fast response time (~30 us) hidden in the transient state by removing the two response components related to the flexoelectricity and the elongation of the helical pitch from the electro-optic effect. The novel fast component can potentially be used for device applications requiring fast-switching characteristics such as field-sequential color displays and light modulators.

Light guiding, reshaping, and imaging of complex nematic structures (Invited Paper)
Slobodan 7umer, Univ. of Ljubljana (Slovenia) and Jozef
Confidence 9769:
Emerging Liquid Crystal Technologies XI

Stefan Institute (Slovenia); Miha Cancula, Simon ?opar, Univ. of Ljubljana (Slovenia); Miha Ravnik, Univ. of Ljubljana (Slovenia) and Jo?ef Stefan Institute (Slovenia)

High birefringence, softness, and responsivity to external stimuli of liquid crystals allow forming and manipulating complex topological defect structures. This potential is recently attracting a lot of attention for possible applications to control the light flow. We focus our attention to two examples: i) Although in studies of frustrated cholesteric liquid crystals the multiphoton fluorescence confocal polarization microscopy is the crucial approach there is still a need for better understanding the details obtained by polarized optical microscopy (POM) [Orlova et al., Nat. Comm. 2015; Varanytsia & Chen, SPIE 2015]. We decided to uncover details of complex POM images by coupling our customized finite difference time domain (FDTD) calculation of electromagnetic fields with a modified Jones matrix approach where light refraction is taken into account. This allows us to cover very different scales. ii) Several studies of colloidal particles demonstrate formation of super-structures where particles are entangled by nematic disclination lines [Tkalec et al, Science 2011; ?opar et al., PNAS 2015]. The interest in using disclinations as possible light coupling elements stimulated our study of light propagation along disclinations. To be able to cover situations when light intensity is high enough to locally reorient nematic media we linked our FDTD method to our Landau - de Gennes approach for nematic structure simulations that includes also dielectric coupling of optical field to nematic ordering.

9769-24, Session 6

Liquid crystal devices with continuous phase variation based on high-permittivity thin films (Invited Paper)

Oliver Willekens, Kristiaan Neyts, Jeroen Beeckman, Univ. Gent (Belgium)

Most liquid crystal devices use transparent conductive electrodes such as indium tin oxide (ITO) to apply a potential difference in order to achieve electro-optic switching. As an alternative, we study a device with narrow metallic electrodes in combination with dielectric layers with large electric permittivity. In this approach the applied voltage can be a continuous function of the lateral distance from the electrode line. Simulations for a 1 dimensional beam-steering device show that the switching of the liquid crystal (LC) director depends indeed on the distance from the addressing electrodes and on the value of the relative permittivity. We have fabricated a proof of concept device with homogeneous ITO on one substrate and 60um spaced metallic finger electrodes covered by lead zirconate titanate (PZT, relative permittivity around 500) on the other substrate. In this device the LC director between the electrode lines tilts by nearly 40° with respect to the substrate plane, whereas no tilt is observed for the uncoated reference sample at the same voltage. An added advantage is that the proposed configuration has a lower resistivity and dissipates less heat, due to the dielectric character of the PZT. This indicates that this technology could be used in low-power LC devices. The results show that using dielectrics with high relative permittivity in liquid crystal devices could form a cost-efficient and low-power alternative to many LC technologies where a gradient electric field is desirable.

9769-25, Session 6

Confinement-sensitive optical response of cholesteric liquid crystals in electrospun fibers

Eva Enz, Martin-Luther-Univ. Halle-Wittenberg (Germany); Vera LaFerrara, ENEA (Italy); Jan P. F. Lagerwall, Giusy Scalia, Univ. du Luxembourg (Luxembourg)

Cholesteric liquid crystals (LCs), like other types of LCs, can be confined inside polymeric fibers by coaxial electrospinning. In this way the interesting optical properties of cholesterics could be transferred to very long fibers that can form flexible or rigid mats according to the outer sheath material. Sectioning the fibers with focused ion beam, the inner cavities hosting the LC could be estimated, finding height dimensions well below a micrometer of dimension.

The changes in color and texture of the LC in the core of the fiber could be correlated to the shape and dimension of the cavities, revealing a unique behavior due to the submicrometer confinement. Differences in cavity dimension, as small as in the order of tens of nanometers, can influence the optical properties, producing a change in color from the LC. This is attributed to a change in helical pitch of the cholesteric, in response to the alignment conditions at the boundaries. Since the LC must form an integer number of half-pitches to fill the cavity, regardless of the dimension, it has no other choice than to adapt the pitch to the cavity size.

9769-26, Session 7

Crossover positive biaxial nematic to negative biaxial nematic phase in lyotropic liquid crystals (Invited Paper)

Antonio M. Figueiredo Neto, Univ. de São Paulo (Brazil); Erol Akpinar, Abant Izzet Baysal Univ. (Turkey); Dennys Reis, Univ. de São Paulo (Brazil)

Lyotropic mixtures with a surfactant and co-surfactant may present three nematic phases, two uniaxial and one biaxial (NB). The alignment behavior of the NB in the presence of may be used to classify the biaxial phase as being of the NB+ or NB- type, however belonging to the same and unique biaxial phase. Mixtures of dodecyltrimethylammonium bromide (DTB)/sodium salt from the Hofmeister anions series/1-dodecanol/water, presenting the NB, were prepared to investigate the effect of these anions on the existence of the NB phase, and the uniaxial to biaxial phase transitions. Laser conoscopy, optical microscopy and X-ray scattering were used to characterize the phases and phase transitions. The results indicated that the Hofmeister anions were bounded to the head groups of DTB molecules at the micelles' surfaces, which significantly affect the different orientational fluctuations responsible for the formation of different nematic phases, the biaxial phase domains and the uniaxial to biaxial phase transition temperatures. The partial phase diagrams of the mixtures were established. In particular regions of the phase diagrams, an anomalous behavior was observed in the crossover NB- to NB+: the contrast of the conoscopic fringes almost vanishes, and the sample looses its alignment. This behavior was interpreted as a decrease in the mean diamagnetic susceptibility anisotropy of the sample, which is related to the shape anisotropy of the micelles. We observed that these mixture present smaller micellar shape anisotropy when compared to other lyotropic micellar systems presenting the NB phase. Financial support: INCT-FCx, NAP-FCx, CNpq, FAPESP, CAPES, TÜB?TAK.

9769-27, Session 7

Highly anisotropic nanowires from the self-assembly of discotic liquid crystals (Invited Paper)

Ji Hyun Park, Seoul National Univ. (Korea, Republic of); Yoichi Takanishi, Kyoto Univ. (Japan); Massimiliano Labardi, Univ. di Pisa (Italy); Kyung Ho Kim, Youn Sang Kim, Yung Woo Park, Seoul National Univ. (Korea, Republic of); Jan P. F. Lagerwall, Univ. du Luxembourg (Luxembourg) and Seoul National Univ. (Korea, Republic of); Jun Yamamoto, Kyoto Univ. (Japan); Giusy Scalia, Univ. du Luxembourg (Luxembourg) and Seoul National Univ. (Korea, Republic of)
Discotic molecules can assemble into columnar structures that are attractive for opto-electronic applications. The assembly of discotic molecules can be influenced and even driven by the educated choice of solvents since their molecular structure play a key role in the assembly process. In aromatic solvents standard discotic molecules can assemble into nanowires that are tens of micrometer long and spontaneously aligned along a common direction, forming anisotropically nanostructured films. The aggregation depends on the solvent type, as observed in solution by x-ray and dynamic light scattering but also on the substrate and preparation conditions when deposited to realize films. The contribution of the preparation process is evident when monitoring the films by atomic force microscopy as temperature varies or when comparing them to the needles of discotic molecules grown in excess of solvent. Our study shows that the formation of the wires results from the interplay of the LC self-assembly and preparation process. The high polarizability observed along the columnar axis reflects the overlap of molecular orbitals responsible for electrical conduction and also the positive optical birefringence of the system. The nanowires have electrical properties clearly superior to pure discotic thin films making those structures advantageous in optoelectronic devices.

9769-28, Session 7
**Optimizing cholesteric liquid crystal shells for photonic applications**
Yong Geng, JungHyun Noh, Jun P. F. Lagerwall, Univ. du Luxembourg (Luxembourg)

We recently demonstrated that colloidal crystal arrangements of monodisperse droplets or shells of planar-aligned cholesteric liquid crystal exhibit intricate patterns of circularly polarized reflection spots of different color [J. Noh, H.-L. Liang, I. Drevsensk-Olenik & J. P. F. Lagerwall, J. Mater. Chem. C, vol. 2, p.806 (2014); J. Noh, I. Drevsensk-Olenik, J. Yamamoto & J. P. Lagerwall, SPIE OPTO, 93840T-93840T (2015)]. The spots appear as a result of photonic cross communication between droplets, hence the patterns reflect the macroscopic arrangement of droplets or shells. Moreover, they are dynamic in the sense that spots are turned “ON” or “OFF” depending on the size of the illuminated area. Apart from being an interesting optical phenomenon, it offers some interesting application opportunities in photonics, due to the unique characteristics of the patterns. However, it turns out that the optical quality of the droplets is frequently inadequate, due to oily streak defects in the cholesteric texture and, in general, uncontrolled deviations of the helix from the desired radial orientation. We are currently carrying out a systematic study of how the optical properties of cholesteric shells depend on the preparation conditions, with the goal to formulate a protocol on how to ensure optimum photonic cross communication within the macroscopic system of close-packed shells. In the presentation we will report on the status of this study.

9769-29, Session 7
**Templated chiral liquid crystalline structures for lasers and stretchable gels (Invited Paper)**
Stephen Morris, Univ. of Oxford (United Kingdom)

Chiral liquid crystalline (LC) mesophases such as the chiral nematic, chiral smectic and blue phases possess the remarkable property that they spontaneously self-organise to form structures that possess a periodic modulation of the refractive index that are typically on a length scale comparable with the wavelength of light [1]. This leads to a range of optical phenomena including a photonic band gap for light that can either be in one dimension (as is the case for the chiral nematic and chiral smectic phases) or three dimensions (as observed in the blue phases). Furthermore, through the construction of a polymer scaffold using reactive mesogens, which are dispersed at a moderate concentration by weight into the non-reactive LC mesogen host, it is possible to template the periodic structure onto other achiral LC materials and potentially non-mesogenic compounds [2, 3]. Such a process then exploits the self-organising features of these chiral LC phases and imparts it onto other materials in a facile manner.

The technological benefits of these chiral LC structures are multifaceted ranging from reflective displays and solar luminescent concentrators to laser devices [4], all of which benefit from the self-organising periodic structure and the existence of the photonic band gap for visible light. In this presentation, we show how the chiral nematic and blue phases may be templated using polymer scaffolds leading to extraordinarily wide temperature ranges in the latter case as well as potentially new electro-optic mechanisms. We present results on laser emission using these templated structures and demonstrate how they can be used to obtain a larger degree of wavelength tuning than is typically observed with conventional polymer-stabilized liquid crystaline materials. Finally, we describe how these materials can be used to produce wavelength tuneable gels based upon both chiral nematic and blue phase LCs [5].

References

9769-30, Session 8
**Liquid crystal light shutters for simultaneous control of haze and transmittance (Invited Paper)**
Tae-Hoon Yoon, Joon Heo, Byeong-Hun Yu, Jae-Won Huh, Pusan National Univ. (Korea, Republic of)

Recently, see-through displays have drawn much attention as one of next-generation displays. There are two basic technologies by which we can realize a see-through display: organic light-emitting diodes (OLEDs) and liquid crystal (LC) displays. The pixel structure of a see-through display includes a transparent window area through which the background image can be seen. Therefore, background images are always seen along with the displayed image. In addition, a see-through display using OLEDs cannot provide the black color. As a result, a see-through display exhibits poor visibility. This inevitable problem can be solved by placing a light shutter at the back of a see-through display.

Light shutter technology can be divided into two types: light absorption and light scattering. Light absorption can be used to control the transmittance, but it cannot block the background image completely. Light scattering can be used to control the haze, but it cannot provide black color. To realize a high-visibility see-through display, we need a light shutter by which we can control haze and transmittance simultaneously. In this talk we would like to introduce technologies for LC light shutters by which we can block the background image and provide black color by utilizing light scattering and absorption effects simultaneously.

9769-31, Session 8
**Liquid crystal alignment on ZnO nanostructure films (Invited Paper)**
Yueh-Feng Chung, Mu-Zhe Chen, Sheng-Hsiung Yang, Shie-Chang Jeng, National Chiao Tung Univ. (Taiwan)

The study of liquid crystal (LC) alignment is important for fundamental researches and industrial applications. The tunable pretilt angles of liquid crystal (LC) molecules aligned on the inorganic zinc oxide (ZnO) films with controllable surface wettability are demonstrated. The ZnO films are deposited on the ITO-glass substrates by the hydrothermal process,
9769-32, Session 8

**Hot pen and laser writable photonic polymer films (Invited Paper)**

Monali Moirangthem, Jelle E. Stumpel, Baran Alp, Pit Teunissen, Cees W. M. Bastiaanssen, Albert Schenning, Technische Univ. Eindhoven (Netherlands)

Smart polymers are regarded as a grand materials challenge and are of great interest for a variety of applications. In such polymers, the properties change in response to an external stimulus. The functional properties can be adjusted autonomously depending on the user needs or upon environmental changes. For precise, responsive functional properties, well-defined hierarchically ordered materials are crucial.

The self-assembly of liquid crystals has proven to be an extremely useful tool in the development these nanomaterials. In my lecture, examples of photopolymerizable mesogens will be presented showing that a wide variety of smart materials can be made from a relative simple set of building blocks. Upon mixing reactive mesogens, liquid crystalline polymer materials can be fabricated that can be applied as actuators and sensors, respectively.

9769-33, Session 8

**Optical polymers with negative photo-elastic property for display applications**

Weijun Zhou, The Dow Chemical Co. (United States); Shih-Wei Chang, Dow Electronic Materials (United States); Jie Feng, The Dow Chemical Co. (United States); Kathleen O’Connell, Dow Chemical Korea Ltd (Korea, Republic of)

Photo-elastic property characterizes stress-induced birefringence optics of materials in the solid state. Materials can be either of positive or negative photo-elasticity types depending on how molecules respond to the applied strain field. With a few exceptions, nearly all optical polymers are known to be of positive photo-elastic type. Molecular origins for negative photo-elasticity have long been a mystery. In this paper, we will present our findings in developing optical polymers with negative photo-elasticity performance. Both sign and magnitude of photo-elastic performance can be changed with a proper molecular design. When coated on a piece of thin glass, materials with positive and negative photo-elastic property showed drastically different response to the applied stress. Those experimental results also agree well with the retardation analysis based on finite element method.

Optical polymers with negative photo-elasticity can be particularly useful for compensating stress-optics effect of thin glass used in manufacturing liquid crystal displays. It is well known that undesirable optical retardation can be generated in the glass substrate when the panel is subject to curvature or bending stress through known stress-optical effect.[1-2] The magnitude of optical retardation albeit small can lead to noticeable light leakage due to the amplification effect of liquid crystal molecules sandwiched between the top and bottom glass. A negative photo-elasticity material can be coated onto glass substrate to effectively suppress stress-optics effect induced light leakage with this novel photo-elasticity approach.

References:


9769-34, Session 8

**Electrical control of reflection wavelength and bandwidth in cholesteric liquid crystals**

Timothy J. White, Kyung Min Lee, Vincent P. Tondiglia, Air Force Research Lab. (United States)

The presence, position, and properties of the selective reflection of polymer stabilized cholesteric liquid crystals can be readily controlled with applied DC fields. The key to this mechanism is the development of a structurally chiral polymer stabilizing network that when subject to electric field, undergoes distortion. In this contribution, we detail our recent work focusing on optimizing the response time of these materials as well as improving the general optical properties.

9769-35, Session 8

**Spontaneous slippery interfaces created by the interface melting effect**

Masumi Yamashita, Yoichi Takanishi, Jun Yamamoto, Kyoto Univ. (Japan)

Anchoring force on the orientation films in the liquid crystal (LC) display devices plays important roles for any types of display modes, such as IPS, STN, VA and OCB, etc. However, it also induces deterioration of efficiencies, such as enlargement of the driving voltage or deceleration of the response speed. We have invented the concept of “Slippery interfaces”, which has zero anchoring force for the attached LC molecules on the interfaces. We also successfully demonstrated the large reduction of driving voltage (<1 order of DH-FLC mode display device keeping the fast switching response (10-100 sec). In comparison with above modes on the nematic LC display, anchoring force on the interfaces is entirely not necessary due to the spontaneous recovery torque produced by the helix of FLC.

Here, we found the principle for the spontaneous formation of slippery interfaces on the glass plates of LC device. Complete wet thin isotropic-nematic interfaces appear on the polymer coated glass plates, by introducing the dopant which has strong affinity to the coated polymer rather than LC molecules. Since the concentration of the dopant should be concentrated automatically near the polymer coated glass plate due to their affinity, then the I-N phase transition temperature strongly decreases and isotropic thin layers appear on the plates. Key points for the design of the slippery interface is the combinations among three elements, namely, LC, coated polymer and dopants to satisfy the following conditions: (1) Complete wetting condition should be well satisfied both on the interfaces between isotropic-nematic and isotropic-polymer surface. (2) Homogeneous alignment should be kept on the isotropic-nematic interface. (3) Isotropic phase should not be drying up even in lower temperature region. Furthermore, we measure anchoring force by rotating magnetic field method near the surface melting transition temperature, and successfully confirmed the slippery zero anchoring state.

9769-36, Session 8

**Continuous phase modulation in polymer-stabilized liquid crystals (Invited Paper)**

Alexander Lorenz, Univ. Paderborn (Germany); Larissa Braun, Valeria Kolosova, Technische Univ. Berlin
Continuous optical phase modulation was systematically investigated in a nematic host liquid crystal (LC), which was stabilized with in-situ generated photopolymer. Various driving modes were investigated. With presence of a chiral dopant, polarization independent and fast (τa = 300 μs) electro-optic responses were found in both blue phase mode [1,2] and uniformly standing helix mode [3,4]. Anyway, high driving voltages > 100 V were required to achieve phase modulation depths > (π) in reflective test cells with planar electrodes. In contrast, much lower driving voltages < 15 V were required in a polymer-network LC [5] based on the same host LC if no chiral dopant was present. In this driving mode, the response times were slightly increased but turned out fast enough to achieve 200 Hz modulations with high phase contrast.

References


9769-38, Poster Session

Photo-electrically tunable liquid-crystal Fresnel lens with Sagnac interferometer

Chie-Tong Kuo, Shih-Hung Lin, Bing-Yau Huang, Jian-Yu Lee, Chun-Lung Chen, National Sun Yat-Sen Univ. (Taiwan)

The liquid-crystal (LC) Fresnel lens has received much attention in optical devices because it possesses the dynamic focusing efficiency and simple fabrication processes. In the previous work, the electrode with concentric rings or Fresnel-like photo-mask has been adopted to fabricate the fixed focal length of LC Fresnel lens. In order to achieve the Fresnel lens with tunable focal length, the Sagnac interferometer has been used for producing an interference pattern with a series of concentric circular bright and dark bands, which is similar to the general Fresnel zone plate. In this study, an optically and electrically tunable LC Fresnel lens with photoconductive polymer layer (PVK/C60) and Sagnac interferometer has been investigated. The absorbance of the PVK can be enhanced with the dopant of C60 in visible wavelength range. By using Sagnac interferometer with visible wavelength, a Fresnel-like pattern can be induced on the PVK/C60 layer which results in conductive and nonconductive structures corresponding to bright and dark regions. Thus, a LC Fresnel lens can be constructed through the mismatch of refractive index between adjacent zones with an external voltage. The focal length of the proposed Fresnel lens can be easily tuned by varying the size of the Sagnac pattern and the focusing efficiency can also be controlled optically and electrically.

9769-39, Poster Session

Bistable light shutter using dye-doped liquid crystals for a see-through display

Jae-Won Huh, Joon Heo, Byeong-Hun Yu, Tae-Hoon Yoon, Pusan National Univ. (Korea, Republic of)

See-through displays have got high attention as one of the next generation display devices. Especially, see-through displays that use organic light-emitting diodes (OLEDs) and liquid crystal displays (LCDs) have been actively studied. However, a transparent OLED cannot provide black color because of their see-through area. Although a transparent LCD can provide black color with crossed polarizers, it cannot block the background. This inevitable problem can be solved by placing a light shutter at the back of the see-through display.

To maintain the transparent or opaque state, an electric field must be applied to a light shutter. To achieve low power consumption, a bistable light shutter using polymer-stabilized cholesteric liquid crystals (ChLCs) has been proposed. It is switchable between the translucent and transparent states only. Therefore, it cannot provide black color. Moreover, it cannot block the background perfectly because of poor performance in the translucent state. In this work we will introduce a bistable light shutter using dye-doped ChLCs. To improve the electro-optic characteristics in the opaque state, we employed a crossed electrode structure instead of a parallel one. We will demonstrate that the light shutter can exhibit stable bistable operation between the transparent homeotropic and opaque focal-conic states thanks to polymer stabilization.

9769-40, Poster Session

Observation of thermally induced movement of a beam deflected by a liquid crystal spatial light modulator

Bosanta R. Boruah, Santanu Konwar, Indian Institute of Technology Guwahati (India)

Liquid Crystal Spatial Light Modulators (LCSLM) are of great importance in various applications such as in adaptive optics, optical microscopy, optical trapping etc., due to their capability to reconfigure the amplitude, phase and polarization profiles of an incoming laser beam. In the above applications the LCSLMs are basically used to display computer generated holograms which give rise to diffraction orders when the hologram is illuminated with a laser beam. In almost all such applications it is essential to constrain the diffracted beams to a certain desired position. However beam position fluctuates due to various reasons, primarily due to mechanical vibrations, creating great disturbances in all such applications. Thus, these beam fluctuations need to be minimized. In order to minimize the beam position fluctuations it is very important to know the cause and the nature of the fluctuations. In this work an attempt has been made to perform a thorough investigation on the fluctuations of the diffracted as well as the undiffracted beams from the LCSLM. It has been found that there exists a close relationship between these fluctuations and the power on-off instants of the LCSLM used. This relationship is independent of the nature of the beams under consideration, i.e. whether the beam is a diffracted or an undiffracted one, both show the same behaviour. Our observations indicate that the beam fluctuations may have some dependency on the heat dissipation from the LCSLM when it is the powered on configuration. In this paper we will provide a more detailed investigation on the causes and nature of the beam fluctuations from an LCSLM along with experimental evidences.

9769-41, Poster Session

Electro-magnetic simulation of image quality of near-eye displays containing surface gratings or holographic gratings

Hagen Schweitzer, Daniel Asoubar, Michael Kuhn, LightTrans GmbH (Germany); Christian Hellmann, Wyrowski Photonics UG (Germany); Frank Wyrowski, Friedrich-Schiller-Univ. Jena (Germany)
Near eye displays often consists of a thin light pipe for guiding light from a display or laser scanner to the human eye. Surface gratings and holographic gratings can be used for coupling light into the light pipe, for decoupling light from the light pipe or for deflecting light within the light pipe. Single mode lasers, multimode lasers or LEDs can be used as light sources. The simulation and the design of near eye displays containing gratings is a today’s challenge in optical engineering. The presentation introduces a new propagation concept called Geometric Field Tracing which enables a fast and accurate analysis of near eye displays including all light properties and a precise analysis of all surface gratings and holographic gratings. For an accurate simulation of near eye displays we use a locally rigorous solver of Maxwell’s Equations. This ensures that diffraction efficiency, polarization and phase of diffraction orders can be taken into account correctly although they strongly depend on both, the wavelength and the incident angle. We show that the new algorithm also considers higher diffraction orders, speckle effects and interferences which may appear depending on the properties of the light source. A precise simulation of the image quality (PSF, MTF) of the display becomes feasible since the simulation is based on a fully electromagnetic modeling of light including amplitude, phase, polarization as well as temporal and spatial degree of coherence. Presented applications and results are based on the software VirtualLab Fusion.

Design and synthesis of temperature-independent zero-birefringence polymer
Mio D. Shikanai, Akihiro Tagaya, Yasuhiro Koike, Keio Univ. (Japan)
Zero-zero birefringence polymer (ZZBP) which exhibits neither orientational birefringence nor photoelastic birefringence are required for higher definition liquid crystal displays (LCDs). But orientaional birefringence shows temperature dependence and the former described ZZBP starts to exhibit orientational birefringence at a certain temperature. Talking about LCDs which are used in places where the temperature changes, a polymer film that shows no temperature dependence of orientational birefringence is required. By copolymerizing monomers with different signs of temperature coefficient of intrinsic birefringence, a polymer film that shows no temperature dependence of orientational birefringence with a relatively high glass transition temperature was successfully prepared.

Nanotube networks in liquid crystals
Stefan Schymura, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany) and Martin-Luther-Univ. Halle-Wittenberg (Germany); Jan P. F. Lagerwall, Giusy Scalia, Univ. du Luxembourg (Luxembourg)
Liquid crystals (LCs) are very attractive hosts for the organization of anisotropic nanoparticles such as carbon nanotubes, allowing to bring macroscopically and tune the electrical and optical properties of nanoparticles. Different types of LCs have demonstrated the ability to organize nanotubes, showing the generality of the approach, i.e., that the liquid crystallinity per se is the driving factor for the organization. Compared to standard nanotube composites (e.g. with disordered polymer hosts) the introduction of, for example, carbon nanotubes into an LC allows not only the transfer of the outstanding CNT properties to the macroscopic phase, providing strength and conductivity, but these properties also become anisotropic, following the transfer of the orientational order from the LC to the CNTs. The LC molecular structure plays an important even if ancillary role since it enters in the surface interaction, fulfilling a mediating action between the particle and the bulk of the LC. Due to the surface interaction, the LC can be strongly affected by the presence of CNTs. Surprisingly, even networks of CNTs can be aligned by the LC field. The aligning host can also contribute to reduce the percolation threshold of carbon nanotubes, thus promoting network formation. These are attractive properties for novel nanoparticle composites.

Numerical analysis of polarization gratings using the rigorous coupled wave analysis method
Xiao Xiang, North Carolina State Univ. (United States)
Polarization gratings (PGs) are generally described as periodic profiles of spatially varying optical anisotropy. Recently twist-induced PG has been reported and shown high diffraction efficiency for a wide-band source compared to the non-twist PG. This kind of new elements can be used in various optical devices and imaging systems. Here we report a new numerical analysis for both primary type and twist-induced PG utilizing rigorous coupled wave analysis (RCWA). Our RCWA method applied a newly reported formulation of scattering matrix and is modified to simulate multi-layer anisotropic gratings accurately and efficiently. Without the paraxial approximation, we can simulate the angular and spectral response of polarization gratings rigorously and thus a complete understanding of the element is provided, which can help us optimize its parameters for specific applications. In this paper, we will firstly introduce the modified RCWA method and validate it for primary type PG and then focus on the recently reported twist-induced PG. Diffraction characteristics including the efficiency, angular and spectral response, and polarization sensitivity are investigated. Comparisons with experimental data and other simulation tools show good agreement.

Dielectrophoretic manipulation of nematic and isotropic droplets
Bomi Lee, Jang-Kun Song, Sungkyunkwan Univ. (Korea, Republic of)
Dielectrophoresis can provide a delicate tool to control electrically neutral particles in colloids. The dielectrophoresis is usually applied to solid particles or heterogeneous liquid droplet in continuous liquid, but we devised and investigated the dielectrophoresis of isotropic droplets within nematic phase or vice versa. Using multi-components liquid crystal mixtures that exhibit relatively wide temperature range of nematic-isotropic coexistence, we achieved a field-induced phase separation between isotropic and nematic. We also fabricated the isotropic-nematic filaments that was achieved using a biased surface preference for either isotropic or nematic phase of the alignment layer. The dielectrophoretic manipulations of isotropic and nematic droplets required much lower driving voltage compared to that for the electro wetting type devices. In addition, we observed the bi-directional actuation of isotropic droplets using anisotropic dielectric property of liquid crystal, which is not possible in usual dielectrophoresis. The bidirectional actuation was achieved by controlling the LC director within the cell so as to change the sign of the difference between the effective dielectric constant of nematic and isotropic liquid crystals. We simulated the bi-directional dielectrophoresis by performing the LC director calculation and the corresponding dielectrophoresis. The simulation results matched well with the experimental data. Thus, the bi-directional dielectrophoresis using isotropic and nematic droplets may open new possibility of electro-optical applications using liquid crystals.
Narrow band pass filter using Birefringence film and quarter-wave film

Dong-Kun Lee, Jang-Kun Song, Sungkyunkwan Univ. (Korea, Republic of)

While a pixel in a color image has three colorimetric information of RGB, that in a spectral image contains full spectral information, several tens times more information compared to the color image. Hence, the spectral image is widely applicable in biology, material science, and environmental science. Although several methods for spectral image acquisition have been suggested to date, those methods are expensive, bulky, or slow in actual device. In this work, we designed a novel type of tunable narrow band-pass filter using rotatable polarizer, quarter-wave plate, and birefringence films. Different from the conventional Lyot-Ohman type filter, we do not use a liquid crystal layer. The selection of wavelength is made by rotating the polarizer in our filter set, and adopted a piezoelectric rotational actuator for that. We simulated to find the optimal conditions of the filter set, and finally, fabricated a filter module. The minimum band width was 5 nm, which is suitable for usual spectral imaging and can be reduced further if necessary, and the wavelength of light passing through the filter set was continuously selectable. After setting the filter in a microscope, we obtained a spectral image set for a bio sample that contained full spectrum information in each pixel. Using image processing, we could demonstrate to read out the spectral information for any selected position.
Emissive and reflective properties of curved displays in relation to image quality (Invited Paper)

Pierre M. Boher, Thierry Leroux, Thibault Bignon, Véronique Collomb-Patton, ELDIM (France); Pierre Blanc, Labs. d’Essai de la FNAC (France); Etienne Sandré-Chardonnel, Eclat Digital Recherche (France)

Flexible displays and curved TVs recently appear on the market. Nevertheless, the fact that the display is no more flat induces new visual effects that must be studied specifically. In 2012, we have shown how to compute the changes in the display aspect when a display is curved along one direction [1]. This computation was based on viewing angle measurements made in flat configuration and geometric considerations but we have also studied recently how to measure curved displays directly [2]. Recently the stress induced by the curvature on LCD displays has been studied [3] and the impact of the curvature on reflected parasitic light has been investigated [4].

The purpose of the proposed paper is to present a general method based on the measurements of the emissive and reflective properties of such displays to deduce performances in realistic using conditions taking into account the shape of the display and the illumination environment. Emissive and reflective properties are measured using ELDIM Fourier optics viewing angle multispectral system that provides not only the angular dependence but also the spectral dependence which is needed to compute the reflective properties in any illumination environment. Display aspect for various observer positions and under simple collimated beam illumination conditions is deduced and compared to imaging measurements. In addition, physico-realistic simulations inside any kind of CAD scene and under complex illumination are computed using new capabilities of Ocean, a commercial ray tracing software [5].


See-through autostereoscopic 3D display with visual tracking

Jong-Young Hong, Chang-Kun Lee, Soon-gi Park, Jonghyun Kim, Seoul National Univ. (Korea, Republic of); Kyung-Hoon Cha, Ki Hyung Kang, SAMSUNG Electronics Co., Ltd. (Korea, Republic of); Byoungho Lee, Seoul National Univ. (Korea, Republic of)

Augmented reality (AR) is receiving the spotlight and has been actively researched, recently. AR is the technique of overlaying virtual information to real world. Among the human senses, it is well known that the vision is the most important sense that gives us most of information. Therefore, it is important to implement the see-through three-dimensional (3D) display for realizing the virtual reality (VR) and AR. In general, the parallax barrier is most widely used technology to make autostereoscopic 3D display due to its competitive prices and ease of manufacture. However, the conventional parallax barrier technology cannot provide the AR property because of the opaque display panel.

In this paper, we propose the see-through parallax barrier display with transparent liquid crystal display (LCD). The opaque backlight of the LCD is detached and moved to the side. The number of views of parallax barrier is decided as small as possible to achieve high transparency, and visual tracking is applied to enlarge the viewing region to compensate the shortness of the number of views. Proper viewing images are displayed according to the position of the observer through the visual tracking, and hence, full parallax can be provided and the viewing region is enlarged up to the full field of view of the tracking device. Therefore, the proposed parallax barrier based on the small number of views and visual tracking provides the high transparency and the large viewing region simultaneously. The implementation of the proposed system will explained. The transparency data, the crosstalk and the intensity uniformity among different views will be discussed to evaluate the quality of the proposed system.

Feasibility study on the use of liquid crystal/dye cells for digital signage

Shunsuke Itaya, Nada Dianah Binti M. Azumi, Masamichi Ohta, Shintaro Ozawa, Ichiro Fujiyeda, Ritsumeikan Univ. (Japan)

We have mixed elongated dye molecules (Coumarin 6, Sigma-Aldrich) with a nematic liquid crystal material (MLC-301B, Merck) and injected the mixture into the 87m-wide gap between two glass substrates, each equipped with a transparent conductive electrode and an alignment layer. When excited by blue laser light, the cell emits green-yellow light. Its radiation pattern is described by a simple model based on tilted electric dipoles. A bias of 10V is large enough to alter the director of the liquid crystal molecules from parallel to vertical configuration. Accordingly, the absorption of the laser light varies with the bias. So does the photoluminescence from this cell. The emitted light is mostly polarized along the long axis of the dye molecule. With an addition of a polarizer, it is feasible to modulate the intensity of the light emitted by such a cell. A part of the light emitted by the dye molecules is trapped inside the glass substrates due to total internal reflection at the air/glass boundary. As in the case of a Luminescence Solar Concentrator, one can attach solar cells to the edges of the cell to harvest the light trapped inside the substrates. These features might be utilized in a power-generating, digital signage system to be placed on building walls for example. Addition of an excitation light source would enable in-house operation. For example, one can either scan a blue laser light as in the case of the Prysm technology or stack a backlight module emitting in blue or ultraviolet.

Autostereoscopic display concept with time-sequential wavelength-selective filter barrier

Silvio Jurk, Mathias Kuhlmeier, Roland Bartmann, Bernd Duckstein, René de la Barré, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany)
The wavelength selective filter barrier type assures to illuminate a display area more homogeneous than common autostereoscopic barrier. However, such construction is still used rather rarely. A spatial multiplexed autostereoscopic 3D display design with a strip barrier consisting of switchable color filters is presented. The time sequential operation mode is a supplemental option. Wavelength selective filter barrier arrangements exhibit characteristics different from common barrier displays with similar barrier pitch and ascent. In particular these constructions show strong angular luminance dependency under barrier inclination specified by correspondent slant angle. Further features are caused by the time sequential implementation. It is important to make sure that quick eye or eyelid movement must not lead to visible color break pattern. Altogether, those circumstances much delimit the possibility to find well working and usable display designs by comparison to usual barrier displays. We present a display concept that is widely insensitive to moving artefacts and moirés. It is possible to use the researched display design as a single user system as well as a multi user display and it is possible to implement user adaptive control concepts. In case of tracked single user mode the adaption in x-z-direction is continuously. The variation of the design was analyzed with simulation software by modelling of wavelength-selective barrier arrangement. For the experimental verification, commercially available display components were used for a demonstrator. The barrier strips were realized by one of the display matrix components.

9770-5, Session 1
Super multi-view display for analyzing human cognition
Chulwoong Lee, Sung-Jin Lim, Hosung Jeon, Joonku Hahn, Kyungpook National University (Korea, Republic of)

Recently, super multi-view technology has emerged as one of the most popular research topic and many studies have been done to improve the quality of such super multi-view display. In this paper, we present our specific experiment for human cognition. We designed an open system for the special purpose that the human cognition of 3D contents is examined. In comparison of the previous super multi-view displays, the number of views in our system can be controlled. Our system is generally divided into two parts. One is a projection part. The projection part is configured with a high-speed digital micro-mirror device (DMD). The other is an observation part. The projected image is observed through the observation part which consists of a 4f system with an optical chopper at Fourier domain. In this part, 4f system consists of two parallel binoculars. The optical chopper plays a function to define the range of direction of the rays which can be observed through the observation part. Our system has a great advantage that the effect of the number of views can be evaluated at the common system. We can change the number of views, by changing the synchronization ratio which determine the speed of the opening of the optical chopper and the refresh time of the DMD. We expect that this system will be useful for understanding the principle of the human cognition for 3D display.

9770-6, Session 1
The synthesis and display of digital stereoscopic wayang kulit shadow images
Gea O. Parikesit, Univ. Gadjah Mada (Indonesia)

Shadow puppetry is possibly one of the oldest form of entertainment made by humans, as its history dates back to at least the second century BCE. Recently several artists in the field of shadow puppetry, e.g. the TED-Yellow Christine Marie, have used colored shadows to demonstrate that shadows can be displayed stereoscopically (see: http://cimimarie.com/christinemarie/Christine_Marie.html). Optical engineering of the stereoscopic shadow images have also been reported where the shadows can be manipulated by using the positions of the puppets, the light sources, and the viewers with respect to the screen. The phenomenon of colored shadows, which forms the basis of stereoscopic shadow images, was first documented by Goethe in 1810, where he described how multiple shadows with various colors can be casted by using several colored light sources simultaneously.

In this paper we report the application of digital image synthesis to mimic the stereoscopic shadow images. We are particularly concerned with the shadow images that are relevant to the art of Wayang Kulit from Indonesia, which has been designated since 2003 by UNESCO (United Nations Educational Scientific and Cultural Organization) as an intangible cultural heritage of humanity (see: http://www.unesco.org/culture/ich). This particular form of art is usually displayed using a set up that consists of a light source using a Halogen lamp or a coconut oil lamp, two-dimensional puppets that are crafted from buffalo skin and equipped with articulated arms, and a screen that is made from a white cotton sheet. We will first review the governing equations that govern the optics of 3D Wayang Kulit images. Afterwards we will present our digital image synthesis method, where we compute the colored shadow images that the puppets would cast on the screen. In the subsequent section, we will describe our method to animate the digital 3D Wayang Kulit images, in which we compute the motion of the colored shadow images under puppet translation and rotation. The next section provides the general conclusions of this paper. The resulting digital images can be used in virtual shadow puppetry or in computer animated games involving stereoscopic displays. Note that further studies on the visual discomfort by stereoscopic shadow images are necessary in the near future, as suggested by similar studies in stereoscopic images in general.

9770-7, Session 2
Brightness property of micro-capsules diffuser screen in laser projection display
Jun Kondo, Satoru Okagaki, Kuniko Kojima, Yuzo Nakano, Akihisa Miyata, Mitsubishi Electric Corp. (Japan)

In recent years, the development of displays, projectors, and the like which use laser light sources have been advanced. As a laser light source is used, it provide wide color gamut and compact an optical system; on the other hand, the speckle noise is generated. We make a proposal about the microcapsule diffuser screen with the purpose of reducing the speckle noise on a laser rear projection display. This microcapsule diffuser screen has a screen surface in which microcapsules (~100um) containing charged diffuser particles are applied; where an electric field is charged from the outside and, thus, the diffuser particles in the capsule are randomly agitated to reduce the speckle noise. In this study, we researched diffusion tendency against the diameter of agitating diffuser particle image depends on diameter of agitating diffuser particle. If the diameter is small (~1um), incident light ray is back scattered. More over there are diffusion factor excepting agitating diffuser particle, which is caused by refractive index difference between disperse medium and binder material and circularity cross section shape of the microcapsule. This diffusion is unnecessary and decrease in light utilization efficiency. Therefore projected image is dark.

In this study, we researched diffusion tendency against the diameter of agitating diffuser particle, refractive index difference of each elements and the cross section shape by light ray simulation to improve brightness. In addition, we studied total screen configuration which applied Fresnel lens screen and general diffuser sheets to improve the brightness and the speckle noise reducing effect.

9770-8, Session 2
An novel screen design for anti-ambient light front projection display with angle-selective absorber
Tianju Liao, Peking Univ. (China); Weigang Chen, Kebo He, The Chinese Univ. of Hong Kong, Shenzhen (China);
Moiré pattern visibility of touch sensor module with electrode mesh structure in oblique view

Marzieh Pournoury, Samsung Electro-Mechanics (Korea, Republic of); Ali Zamiri, Korea Univ. (Korea, Republic of); Taeyoung Kim, Victor Yurlov, SAMSUNG Electro-Mechanics (Korea, Republic of); Kyunghwan K. Oh, Yonsei Univ. (Korea, Republic of)

Recently, capacitive touch sensor with the metal materials has become qualified for substitution of ITO; however several obstacles have to be solved. One of the most important issues is moiré phenomenon. Although, random patterns are provided by some companies to avoid the moiré but they cause a haggard feeling. Therefore, periodic patterns are preferred in which there is the possibility of minimizing the moiré.

In this paper the visibility problem of the metal-mesh, in touch sensor module (TSM) is numerically considered. Based on human eye contract sensitivity function (CSF), moiré pattern of TSM electrode mesh structure is simulated with MATLAB software for 8 inch screen display in oblique view. The touch sensor structure which is applied in this study is a sensing and driving layer.

The standard deviation of the moiré generated by the superposition of electrode mesh and screen image is calculated to find the optimal parameters which provide the minimum moiré visibility. To create the screen zones by the corresponding micro-lens array, rectangular function is used. Finite element mesh pattern is defined as the multiplication of screen pixel array and mesh electrodes. Then, the filtered image is obtained by multiplication of Fourier transform of finite mesh pattern and calculated CSF for three different observer distances, L=200, 300 and 400 mm. Finally the moiré standard deviation is calculated (contrast of the image) by taking inverse Fourier transform and sampling the central area. Relative discrepancy between numerical and analytical solution is less than 0.8% for viewer distance of 200mm.

Dual-view 3D displays based on integral imaging (Invited Paper)

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We propose three dual-view integral imaging (II) three-dimensional (3D) displays. In the first display, each elemental image (EI) is cut into a left and right sub-EIs, and they are refracted to the left and right viewing zone respectively. The light from the left and right sub-EIs is reconstructed alternately with a refresh rate up to 120HZ. The viewing angle and 3D resolution are the same as the conventional II 3D display.

In the second display, a polarizer parallax barrier is used in front of both the display panel and the MLA. The polarizer parallax barrier consists of two parts with perpendicular polarization directions. The elemental image array (EIA) is cut to left and right parts. The lights emitted from the left and right part are modulated by the left MLA and reconstruct a 3D image in the right viewing zone, whereas the lights emitted from the right part reconstruct another 3D image in the left viewing zone. The 3D resolution is decreased. In the third display, an orthogonal polarizer array is attached onto both the display panel and the MLA. The orthogonal polarizer array consists of horizontal and vertical polarizer units and the polarization directions of the adjacent units are orthogonal. In State 1, each EI is reconstructed by its corresponding micro-lens, whereas in State 2, each EI is reconstructed by its adjacent micro-lens. 3D images 1 and 2 are reconstructed alternately with a refresh rate up to 120HZ. The viewing angle and 3D resolution are the same as the conventional II 3D display.

Moiré reducing two-dimensional diffractive optical low-pass filter made from molded plastic

Yosuke Sakohira, Kazuya Yamamoto, Makoto Okada, Nalux Co., Ltd. (Japan)

A two dimensional sinusoidal diffraction grating is developed for a moiré-reducing low-pass filter. Typical display units have image pixels arranged systematically in two dimensions, with non-illuminating regions between the image pixels. Using a conventional lens to view this display, the images pixels and the region between the pixels are both magnified, and the resulting image is unpleasant to the human eye, especially with color displays, called the screen door effect. This pixel problem is typically solved with a low-pass filter using a diffraction grating. However, depending on the period of the diffraction grating compared to the period of the image pixels, Moiré can be seen.

In recent years, organic electroluminescence displays with a small fill factor are growing popular, but such displays are usually more prone to the screen door effect and moiré. With conventional optical low-pass filters, only the pixel pitch in the vertical and horizontal directions are taken into account, but this is insufficient with small fill-factor pixels, and consideration for various diagonal periods is needed.

A two dimensional sinusoidal structure diffraction grating is developed for a moiré-reducing low-pass filter. The angle of the grating with the image pixel arrangement, the distance between the display and the grating, the grating depth, and the grating period are all chosen appropriately, and take into account multiple non-adjacent diagonal image pixel periods for all colors, consequently reducing moiré and the screen door effect. We present the calculations and evaluation results from plastic samples made by lithography toolod molds.

Moiré pattern reducing two-dimensional diffractive optical low-pass filter made from molded plastic

Zhaoyu Zhang, Chinese Univ. of Hong Kong, Shenzhen (China)

Ambient light is destructive to the reflective type projection system’s contrast ratio which has great influence on the image quality. In contrast to the conventional front projection, short-throw projection has its advantage to reject the ambient light. In order to direct light from a large angle due to the low lens throw ratio to the viewing area which is in front of the screen, Fresnel lens-shaped reflection layer is often used. The structure separates the path of the ambient light and projection light, creating the chance to solve the problem that ambient light is mixed with projection light. However, with solely the lens-shaped reflection layer is not good enough to enhance the contrast ratio due to the scattering layer, which contributes a necessarily wide viewing angle, could interfere with both light paths before hitting the layer. So we propose a new design that sets the draft angle surface with absorption layer and adds an angle-selective absorber to separate these two kinds of light. The absorber is designed to fit the direction of the projection light, leading to a small absorption cross section for the projection light and respectively big absorption cross section for the ambient light. We have simulated the design with Tracepro, a ray tracing program and find a nearly 8 times contrast ratio enhancement against the current design in theory. This design can hopefully provide efficient daily life display with better viewer satisfaction.

Moiré reducing two-dimensional diffractive optical low-pass filter made from molded plastic

Fourier holographic display for augmented reality using holographic optical element

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A method for realizing a three-dimensional (3D) augmented reality (AR) in Fourier holographic display system is proposed. A holographic optical element (HOE) with the function of Fourier lens is adopted in the system. Recently, some reports focused on displaying 3D virtual images using super multi-view and light field display techniques in AR. Comparing with those 3D techniques, holography is the closest way to provide all of 3D depth cues for human. The holographic display in Fourier configuration is implemented by placing a lens in front of a spatial light modulator (SLM). It causes the real scene located behind the Fourier lens to be distorted. In the proposed method, since the HOE functions as the lens just for the Bragg matched condition, there is not any distortion when observing the real scene through the HOE. Furthermore, optical characteristics of the recording material were measured for confirming the feasibility. Because, plane waves modulated by an SLM propagate to different directions corresponding to the diffraction angles, there are some Bragg mismatched components for the HOE. The experimental results verified that the direction of reconstructed waves linearly changes according to that of the probe wave change in the range of the SLM diffraction angle. Thus, the wavefront distortion is only related to the tilting angle between the SLM and the HOE. In the display process, an algorithm for the computer generated hologram is proposed for compensating the wavefront distortion. The see-through effect of the holographic display is confirmed experimentally.

9770-13, Session 3

Master-oscillator power-amplifier in the red spectral range for holographic displays

Gunnar Blume, Johannes Pohl, David Feise, Jörg Wiedmann, Peter Ressel, Bernd Eppich, Alexander Sahm, Arnim Ginolas, Oliver Nedow, Maik Jendrzejewski, Pia Johne, Julian Hofmann, Bernd Sumpf, Götz Erbert, Katrin Paschke, Ferdinand-Braun-Institut (Germany)

RGB light sources with a coherence length of several meters are required for holographic displays. Furthermore, these emitters must be sufficiently small in size, to be employed in today’s consumer market products. Therefore, an all-semiconductor based solution is preferred. We developed red-emitting semiconductor lasers near 635 nm and 647 nm with internal distributed Bragg reflectors and suitable amplifiers at these wavelengths to boost their output power. We investigated tapered amplifier with ridge waveguide sections [1] as well as truncated tapered designs [2] in master-oscillator power-amplifier configuration (MOPA). This allows the generation of diffraction limited single mode emission by the MO chip and subsequent amplification of the radiation by the PA chip by more than 10 dB, without significantly degrading the coherence properties. We successfully demonstrated an optical output power of more than 300 mW at 635 nm [1] and 500 mW at 647 nm [3]. The radiation featured a linewidth below 10 MHz, which corresponds to a coherence length of at least several meters, well suited for a holographic system.

At the conference we will present strategies to miniaturize the MOPA systems, and to improve the output power in order to increase the size of holographic displays.


9770-14, Session 3

Lightweight high-brightness helmet-mounted head-up display system

Mathieu Wagner, Thibault North, Stéphane Bourquin, Haute Ecole Spécialisée de Suisse occidentale (Switzerland); Lucio Kilcher, Lemoptix (Switzerland)

Head mounted displays (HMDs) have been a topic of interest in the last two decades for their numerous applications in fields such as medicine or aviation. This interest nowadays reawakens with the ubiquity of portable devices. HMD systems may be used either for hand-free interaction with electronic devices or for augmented reality (AR). In AR, a wide-angle image is displayed in the user field-of-view (FOV), and virtual objects can be mapped to objects in the real world view. Helmet-mounted display systems (HDS), on the other hand, are typically less invasive and only require that information be displayed onto the user FOV. One specific application of HDSs is displays targeting motorcycle users to provide driving information. Previous work include monocular systems, which rely the image of a screen to the user eye. Such systems are often bulky, may reduce the user FOV, lack luminosity, or require optical components in the vicinity of the eye. These constraints need to be relaxed to ensure maximal comfort and security.

In this paper, we present a new HDS for motorcycle users. A 2D-MEMS micro-projector is used to form an image directly onto the retina of the user. The HDS consists of an optomechanical 3D-printed module, attached to the bottom of the helmet, fully adjustable to fit the morphology of most users. Results indicate that a binocular virtual image of 7”x5” can be projected with sufficient luminosity on a sunny day, and that the system is compatible with UN regulations for protective helmets.

9770-15, Session 4

A portable intra-oral scanner based on sinusoidal pattern of fast phase-shifting

Chia-Ming Jan, Metal Industries Research & Development Ctr. (Taiwan); Ying-Chieh Lin, Metal Industries Research & Development Ctr (Taiwan)

This paper presented an algorithm of space mapping between projections and capturing orientation exchange of intra-oral scanning configuration. We analyzed and discovered an architecture based on Active Triangulation, which included a line-shape laser diode, a beam shape generator, and an adaptive CMOS sensor. The main purpose aimed to its accuracy of the laser scanning. Consequently, we integrated the dynamic triangulations into a self-designed library of CAD/CAM to approach the pixels mean error about 0.00509909. The multi-view point cloud registration integrated into our portable device is another highlight so as to achieve the raw data integration for complex surface of tooth. More specifically, we modified the compensation of Barrel Distortion so that an ease of calibration was developed well by our system. By utilizing the OpenGL library, the development of triangulation grid method can be directly exchanged from multi- point clouds, which demonstrated the accuracy of grid about 1.4569um accompanied with the STL open format.

9770-16, Session 4

Fully transparent thin film transistors based on zinc oxide channel layer and molybdenum doped indium oxide electrodes

Mateusz T. Madzik, Elangovan Elamurugu, Jaime Viegas, Masdar Institute of Science & Technology (United Arab Emirates)
A unique feature of metal oxide thin film transistors (TFT) is their transparency. In contrast to silicon based technology, they are suitable for numerous application including displays and sensors. In this work we report the fabrication of thin film transistors (TFT) with zinc oxide channel and molybdenum doped indium oxide (IMO) electrodes, achieved by room temperature sputtering. Hafnium oxide was used as gate dielectric, deposited by atomic layer deposition. A set of devices was fabricated, with varying channel width and length from 5 ?m to 300 ?m for different deposition parameters, along with a control substrate dedicated for the study of channel and electrode materials. This approach allows to directly relate changes in key device properties to deposition parameters. Output and transfer characteristics were then extracted to study the performance of thin film transistors, namely threshold voltage, on-resistance, saturation current and channel mobility, enabling to determine optimal fabrication process parameters. Additionally, measurements of optical transmission in the UV-VIS-IR are also reported. Finally, we present an optoelectronic comparison between ITO and IMO electrode based FETs.

9770-17, Session 4

Additive direct printing for silver nanowire electrode array

Yeongjun Lee, Sung-Yong Min, Su-Hun Jeong, Tae-Sik Kim, POSTECH (Korea, Republic of); Ju Yeon Won, Inha University (Korea, Republic of); Hobeom Kim, POSTECH (Korea, Republic of); Jae Kyeong Jeong, Inha University (Korea, Republic of); Tae-Woo Lee, POSTECH (Korea, Republic of)

Ag nanowires (AgNWs) have low sheet resistance and high optical transmittance and are therefore promising candidates as an alternative to conventional transparent and brittle indium-tin-oxide (ITO) electrodes. However, use of existing short AgNWs has allowed fabrication of only randomly-dispersed sheet-type transparent electrodes, so the approach it cannot take full advantage of nanoscale electrodes (nanoelectrode). Moreover, the conventional solution-dispersed AgNWs have the limitations such as low dispersion uniformity, poor surface roughness, high optical haze and low controllability, which should be resolved. Here, we report the use of our additive nanoscale printing (Electrohydrodynamic Nanowire Printing: ENP) as a simple, fast and inexpensive method to print a new AgNWs platform for use as a transparent electrode. ENP produces highly-aligned and individually position-controllable AgNWs with an average diameter of 695 nm and low resistivity of 5.7 ?cm, which is comparable with that of bulk Ag (1.6 ?cm). We fabricated various FETs including all-NF FETs (carrier mobility ~ 2.08 cm2·V-1·s-1) that use two strings of Ag NFs, one as a nano-sized source nanoelectrode and one as a drain nanoelectrode. We also demonstrated organic light emitting diodes (OLEDs), transparent heaters and touch screen panels, thereby proving the feasibility using of printed AgNW transparent electrodes. Our new AgNW platform will be useful for fabrication of various kinds of future nanoelectronics.
9771-1, Session 1  
**Single-beam Denisyuk holograms recording with pulsed 30Hz RGB laser (Invited Paper)**

Stanislovas J. Zacharavas, Ramunas Bakinis, Algimantas Stankauskas, Geola Digital uab (Lithuania)

It is well known fact that holograms can be recorded either by continuous wave (CW) laser, or by single pulse coming from pulsed laser. However, multi-pulse or multiple-exposure holograms were used only for interferometric measurements as well as for information storage.

We have used Geola’s pulsed RGB laser to record Denisyuk type holograms. Objects situated at the distance of more than 30cm we successfully recorded employing the multi-pulse working regime of the laser.

We have used laser operating at 440, 532, 660 nm wavelengths emitting pulses of laser radiation at the frequency of 30Hz, pulse duration of 50ns (440 and 660nm) and 35ns (535nm). Laser energy per pulse 1, 5 and 2 mJ at 440, 532 and 660 nm wavelengths. As photosensitive medium we have used Slavich-Geola PFG-03C.

Radiations with different wavelengths were mixed into “white” beam, collimated and directed onto the photoplate. For further objects illumination an additional flat mirror was used.

9771-2, Session 1  
**Precision holographic optical elements in Bayfol(R) HX photopolymer (Invited Paper)**

Friedrich-Karl Bruder, Bayer MaterialScience AG (Germany); Hyungseok Bang, LG Display Co., Ltd. (Korea, Republic of); Thomas P. Fäcke, Rainer Hagen, Dennis Hönel, Enrico Orselli, Christian Rewitz, Thomas Rölle, Günther Walze, Bayer MaterialScience AG (Germany); Dalibor Vukicevic, Universite de Strasbourg (France)

The versatility of Volume Holographic Optical Elements (vHOE) is high, especially because of their tunable angular and spectral Bragg selectivity. Those unique lightweight, thin and flat optical elements are enabled by the new instant developing photopolymer film Bayfol®HX technology, which allows to mass produce cost effective diffractive optics due to its simplified and robust holographic recording process.

From a pure scientific point of view volume holography is well established. In practice though, commercially available optical design software is not adapted to handle the specific characteristics of photopolymer diffractive optical elements and their recording. To achieve high quality vHOE precision optics, the recording setup needs to accommodate several aspects that will be covered in this paper. We report on means how to deal with photopolymer shrinkage and average refractive index changes of the recording media. An important part in diffractive optics design is the compensation of different conditions between the holographic recording setup and vHOE integration into a final product. Usually substrates might need to be changed (in material, in refractive index) as well the illumination sources are using incoherent light having angular and spectral emission profiles with finite bandwidth.

Recently special in- and out-coupling vHOEs are becoming attractive e.g. in near eye displays and in compact lighting devices. We will report on design considerations and adjustments to the recording condition for a specific in-coupling vHOE and demonstrate the effects of pre-compensation on this example.

9771-3, Session 1  
**Dual-page reproduction with the using of a transmitted reference beam in holographic data storage**

Yutaro Katano, Tetsushiko Muroi, Nobuhiro Kinoshita, Norihiro Ishii, Nobuo Saito, NHK Japan Broadcasting Corp. (Japan)

Holographic Data Storage (HDS) is suitable for long-term archival storage to record and store 8K ultra high definition television (8K Super Hi-Vision) which we are conducting research and development in as a next-generation broadcast media. HDS has a high data transfer rate and large capacity. For high-speed data reproduction, we have proposed the method of simultaneous dual-page reproduction by irradiating the hologram with two types of polarization of reference light, which has the potential to double the number of the reproduced data pages per unit in the same amount of time. However this method requires a higher power laser source in the optical setup to split the beam into two reference beams and not increase the irradiation time per unit data page. This study presents the efficient dual-page reproduction reusing the reference beam, most of which passes through the medium after reconstruction. The transmitted reference beam can be changed into the second reference beam whose polarization is orthogonal to that of the original reference beam by passing through a half-wave plate. These two reference beams enter the medium at a different incident angle, then two reconstructed beams with polarization that is orthogonal to each other are obtained. Therefore two different data pages can be simultaneously reproduced without increasing the output power of the laser. This presentation shows the experimental results and potential for improving data transfer rates using an energy-efficient approach.

9771-4, Session 2  
**Ultra-realistic imaging and OptoClones(TM)**

Hans I. Bjelkhagen, Glyndwr Univ. (United Kingdom); Alkiviadis Lembessis, Andreas Sarakinos, The Hellenic Institute of Holography (Greece)

Recent improvements in solid state CW lasers, recording materials and light sources for displaying color holograms (such as LED lights) are described. Full-color analogue holograms can now be created with substantially better image characteristics than previously possible, leading to new types of displays and applications. Such holograms are referred to as OptoClones™ in particular new recording systems, based on recent DPSS and semiconductor lasers, combined with novel ultra-fine-grain panchromatic silver halide recording materials have now demonstrated such holograms of both lower noise and higher spectral accuracy. The goal is to be able to record holograms which display the colors of the recorded object as accurately as possible. In particular, recording museum artifacts using movable holographic equipment is reviewed. The most recent Progress in illumination technology, for example the new LED lights, is leading to a further major reduction in display noise and to a significant increase of the clear image depth and brightness of such holograms. The possibility to record ultra-realistic images depends on selecting the optimal recording laser wavelengths. The most recent recorded OptoClones™ are the Fabergé Eggs at the Fabergé Museum in St. Petersburg, Russia.
9771-6, Session 2

Concurrent studies on artworks by digital speckle pattern interferometry and thermographic analysis

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In this study Digital Speckle Pattern Interferometry and Thermographic Analysis have been utilized in the field of cultural heritage artifacts diagnostics. Both the techniques are non-invasive and non-destructive ideal diagnostic tools, that can be applied on almost any type of archaeological findings and works of art, providing relevant information about their state of conservation. Qualitative and quantitative characterization of the objects under test, regarding detachments of layers, delaminations, cracks, inclusions, hidden flaws, and so on, can be obtained. We report on a comparative, inspection that we carried out on several samples. We analyzed both original objects (a painting on wood, a fragment of painting on canvas, a Mexican terracotta figurine, a bronze sculpture) as well as models of frescoes. Jointly measurements were implemented, in order to complement the results of the two techniques, in the attempt to overcome typical ambiguities resulting from utilizing the respective capabilities of each one of the distinct techniques (for example discriminating surface and/or subsurface damages, discontinuities, defects, etc.). Whole body structural behavior, as well as defects in restricted areas, were revealed on the objects under test. The results obtained demonstrate that concurrent measurements by Digital Speckle Pattern Interferometry and Thermographic Analysis largely improve the traditional art-restorers diagnostics methods.

9771-7, Session 2

Silent images in dialogue

Maria Isabel Azevedo, Elizabeth Sandford-Richardson, Martin J. Richardson, De Montfort Univ. (United Kingdom); Luis Miguel Bernardo, Helder M. Crespo, Univ. do Porto (Portugal)

We could consider three principal ways to show the movement in a digital holographic image. The holographic plate is static and a projector is lighting it in movement, or the holographic plate is placed under a mechanism that moves it and the lighting is static, or the holographic plate and the lighting are statics and the viewer is moving in front of the holographic plate. According to our previous work a viewer in front of a digital holographic image becomes a reflection of engagement creating a performance, this means the viewer’s movement is creating a temporal identity between the image seeing and the act of seen, we are considering a performance space created by the holographic image, the viewer and the space in between.

In this series of digital art holograms and lenticulars, we used the HoloCam Portable Light System with the 35 mm cameras, Canon IS3, Nikon D3100 and the Canon 700D, to capture the image information, it was then edited on the computer using Motion 5 and Final Cut Pro X programs. We are presenting several actions in the digital holographic space. The figures are in dialogue within the holographic space and the viewer, in front of the holographic plate. In holography the time of the image is the time of the viewer presence. And that particular feature is what distinguishes digital holography from other media.

9771-10, Session 3

Development of 3D holographic endoscope

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Endoscopes are used frequently in medical operations to reach locations and visualize the tissues and the organs in human body where otherwise it would be impossible to observe. Classical endoscopes have a large field of view and produce a very high quality images but at the same time due to nature of the optics it induces distortions. In addition, the images are being two dimensional, the exact dimensions of the objects are hard to determine and quite dependent on the experience and mastery of the operator.

Here we present development of a 3D optical imaging medical endoscope that is capable of holographic imaging of a scene or object and at the same time that can be used as a classical endoscope. The recorded hologram enable us to calculate the 3D information of the scene or the object and we overlay this information on the 2D picture. This capacity will provide correction of the object image distortions as well as providing a more realistic 3D view of the object.

Reference wave required for the hologram recording is obtained in different ways. First, as in the classical holography recording, splitting the laser beam before the object illumination, and secondly creating the reference beam from the object beam itself. This second method does not require path-length matching between the object wave and the reference wave and allows the usage of short coherence length light sources. Both methods are compared and the experimental results will be presented.

9771-11, Session 3

Virtual interferogram-generation algorithm for phase measurement using two interferograms

Jin Nozawa, Atsushi Okamoto, Hokkaido Univ. (Japan); Masataka Toda, Yasuyuki Kuno, AISIN SEIKI Co., Ltd. (Japan); Akihisa Tomita, Hokkaido Univ. (Japan)

Phase-shifting digital holography is a technique for phase measurement with high spatial resolution and applies in many fields. This technique typically requires four phase-shifted interferograms between signal beam and reference beam. We focused on the two-step phase shifting algorithm, which needs only two phase-shifted interferograms and an intensity distribution of the reference beam to reduce the number of required interferograms. However, in this algorithm, the intensity of the reference beam must be much greater than that of the signal beam because this algorithm uses the quadratic formula and the inside of square root must be positive. This leads to the saturation of the dynamic range of the image sensor and a degradation of accuracy. In this paper, we propose a virtual interferogram-generation algorithm (VIGA) to improve the performance of phase-shifting digital holography using two interferograms. This algorithm virtually generates a π phase-shifted interferogram by the intensity distribution of a signal beam and that of a reference beam with an observed interferogram. Therefore, capturing two real interferograms and generating two virtual interferograms, the four-step phase shifting algorithm can be used for this method. Comparing to the conventional algorithm, the VIGA has no limitation in terms of the magnitude of the intensity. This means that the intensity of reference beam and that of signal beam can be equalized and the saturation of dynamic range of image sensor can be prevented. Therefore, the VIGA makes highly accurate phase measurement possible owing to the effective utilization of the dynamic range of image sensor.
Enhancing phase retrieval speed for real-time interferometer and ESPI by two-dimensional continuous wavelet transform

Chun-Hsiung Wang, Kuan-Yu Hsu, Chih-Kung Lee, National Taiwan Univ. (Taiwan)

A real-time three-dimensional surface profile metrology system was implemented by integrating Fourier Transform (FT) based algorithms to convert interference intensity fringes to wrapped frequency phase maps and then to unwrapped phase maps. The revival of this field can find its roots in recognizing the development of high-resolution high-speed CCD/CMOS over the years.

Continuous Wavelet Transform (CWT), which possesses the ability to construct a characteristic mother wavelet of good time and frequency localization according to different fringes conditions, was implemented with an attempt to reduce redundant fitting process of ordinary Short Time Fourier Transform (STFT) and therefore to accelerate the FT-related algorithms needed. Implemented with the efficient wavelet construction process by using CWT, Electronic Speckle Pattern Interferometer (ESPI) was adopted to take advantage of this new process.

Different form using several phase shifting steps before to solve the direction ambiguity, which takes time to capture multiple intensity maps during measurement, the phase maps needed were retrieved from a single frame interference fringes. It is to be noted that this one-image interference fringe was captured by having a pre-introduced spatial carrier frequency embedded within the experimental setup so as to remove the directional ambiguity. CWT was also introduced as an adaptive windowed FT to deal with different signal-to-noise ratios, which is expected to achieve higher accuracy and faster processing speed. For phase unwrapping, Poisson’s equation with Neumann boundary condition was solved by using CWT as well. The benefit of using CWT as compared to FT and STFT was demonstrated experimentally.

Holographic imaging through a scattering medium by diffuser assisted statistical averaging

Michael Purcell, Manish Kumar, Stephen C. Rand, Univ. of Michigan (United States)

The ability to image through a scattering or diffusive medium such as tissue or hazy atmosphere is a goal which has garnered extensive attention from the scientific community. Existing imaging methods in this field make use of phase conjugation, time of flight, iterative wave-front shaping or statistical averaging approaches, which tend to be either time consuming or impractical. In this study, we introduce a novel and practical way of statistical averaging which makes use of a rotating ground glass diffuser to nullify the adverse effects caused by speckle introduced by the first static diffuser / aberrator. This is a Fourier transform-based, holographic approach which demonstrates the ability to recover detailed images and suggests that further remarkable improvement upon this process may be achieved. Furthermore, although current experiments were performed with 2D flat images, this method can be easily adapted for recovery of 3D extended object information. The simplicity of this approach makes it fast, reliable, and potentially scalable into a portable technology. Since imaging through a diffuser has direct applications in biomedical imaging and military technologies this method may be used together with other techniques to advance imaging capabilities in many fields.
Common path depth-filtered digital holography for high-resolution imaging of buried semiconductor structures

Markus Finkeldey, Falk Schellenberg, Nils C. Gerhardt, Christof Paar, Martin R. Hofmann, Ruhr-Univ. Bochum (Germany)

We investigate digital holographic microscopy in reflection geometry for non-destructive 3D imaging of semiconductor devices. This technique provides high resolution information of the inner structure of a sample while maintaining its integrity. As an example we use our setup to localize the precise spots for laser fault injection, in the security related field of side-channel attacks.

While digital holographic microscopy techniques easily offer high resolution phase images of surface structures in reflection geometry, they are typically incapable to provide high quality phase images of buried structures due to the interference of reflected waves from different interfaces inside the structure. In order to investigate buried structures we use a concept called depth-filtered digital holography (DFDH). The method allows to separate phase images originating from different depths using a technique comparable to phase-resolved optical coherence tomography.

Our setup includes a sCMOS camera for image capture, arranged in a common-path interferometer to provide very high phase stability. A tunable external cavity semiconductor laser serves as the light source. As a proof of principle, we show sample images of the inner structure of modern microcontrollers. By imaging from the backside for a set of samples with Si-substrates thinned to different thicknesses we determine the achievable axial resolution obtained from the phase in the holograms. To investigate the efficiency of the DFDH approach we are comparing the results with additional numerical depth filtering methods. Finally, we compare our holographic method to classic optical beam induced current (OBIC) imaging to demonstrate its benefits.

Investigation of particles located in the water by digital holography

Victor V. Dyomin, Denis V. Kamenev, National Research Tomsk State Univ. (Russian Federation)

A method of automatic processing of particles digital hologram is described. The technique of the information extraction from digital hologram of particles is suggested. These methods allow evaluation the average particle size and estimation the concentration of particles and the particle size distribution. It is applicable for objects whose shape is not interesting from the research viewpoint. According to the developed model it assumes that the shape of the particles cross-sections is close to a circle or ellipse. The method includes several stages: digital hologram reconstruction “layer by layer” and 2-D display of holographic image of the volume contained the particles, its processing, binarization, and particles parameters measurement. To get the particle size distribution and particles concentration an erosion operations certain amount of times. During the erosion operation use to binary 2-D display of the volume, the particles with certain size disappear, and their number is calculated. One of the main advantages of the algorithm is automation the process of getting the above information and possibility to produce video based on holographic data. The method was applied for air bubbles and particles of sand settled in water. Video based on holographic data is created. For every frame of holographic video the particles size distribution is received, the average size and particles concentration of the volume with a given depth is estimated. The accuracy of algorithm is estimated, limits of its applicability is determined.

Study on the diffraction pattern and micro-mirror angle of digital micro-mirror device (DMD) for collinear holographic data storage system

Yong Huang, Xiao Lin, Xiaotong Li, Yabin Cheng, Ke Xu, Guoguo Kang, Beijing Institute of Technology (China); Hideyoshi Horimai, Toyohashi Univ. of Technology (Japan); Xiaodi Tan, Beijing Institute of Technology (China)

Holographic data storage technology is becoming more and more important with the increasing demand of data storage in the era of big data. Collinear holography as a novel writing and reading technology for a holographic storage system is very promising and differs from conventional off-axis holographic technology. Digital micro-mirror device (DMD) as the spatial light modulator to add 2D reference and information pattern is the key element in collinear holography. Optimal utilization of the DMD is thus very important for system performance. In this work, we studied the diffraction pattern created by DMD and the effect of micro-mirror angle of DMD for data storage performance theoretically and experimentally, which will provide valuable guidelines for device fabrication and system optimization.

In this study, we propose the technique to improve the viewing zone continuity, which increases the spatial frequencies of speckle patterns to invisibilize them, instead of removing them. Virtual viewpoints are inserted between real viewpoints to make an interval of the viewpoints smaller than the pupil diameter of eyes to improve the viewing zone continuity. In this case, regular interference patterns appear in the reconstructed images because random phases were added to the parallax images to improve the continuity of the viewing zone.

We previously proposed the calculation technique for computer-generated holographic stereogram based on multi-view display. In this study, we extend our previous work to study the diffraction pattern and micro-mirror angle of DMD for holographic data storage system.

We investigated digital holographic microscopy in reflection geometry for non-destructive 3D imaging of semiconductor devices. This technique provides high resolution information of the inner structure of a sample while maintaining its integrity. As an example we use our setup to localize the precise spots for laser fault injection, in the security related field of side-channel attacks.

While digital holographic microscopy techniques easily offer high resolution phase images of surface structures in reflection geometry, they are typically incapable to provide high quality phase images of buried structures due to the interference of reflected waves from different interfaces inside the structure. In order to investigate buried structures we use a concept called depth-filtered digital holography (DFDH). The method allows to separate phase images originating from different depths using a technique comparable to phase-resolved optical coherence tomography.

Our setup includes a sCMOS camera for image capture, arranged in a common-path interferometer to provide very high phase stability. A tunable external cavity semiconductor laser serves as the light source. As a proof of principle, we show sample images of the inner structure of modern microcontrollers. By imaging from the backside for a set of samples with Si-substrates thinned to different thicknesses we determine the achievable axial resolution obtained from the phase in the holograms. To investigate the efficiency of the DFDH approach we are comparing the results with additional numerical depth filtering methods. Finally, we compare our holographic method to classic optical beam induced current (OBIC) imaging to demonstrate its benefits.

In this study, we propose the technique to improve the viewing zone continuity, which increases the spatial frequencies of speckle patterns to invisibilize them, instead of removing them. Virtual viewpoints are inserted between real viewpoints to make an interval of the viewpoints smaller than the pupil diameter of eyes to improve the viewing zone continuity. In this case, regular interference patterns appear in the reconstructed images instead of the speckle patterns. The proper phase modulation of the parallax images displayed to the real and virtual viewpoints increases the spatial frequencies of the regular patterns. Human eyes have no sensitivity to the spatial frequencies higher than 50 - 60 cycles/degree.

The proposed technique was experimentally verified. The number of real viewpoints was 1678, and the total viewpoints was increased to 32716 by adding the virtual viewpoints. The spatial frequency of the regular speckle patterns was 74 cycles/degree. We confirmed the generation of the continuous viewing zone and the reduction of speckle patterns.
Daping Chu, Univ. of Cambridge (United Kingdom)
Yuanbo Deng, Univ. of Cambridge (United Kingdom);
Sundeep Jolly, Nickolaos Savidis, Bianca Datta, V. Michael Bove Jr., MIT Media Lab. (United States); Daniel Smalley, Brigham Young Univ. (United States)
B.C. Shin, Hoonjong Kang, Korea Electronics Technology Institute (Korea, Republic of)
Shunsuke Igarashi, Tomoya Nakamura, Tokyo Institute of Technology (Japan); Kyoji Matsushima, Kansai Univ. (Japan); Masahiro Yamaguchi, Tokyo Institute of Technology (Japan)

9771-20, Session 5

Gaze contingent hologram synthesis for holographic head-mounted-display
Jisoo Hong, Youngmin Kim, Sunghee Hong, Choonsung Shin, Hoonjong Kang, Korea Electronics Technology Institute (Korea, Republic of)

Development of display and its related technologies provides immersive visual experience with head-mounted-display (HMD). However, most available HMDs provide 3D perception only by stereopsis, lack of accommodation depth cues. Recently, holographic HMD (HHMD) arises as one viable option to resolve this problem because hologram is known to provide full set of depth cues including accommodation. Moreover, by virtue of increasing computational power, hologram synthesis from 3D object represented by point cloud can be calculated in real time even with rigorous Rayleigh-Sommerfeld diffraction formula. However, in HMD, rapid gaze change of the user requires much faster refresh rate, which means that much faster hologram synthesis is indispensable in HHMD.

Because the visual acuity falls off in the visual periphery, we propose here to accelerate synthesizing hologram by differentiating density of point cloud projected on the screen. We classify the screen into multiple layers which are concentric circles with different radii, where the center is aligned with gaze of user. Layer with smaller radius is closer to the region of interest, hence, assigned with higher density of point cloud. Because the computation time is directly related to the number of points in point cloud, we can accelerate synthesizing hologram by lowering density of point cloud in the visual periphery. Cognitive study reveals that user cannot discriminate those degradation in the visual periphery if the parameters are properly designed. Prototype HHMD system will be provided for verifying the feasibility of our method, and detailed design scheme will be discussed.

9771-21, Session 5

Progress in off-plane computer-generated waveguide holography for near-to-eye 3D display
Sundeep Jolly, Nickolaos Savidis, Bianca Datta, V. Michael Bove Jr., MIT Media Lab. (United States); Daniel Smalley, Brigham Young Univ. (United States)

Waveguide holography refers to the use of holographic techniques for the control of guided-wave light in integrated optical devices (e.g., off-plane grating couplers and in-plane distributed Bragg gratings for guided-wave optical filtering). Off-plane computer-generated waveguide holography (CGWH) has also been employed in the generation of simple field distributions for image display. We have previously depicted the design and fabrication of a binary-phase CGWH operating in the Raman-Nath regime for the purposes of near-to-eye 3-D display and as a precursor to a dynamic, transparent flat-panel guided-wave holographic video display. In this paper, we describe design algorithms and fabrication techniques for multilevel phase CGWHs for near-to-eye 3-D display.

9771-22, Session 5

Filling factor characteristics of masking phase-only hologram on the quality of reconstructed images
Yuanbo Deng, Univ. of Cambridge (United Kingdom);
Daping Chu, Univ. of Cambridge (United Kingdom)

As the most basic and common algorithm, Gerchberg-Saxton(G-S) algorithm has been implemented to calculate phase CGHs of a 2D target image in this research. The evaluation metrics include image intensity, pattern profile, RMSE(root mean square error) and SSIM(structural similarity ). Firstly, the iteration times of G-S algorithm has been optimized to achieve balance between calculation speed and image quality. Secondly, in practice, only part of the CGH will be illuminated. We choose different filling factor (the selected area to the whole area) of the calculated CGH and leave the rest blank and then evaluate quality of the constructed images. The results show that filling factor will affect the image quality and limitation of filling factor has been found out under certain conditions. Thirdly, the phase modulation levels on a phase-only SLM does not necessarily match that of the calculated CGH. We add proportional phase errors on the CGH first to study the insufficient or over phase modulation of SLM and then we add noise errors onto CGH and study the extra intensity variation of reconstructed image. Results show that the proportional phase errors will affect the reconstructed image in a conjugated way and the noise errors will transfer to the intensity of reconstructed image.

To conclude, different aspects of phase CGH facing practical application have been studied and experiment results show the corresponding influences on reconstructed holographic images.
Proposed method enables us to synthesize the hologram of realistic and deep scene in practical computational time, and overcome the limitation of size in previous RS method.

9771-25, Session 6

Decomposition method for acceleration of large scale CGH calculation on distributed machines

Jackin Boaz Jessie, Shinpei Watanabe, Takeshi Ohkawa, Kanemitsu Ootsu, Takashi Yokota, Yoshihiko Yatagai, Takanobu Baba, Utsunomiya Univ. (Japan)

Holograms calculated on computers, known as Computer generated holography (CGH), demand processing of huge data sets in the order of GigaPixels for display applications. Parallel and distributed computing devices are the only available solution to handle such computation load for which multi-GPUs and PC-clusters are commonly used. These devices can perform huge floating point operations per second, but are very slow in frequent communication between them. On the other hand, to calculate one data point on the hologram we need data from all the points on the object which makes the computation highly data dependent i.e., the data distributed among the parallel devices has to be moved back and forth more frequently, thereby increasing the communication load. Hence the computation power of the parallel devices are wasted due to the communication bottleneck produced by the large data dependency. Hence reducing or totally avoiding communication will put these parallel computing devices to its full potential which in turn considerably increases the computation speed.

We propose a method that efficiently avoids all communications between parallel computing devices by decomposing both the object and hologram planes. The method uses the shifting property of Fourier transform to achieve this. The computed results are verified for correctness by simulated and optical reconstructions. The computations are executed on a 4-node PC cluster with each node having one GPU. The obtained results are compared with the conventional Transpose-Split method and the standard FFTW-MPI library. We could obtain up to 10 times increase in computation speed with compared to the other methods. This calculation method is a promising candidate to be used in real time generation of holograms for dynamic holographic displays.

9771-27, Session 6

Static and dynamic holographic 3D display based on large size materials

Hongyue Gao, Jicheng Liu, Yingjie Yu, Shanghai Univ. (China)

3D display with more information shown is much better than 2D display. Current 3D techniques, such as stereoscopic 3D display, volumetric 3D display and so on, has some problems in them to be solved, and therefore they are not widely applied. Holographic display is a necessary. Therefore, we study hologram printing, including computer generated hologram, holographic storage materials and hologram print system. Furthermore, we realize real time holographic 3D display in large size materials, which solves the problem that dynamic holography cannot reach video rate in materials. In this paper, we will present our work on hologram print and holographic 3D video display. We hope that holographic 3D display can be used in 3D imaging and display to provide more information than 2D ones in the future.

9771-28, Poster Session

Study of gratings with variable periods

Arturo Olivares-Pérez, Israel Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Santa Toxqui-López, Benemérita Univ. Autónoma de Puebla (Micronesia, Federated States of); Mauricio Oratz-Gutiérrez, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); Jorge Ordóñez-Padilla, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Hildia Y. Mejias-Brisuela, Univ. Politecnica de Sinaloa (Mexico)

A theoretical study with sinusoidal amplitude diffraction gratings, that are elaborated with variable periods is shown. Their behavior of the diffraction pattern and the symmetry degree of the gratings were observed. The grating period is increased of fringe to fringe, starting with a small period and ending with a big period, that is, the grating edge, start with high spatial frequency and it finish with low spatial frequency. This modulation kind of the gratings causes a widening in the diffracted orders.

9771-29, Poster Session

Holographic cells with random distribution and determined orientation

Arturo Olivares-Pérez, Israel Fuentes-Tapia, Villa H. Joan-Manuel, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Diffraction gratings behavior was studied, through holographic cells, that are micro circular areas coded with amplitude sinusoidal grating. The orientation and distribution random of the diffraction gratings in the cells, introduced into diffracted orders a random modulation. A study of the behavior distribution was realized as function of the fringes pattern and orientation of each cells, as the cells number.

9771-30, Poster Session

Holographic recording physicochemical mechanism for PVA-FeCl₃ + h[ν]

Jorge Ordóñez-Padilla, Arturo Olivares-Pérez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Photo-physicochemical processes involved in the changes of imaging are described. Holographic gratings by etching process generates photo-crosslinking through electron transfer, by the mobility of the active radical ions, and not active in the system (PVA-FeCl₃ + hv). The reorientation of electric charges by the polarity between atoms and molecules establish intramolecular crosslinks. This process is essential due to the photochemical reaction of reducing Fe³⁺ to Fe²⁺ ion. The optimal holographic film had a diffraction efficiency of 26%.

9771-31, Poster Session

Dynamic gratings recording in liquid crystal light valve in the infrared

Konstantin Shcherbin, Igor A. Gvozdovskyy, The Institute of Physics (Ukraine); Dean R. Evans, Air Force Research Lab.
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9771-34, Poster Session

Measurement of optical activity of honey bee

Mauricio Ortiz-Gutiérrez, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); Arturo Olivares-Pérez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Juan Carlos Ibarra-Torres, Univ. de Guadalajara (Mexico); Marco Antonio Salgado-Verduzco, Univ. Michoacana de San Nicolás de Hidalgo (Mexico)

Optical activity of some substances, such as chiral molecules, often exhibits circular birefringence. Circular birefringence causes rotation of the vibration plane of the linearly polarized light as it passes through the substance. In this work we presents optical characterization of honey as function of the optical activity when it is placed in a polariscope that consists of a light source and properly arranged polarizing elements. Experimental results can provide information on the quality of honey.

9771-35, Poster Session

Optical design of cipher block chaining (CBC) encryption mode by using digital holography

Sangkeun Gil, Univ. of Suwon (Korea, Republic of); Seok-Hee Jeon, Incheon National Univ. (Korea, Republic of); Jong-Rae Jung, Suwon Science College (Korea, Republic of); Nam Kim, Chungbuk National Univ. (Korea, Republic of)

We propose an optical design of cipher block chaining (CBC) encryption mode by using digital holography, which enables the cryptosystem to have higher security strength and faster processing than the conventional electronic method because of the longer security key with the two-dimensional array. In this paper, an optical design of CBC encryption mode is implemented by 2-step quadrature phase-shifting digital holographic encryption technique using orthogonal polarization. The proposed optical setup employs simply three polarizers and one quarter-wave plate phase retarder to obtain the quadrature phase-shifting of π/2 in the reference beam path. A block of plain text is encrypted with the encryption key by applying 2-step phase-shifting digital holographic method, and is changed into a block of cipher text which is a digital hologram. The ciphered digital holograms with the encrypted information are Fourier transform holograms and are recorded on CCDs with 256 gray level quantized intensities in our method. This means that the proposed optical CBC ciphering is a scheme which has analog-type information in the cipher text, while the conventional electronic CBC ciphering is a kind of bit-wise block message encryption processed by digital bits. These encrypted digital holograms are able to be stored by computer and be transmitted over a communication network. The decryption is performed with these encrypted digital holograms and the same encryption key. The proposed optical method is very effective in CBC mode due to the fast processing of large amounts of data and can be applied to various cryptosystem.

9771-36, Poster Session

Diffraction efficiency as function of temperature of holographic gratings into polyvinyl acetate as material holographic replication

Santa Toxqui-López, Benemérita Univ. Autónoma de Puebla (Mexico); Arturo Olivares-Pérez, Israel Fuentes-
The variation of diffraction efficiency as function of temperature of holographic gratings into ethyl acetate (adhesive) is present, this material exhibits excellent properties such as transparency, consistency and easy to handle. The diffraction holographic grating master is copied into ethyl acetate film by direct contact and subsequent exposed at different temperatures. The measurements of the diffraction efficiency have been determined by the ratio of the power of the diffracted light beam to the incident power of the beam.

9771-37, Poster Session

3D fingerprint analysis using transmission-mode multi-wavelength digital holographic topography

Ujitha A. Abeywickrema, Partha P. Banerjee, Akash Kota, Univ. of Dayton (United States); Akhlesh Lakhtakia, Stephen E. Swiontek, The Pennsylvania State Univ. (United States)

The analysis of fingerprints patterns is important for biometric identification. In this work, two-wavelength digital holographic interferometry is used to study the topography of various types of fingerprints. Parameters of a fingerprint (viz., thickness of the oil layer) may depend on the several conditions such as the temperature, time of the day, sweat conditions, etc. which can be used for identification purposes. With two-wavelength holographic interferometry, surface information can be measured with a better accuracy compared to single wavelength phase retrieving techniques. A tunable Argon-ion laser (457.9 nm to 514.5 nm) is used and holograms are recorded on a CCD camera sequentially for each wavelength using selected wavelength combinations. Then the phase is reconstructed for each wavelength and phase difference which corresponds to the synthetic wavelength (4 micrometer to 48 micrometer) is calculated. Finally, the topography is obtained by applying proper phase unwrapping techniques to the phase difference. Interferometric setups that utilize light reflected from the surface of interest have several disadvantages such as the effect of multiple reflections, and object tilt and shadow effects (for Mach-Zehnder configuration). To overcome these drawbacks, digital holograms of fingerprints using a transmission geometry are used. An approximately in-line geometry employing a slightly tilted reference beam to facilitate separation of the 0th diffraction order during holographic reconstruction, is used. Latent fingerprints on forensically relevant substrates viz. transparent glass, which have been developed by the deposition of 50-1000-nm-thick columnar thin films, are analyzed using in-line holography.
9772-1, Session 1

The American Institute for Manufacturing Integrated Photonics: advancing the ecosystem (Invited Paper)

Thomas L. Koch, College of Optical Sciences, The Univ. of Arizona (United States)

No Abstract Available

9772-2, Session 2

Optical and wireless-integrated next-generation access network based on coherent technologies (Invited Paper)

Toshihiko Hirooka, Masato Yoshida, Keisuke Kasai, Masataka Nakazawa, Tohoku Univ. (Japan)

We describe challenges toward the full-coherent convergence of optical and wireless technologies in broadband access networks. In next-generation (5G) mobile networks, the optical fronthaul link between baseband units (BBU) at a central office and remote radio heads (RRH) with antenna elements will form the fundamental infrastructure of a centralized radio access network (C-RAN) accommodating small cells. However, the common public radio interface (CPRI), which is currently used as a fronthaul link interface, transmits baseband signals in a digital radio-over-fiber (DRoF) format and requires a higher bandwidth. This is because the digitization of wireless signals results in an optical bandwidth that typically exceeds 15 times the original wireless signal, which easily requires more than 100 Gbit/s to send 10 Gbit/s wireless traffic. In contrast, recent progress on digital coherent optical transmission technologies has made it possible to utilize both the intensity and phase of an optical field, such as QAM and OFDM, thus enabling high-speed and high-capacity networks with high spectral efficiency. Such a system is almost identical to today’s wireless system as regards coherent transmission except for the carrier frequencies. Therefore, wireless and optical systems can be converged into one system, which we term a full-coherent system. A full-coherent system can offer substantial advantages in terms of transparency, cost, and bandwidth scalability. We will present the latest progress on digital coherent optical transmission technologies and their prospects for deployment for broadband radio access, ultimately realizing a full-coherent integrated network.

9772-3, Session 2

Sub-THz photonic frequency conversion using optoelectronic transistors for future fully coherent access network systems (Invited Paper)

Taiichi Otsuji, Kenta Sugawara, Gen Tamamushi, Adrian Dobroiu, Tetsuya Suemitsu, Victor Ryzhii, Katsumi Iwatsuki, Tohoku Univ. (Japan); Shigeru Kuwano, Jun-ichi Kani, Jun Terada, NTT Access Network Service Systems Labs. (Japan)

[Invited] Next-gen ultra-broadband ubiquitous, resilient access network systems need transparent and direct conversion between optical fiber and sub-THz wave wireless communication networks in order to keep the highest data transmission throughput over the entire ubiquitous environments. The convergence between the optical fiber (wired) and the sub-THz wireless transmissions with coherency will realize the media-independent access network systems in a smartest fashion.

The modulation format could be identical between the optical fiber and the wireless transmissions by developing the digital coherent technology. Since the frequency conversion from the wired optical carrier to the wireless sub-THz carrier can be performed with preserving the carrier coherency, the optical signals can be radiated from an antenna as wireless signals. The key device to realize the fully coherent transmission is an ultra-broadband, high-speed carrier converter.

We investigate the conversion of an optically wired data stream to a sub-THz wireless data and eventually from the wireless sub-THz to an IF band. We examine such functionalities of the photonic frequency down conversions in field effect transistors (FETs). We introduce and compare a graphene-channel FET (G-FET) and an InP-based high electron mobility transistor (InP-HEMT) to perform the photonic double-mixing conversion over the optical frequency bands to the microwave IF bands via sub-THz wireless frequency bands. Experimental results indicate the potentiality of these transistors over the sub-THz wireless frequency bands when the device feature size is scaled down to the level of sub-100 nm.

9772-4, Session 3

Novel optical fibers for data center applications (Invited Paper)

Ming-Jun Li, Corning Incorporated (United States)

The fast growing internet traffic demands for high speed optical interconnects and large information storages in data centers. These applications have short reach distances from a few meters to a few hundred meters, where multimode fiber (MMF) optimized at 850 nm is the fiber of choice for low cost system solutions using VCSELs. MMF has been evolving to improve its bandwidth capability and performance. High bandwidth OM4 MMF with bandwidth of 4700 MHz.km is currently being deployed in data centers. However, further increasing the bandwidth of OM4 beyond OM4 offers very small benefits as the system is limited by chromatic dispersion. Server virtualization, cloud computing, and higher speed ports are now driving networks to 100 Gb/s and eventually higher speeds (400Gb/s) in data centers. To meet the bandwidth demands, new fibers are needed to increase further the data rate and distance and to lower the cost for data center applications.

In this talk, we will discuss new optical fibers for high data rate short reach systems to overcome the current MMF limitations. We will present recent development in MMF to improve system performance. We will discuss bend insensitive MMF, chromatic dispersion compensation at 850 nm using MMF jumpers, wide bandwidth MMF for CWDM applications, and MMF optimized for high bandwidth at a longer wavelength for example 980 nm/1060 nm, or 1310 nm. We will discuss MMF designs and show experimental system performance. In addition to new MMF development, we will present a promising solution for high density parallel optical data links using space division multiplexing (SDM) technology. This technology could potentially offer high bandwidth, low cost and compact optical interconnect systems that are scalable and easy to manage. We will discuss both multicore fibers and few mode fibers for SDM applications in data centers.
9772-5, Session 4

Challenges in the implementation of dense wavelength division multiplexed (DWDM) optical interconnects using resonant silicon photonics (Invited Paper)

Anthony Lentine, Christopher T DeRose, Sandia National Labs. (United States)

Silicon photonics micro-resonator modulators and filters hold the promise for multi-terabit-per-second interconnects at energy consumptions well below 1 pJ/bit. To date, no products exist and little known commercial development is occurring using this technology. Why? In this talk, we review the many challenges that remain to be overcome in bringing this technology from the research labs to the field where they can overcome important commercial, industrial, and national security limitations of existing photonic technologies.

9772-6, Session 4

Next-generation-VCSELs as an enabling technology for green access networks and data centers (Invited Paper)

Werner H. Hofmann, Technische Univ. Berlin (Germany)

Access networks and data-cents are limited by the performance of the internal links. Optical interconnects, based on directly modulated VCSELs with ultimate speed ratings are an enabling technology for this application [1]. For serial 100 Gbps solutions today’s VCSELs have to increase their high speed performance. Here we report about our next generation devices. The devices discussed here are an optimized version of our very successful high-speed, temperature-stable 980 nm VCSELs [2]. Sharing the very short half-lambda cavity and a binary bottom-mirror with 32 pairs, levels were further optimized in order to minimize internal loss. Like previously parasitics are controlled by two oxide apertures and highly conducting current-spreading layers. InGaAs MQW active layers with with strain compensated GaAsP barriers were utilized for high differential gain. The 22 -pair Al2Ga8As/AI0.6Ga0.4As top-mirror was replaced by a 18-pair GaAs/ Al0.9Ga0.1As mirror for lower photon lifetime, better confinement and better heat extraction. The epi-structure was grown by IQE Europe. A detailed small-signal analysis was performed. The VCSELs showed modulation bandwidth around and exceeding 30 GHz. The measured data was fitted to single-mode and multi-mode rate-equation based models assuming self-organized carrier reservoirs formed by spatial hole burning. The common set of figures of merit is extended consistently to explain dynamic properties caused by carrier fluctuations.

Additionally, we discuss various other VCSEL technologies aiming at this application. We address wavelength from visible devices up to classic telecommunications wavelengths.

References

9772-7, Session 4

Silicon photonic Mach Zehnder modulators for next-generation short-reach optical communication networks (Invited Paper)

Cosimo Lacava, Zhixin Liu, Dave Thomson, Optoelectronics Research Ctr. (United Kingdom); Li Ke, Univ. of Southampton (United Kingdom); Jean-Marc Fédéli, CEA-LETI (France); David J. Richardson, Optoelectronics Research Ctr. (United Kingdom); Graham T. Reed, Univ. of Southampton (United Kingdom); Periklis Petropoulos, Optoelectronics Research Ctr. (United Kingdom)

Communication traffic grows relentlessly in today's networks, and with ever more machines connected to the net, this trend is set to continue for the foreseeable future. It is widely accepted that increasingly faster communications are required at the point of the end users, and consequently optical transmission plays a progressively greater role even in short- and medium-reach networks. Silicon photonic technologies are becoming increasingly attractive for such networks, due to their potential for low cost, energetically efficient, high-speed optical components. A representative example is the silicon-based optical modulator, which has been actively studied. Researchers have demonstrated silicon modulators in different types of structures, such as ring resonators or slot light based devices. These approaches have shown remarkably good performance in terms of modulation efficiency, however their operation could be severely affected by temperature drifts or fabrication errors. Mach-Zehnder modulators (MZM), on the other hand, show good performance and resilience to different environmental conditions. In this paper we present a CMOS-compatible compact silicon MZM. We study the application of the modulator to short-reach interconnects by realising data modulation using some relevant advanced modulation formats, such as 4 level Pulse Amplitude Modulation (PAM-4) and Discrete Multi-Tone (DMT) and compare the performance of the different systems in transmission.

9772-8, Session 5

Radio-over-fiber technology and devices for 5G: An overview (Invited Paper)

Stavros Iezekiel, Univ. of Cyprus (Cyprus)

Radio-over-fiber has received renewed impetus due to various worldwide research initiatives in 5G. In this invited talk we will highlight recent developments at the device and integration level that are driving development of systems at various mm-wave and sub-THz carriers, such as 30 GHz, 60 GHz and 120 GHz. Device and circuit technologies such as mode locked lasers, UTC photodiodes, polymer modulators, self-oscillating mixers and optoelectronic oscillators will be reviewed in the framework recent European projects. In addition, we will examine the outlook for monolithic and hybrid integration as a means of meeting size and power consumption requirements in picocell and femtocell applications.

9772-9, Session 5

Multi terabits/s optical access transport technologies (Invited Paper)

Le Nguyen Binh, Thomas T. Wang, Huawei Technologies Duesseldorf GmbH (Germany); Danii Livshits, Alexey E. Gubenko, Innolume GmbH (Germany); Fotini Karinou, Huawei Technologies Duesseldorf GmbH (Germany); Gordon Liu Ning, Huawei Technologies Co., Ltd. (China); Alexey S. Shkolnik, Innolume GmbH (Germany)

Tremendous efforts have been developed for multi-Tbps over ultra-long distance and metro and access optical networks. With the exponential increase demand on data transmission, storage and serving, especially the 5G wireless access scenarios, the optical Internet networking has evolved to data-center based optical networks pressing on novel and economical access transmission systems. This paper presents:
• Experimental platforms and transmission techniques employing band-limited optical components operating at 10G for 100G based at 28G baud. Advanced modulation formats such as PAM4, DMT, Duo-binary etc are reported and their advantages and disadvantages are analyzed so as to achieve multi-Tbps optical transmission systems for access inter- and intra-data-centered-based networks

• Integrated multi-Tbps combining comb laser sources and micro-ring modulators meeting the required performances for access systems are reported. Ten-sub-carrier quantum dot comb lasers are employed in association with wideband optical intensity modulators to demonstrate the feasibility of such sources and integrated micro-ring modulators acting as a combined function of demultiplexing/multiplexing and modulation, hence compactness and economy scale. Under the use of multi-level modulation and direct detection at 56 Gbaud an aggregate of higher than 2Tbps and even 3Tbps can be achieved by interleaved two comb lasers of 16 sub-carrier lines.

• Finally the fundamental designs of ultra-compact flexible filters and switching integrated components based on Si photonics for multi Tera-bps active interconnection are presented. Experimental results on multi-channels transmissions and performances of optical switching matrices and effects on that of data channels are proposed.

9772-10, Session 5

Offset-frequency-spaced two-tone coherent transmission of radio-over-fiber signal with recovered-constellation combining technique

Toshiaki Kuri, Takahide Sakamoto, Naokatsu Yamamoto, National Institute of Information and Communications Technology (Japan)

We have proposed a laser-phase-fluctuation-insensitive optical coherent detection scheme assisted by a digital signal processing technique for radio-over-fiber (RoF) systems. In this system, a “two-tone” local light is used for an individual optical coherent detection of both the carrier and the modulated components of RoF signal, where a frequency separation of two-tone local light is different from that of the RoF signal, which is called “offset-frequency-spaced”. In the demonstration of our schemes, the state-of-polarization (SOP) of the received RoF signal and the two-tone local light was manually matched to get the maximum output after the photo-detection. However, the SOP mismatch is the essential problem for the optical coherent detection. To overcome this problem, polarization diversity is an important technique. Here, we are thinking that there are some polarization diversity techniques, which are applicable to our optical coherent detection scheme. Recently, a combination technique of constellations recovered from two orthogonal polarization components has been newly proposed as one of polarization diversity techniques in offset-frequency-spaced two-tone optical coherent transmission of radio-over-fiber signal. With this technique, successful combination of 10-Gbaud quadrature-phase-shift-keying constellations recovered from two orthogonal polarization components after 20-km standard single-mode fiber transmission is experimentally demonstrated for some SOPs and the transmission quality is also evaluated. As a result, it is shown that the polarization diversity effect can be maintained.

9772-12, Session 5

Evaluation of quadrature-phase-shift-keying signal characteristics in W-band radio-over-fiber transmission using direct in-phase/quadrature-phase conversion technique

Meisaku Suzuki, Aoyama Gakuin Univ. (Japan); Atsushi Kanno, Naokatsu Yamamoto, National Institute of Information and Communications Technology (Japan); Hideyuki Sotobayashi, Aoyama Gakuin Univ. (Japan)

Radio over fiber (RoF) technology is promising to realize seamless conversion between optical and wireless signals for future networks. In conventional millimeter-wave RoF transmission techniques, a heterodyne-based detection is adopted for frequency down-conversion in a receiver. However, the heterodyne technique that provides an intermediate frequency (IF) component requires broad-bandwidth analog-to-digital converters and IF amplifiers because the bandwidth of the devices in the receiver should have at least twice of the bandwidth of the received signal to acquire double sideband components identically. Therefore, a direct frequency conversion technique is desired for reducing the cost of the receiver. However, it is difficult to separate the received signal into in-phase/quadrature-phase (IQ) components owing to a frequency response of an IQ imbalance; the imbalance could degrade IQ signal quality especially at high frequency. We demonstrate quadrature phase-shift keying (QPSK) signal transmission using direct IQ conversion in the W-band (75-110 GHz). The direct IQ down-converter performs frequency down-conversion of the received signal at the frequency from the W-band to two baseband components by IQ mixing technique. Observed IQ imbalance of the converter was measured to be +/-10 degrees at the frequency of DC-26.5 GHz. The QPSK signal transmission in the W-band is demonstrated with various symbol rates (1-8 Gbaud), and bit error rates (BERs) of the received signal were evaluated. These evaluation results of the characteristics on the direct IQ down-converter in the W-band show the possibility of the application to the W-band receiver for future high-speed wireless access communication system.

9772-11, Session 5

Low-latency fiber-millimeter-wave system for future mobile fronthauling (Invited Paper)

Pham Tien Dat, Atsushi Kanno, Naokatsu Yamamoto, National Institute of Information and Communications Technology (Japan); Tetsuya Kawanishi, Waseda Univ. (Japan)

Radio-over-fiber (RoF) systems have been considered as an important technology for small cells-based mobile networks. However, the use of fiber cables may not be feasible in many scenarios because of physical and economic constraints. A seamless combination of fiber and millimeter-wave (MMW) systems can be very attractive for future heterogeneous mobile networks such as 5G because of its flexibility and high bandwidth. Analog mobile signal transmission over seamless fiber-MMW systems is very promising to reduce the latency and the required bandwidth, and to simplify the systems. However, stable and high-performance seamless systems are indispensable to conserve the quality of the analog signal transmission. In this paper, we present several technologies to develop such seamless fiber-MMW systems. In the downlink direction, a high-performance system can be realized using a high-quality optical MMW signal generator and a self-homodyne MMW signal detector. In the uplink direction, a cascade of radio-on-radio and RoF systems using a burst-mode optical amplifier can support bursty radio signal transmission. A full-duplex transmission with negligible interference effects can be realized using frequency multiplexing in the radio link and wavelength-division multiplexing in the optical link. We also present a high-spectral efficiency MMW-over-fiber system using an intermediate frequency over fiber system and a high quality remote delivery of a local oscillator signal. Successful transmission of multiband and multiple-input multiple-output LTE-A signals over the systems is demonstrated.
9772-13, Session 6

**Multimode fibers in millimeter-wave evolution for 5G cellular networks (Invited Paper)**

Carmen Vazquez, David Montero, Wendy Ponce, Pedro Contreras Lallana, D. Larrabeiti, Univ. Carlos III de Madrid (Spain); Julio Montalvo, Telefonica (Spain); Alberto Tapetado Moraleda, Plinio Jesus Pinzon Castillo, Univ. Carlos III de Madrid (Spain)

The explosion of mobile traffic fosters 5G (5th Generation) cellular network evolution to increase the system rate 1000 times higher than the current systems in 10 years. Motivated by this problem, there are several studies to integrate mm-wave access into current cellular networks. Some of them include mm-wave small cells basestations and a conventional macro basestation connected to Centralized-RAN to efficiently operate the system, and using up to 7GHz of continuous spectrum available worldwide at the 60GHz unlicensed band [K. Sakaguchi et al, 2015]. Wireless backhole and access are proposed in those small cell networks and measurements of system bandwidth in excess of 500 MHz at 28 GHz are reported [W. Roh et al, 2014]. But under specific scenarios, efficient radio access technology not sensible to should be necessary and fiber optics technology can provide those requirements. To provide cost effectiveness multimode optical fibers can be used to feed the different small cells basestations. Radio over multimode fiber technologies has been proposed in in-building networks [A.M.J.Koonen et al, 2008], for the distribution of optical wireless communication cells [A Hajjar et al, 2015] and in broadband access networks [D.S. Montero et al, 2013][M. C. Parker et al, 2010]. Temperature impairment characterization has also been analyzed over the broadband transmission bands that can be present in the frequency response of multimode fiber (MMF) supporting multiple-GHz carriers delivering schemes [Montero et al, 2012]. Measurements of graded index plastic optical fibers (GI-POF) transfer function are presented in [Montero et al, 2011] highlighting the conditions upon broadband transmission in regions far from baseband can be featured and the availability of a model to describe this performance. From those models different multimode fiber approaches will be described for access mm-wave small cells in 5G cellular networks.

9772-14, Session 6

**Analog and digital transport of RF channels over converged 5G wireless-optical networks**

Le N. Binh, Huawei Technologies Duesseldorf GmbH (Germany)

Under the exponential increase demand by the emerging 5G wireless access networking and thus data-center based Internet, novel and economical transport of RF channels to and from wireless access systems. This paper presents the transport technologies of RF channels over the analog and digital domain so as to meet the demands of the transport capacity reaching multi-Tbps, in the following:

- The convergence of 5G broadband wireless and optical networks and its demands on capacity delivery and network structures.
- Analog optical technologies for delivery of both the information and RF carriers to and from multiple-input multiple-output (MIMO) antenna sites so as to control the beam steering of MIMO antenna in the mmWave at either 28.6 GHz and 56.8 GHz RF carrier and delivery of channels of aggregate capacity reaching several Tbps.
- Transceiver employing advanced digital modulation formats and digital signal processing (DSP) so as to provide 100G and beyond transmission rate to meet the ultra-high capacity demands with flexible spectral grids, hence pay-on-demand services. The interplay between DSP-based and analog transport techniques is examined.

- Transport technologies for 5G cloud access networks and associate modulation and digital processing techniques for capacity efficiency.
- Finally the integrated optic technologies with novel lasers, comb generators and simultaneous dual function photonic devices for both demultiplexing/multiplexing and modulation are proposed, hence a system on chip structure can be structured. Quantum dot lasers and matrices of micro ring resonators are integrated on the same Si-on-Silica substrate are proposed and described.

9772-15, Session 6

**An analog fronthaul scheme for future wireless access based on hybrid time/frequency domain multiplexing**

Chenhui Ye, Xiaofeng Hu, Xiaoaqan Huang, Qingjiang Chang, Zhensen Gao, Xiao Sun, Simiao Xiao, Kaibin Zhang, Alcatel-Lucent Shanghai Bell Co. Ltd. (China)

A consensus has been achieved that BBU centralization will be a dominant technologies in future wireless access networks. To support BBU centralization, a new wireless transport scheme termed as mobile fronthaul has lately been announced and researched. Current popular protocols for fronthaul are all of digital approach, e.g., CPRI, OBSAI. However, digital protocols are extremely bandwidth consuming. Analog schemes are therefore being widely studied for their superiority in spectra efficiency, bandwidth saving in other words. Furthermore, multiplexing scheme in frequency domain (FDM) is commonly adopted when network architecture is concerned. However, FDM turns out sacrificing much of the transport performance, linearity in specific, since the PAPR after FDM is much enlarged. But small signal model is a critical criterion for analog transmission system to follow since linear modulation can only be well achieved when optical modulation index is sufficiently small. We have demonstrated time domain multiplexing (TDM) approach lately showing excellent performance in p2p network architecture for free from PAPR issue, but it asks for costly broadband ADC and is suboptimal in m2mp architectures. Hereby in this paper, hybrid time/frequency domain multiplexing approach is introduced, aiming to eliminate the PAPR issue and relieve the stringent ADC bandwidth requirement. As the experimental demonstration indicates, 4 macro cell sites containing an overall capacity of 100+ LTE-A radio signals can well be accommodated over the proposed fronthaul scheme, showing a 10X more capacity comparing to conventional digital approach like CPRI and is very promising to fit the requirements on future wireless access fronthaul.

9772-16, Session 6

**Practical demonstration of spectrally efficient FDM millimeter-wave radio over fiber systems for 5G cellular networking (Invited Paper)**

Spiros Mikroulis, Tongyang Xu, Izzat Darwazeh, Univ. College London (United Kingdom)

Although today's developed wireless access standards operate at bit rates approaching of 100Mbp/s, current projections predict a rapidly growing wireless data traffic demand with orders of magnitude increase in the next decade. Therefore, the 4G infrastructure has to be upgraded to next generation 5G picocell/femtocell based mm wave (such as 60GHz) scenarios, taking into account cost/complexity, energy consumption, and spectral efficiency. Obviously, such systems need to re-use currently developed infrastructure e.g. FTTx-PON or LTE, benefit from wired-wireless convergence and consider new signal formats that save spectrum yet guarantee signal integrity.

In this work a mm-wave 5G with LTE overlay reconfigurable simple radio over fiber scheme is proposed and experimentally evaluated. All the
required IF (RF) signal processing is performed at a central base station (CBS). Optionally, at the 5G antenna unit, the signal can be easily up converted from IF to mm-wave using a second PON compatible Distributed Feedback (DFB) laser source tuned at the required mm-wave frequency and a high frequency photodiode. A comparison between OFDM and non-orthogonal spectrally efficient (SE) FDM is performed, using in both cases a carrier aggregation scheme in terms of bandwidth efficiency, performance limitations and nonlinear distortion. In all cases the carrier aggregated SEFD only not saves up to 40% of optical and electrical spectra but also is more resilient than OFDM to the nonlinear impairments.

9772-17, Session 7  
**Cyber physical system based on resilient ICT (Invited Paper)**  
Katsumi Iwatsuki, Tohoku Univ. (Japan)  
While development of science and technology has built up the sophisticated civilized society, it has also resulted in quite a few disadvantages in global environment and human society. The common recognition has been increasingly shared worldwide on sustainable development society attaching greater importance to the symbiotic relationship with nature and social ethics. After the East Japan Great Earthquake, it is indispensable for sustainable social development to enhance capacity of resistance and restoration of society against natural disaster, so called “resilient society”. Various subsystems that make up the society become smart physical systems due to fusing with an ICT (Information Communication Technology). To realize resilient society, we need to improve resilience of each CPS, and simultaneously coordinate and cooperate multiple CPSs. It is required for the improvement of resilience in CPS itself to adopt “autonomous, distributed, and cooperative” structure to the CPS. In this presentation, we will talk about the configuration component of ICT and physical system introducing “autonomous, distributed, and cooperative” structure.

9772-18, Session 7  
**Multi-port power router and its impact on resilient power grid systems (Invited Paper)**  
Yuichi Kado, Kyoto Institute of Technology (Japan); Katsumi Iwatsuki, Tohoku University (Japan); Keiji Wada, Tokyo Metropolitan Univ. (Japan)  
We propose the multi-port power router that can be used as a unit cell to easily build a power delivery system in order to meet many kinds of user’s requirements and reduce the system development costs. The router is composed of a three-way isolated DC/DC converter as a core unit, AC/DC converter units, and a software-defined control unit. The router can distribute power in three directions and perform the power interchanging function regardless of DC and AC. Furthermore, many kinds of loads, energy resources, and energy storage devices are connectable to the routers by only rewriting the control software. For multiple energy routers installed at various locations to work cooperatively to implement flexible power interchange in real time, it is necessary to measure the current and voltage amplitude at each node and reflect the results in the phase-shift modulation (PSM) control of each energy router. We consider the communication requirements of a control framework for enabling dynamic adjustments of power flow through the coordinated operation of multiple energy routers placed in different locations. That requires highly accurate time synchronization of the control modules of the energy routers. A strong candidate for the control network is an optical fiber network access system. When optical fiber is used for high-voltage power converter control, electrical isolation, robustness against lightning strikes, and excellent robustness against electrical noise can be expected.

9772-19, Session 7  
**Blind post processed nonlinearity mitigation in multiband OFDM radio over fiber optical transmission**  
Hyoung-Joon Park, Sun-Young Jung, Sang-Kook Han, Yonsei Univ. (Korea, Republic of)  
We propose a blind post-processing method to reduce nonlinear distortion in multiband radio over fiber (RoF) system. Mitigating nonlinear distortion has always been a critical challenge to enhance the transmission in RoF system since the system transmits analog optical signals. However, to keep up with explosive increase in number of mobiles and their data capacity demands, remote antenna unit (RAU) has to be widely and densely distributed with RoF system. Consequently, RAU should be simple and compensation of optical transmission must be fully processed in central office (CO). When it comes to optical uplink transmission of RoF system, post-processing of distortion mitigation will be effective in CO. In this paper, we propose post compensation structure constructed by means of Hammerstein model type filter without inserting preamble. Specifically, Hammerstein model type filter, which is separated into linear and nonlinear parts, is used to compensate both linear and nonlinear distortion of RoF system. The filter coefficients are updated adaptively by using LMS algorithm to adjust variable channel environments. In our experiment, multiband SC-FDMA signal, which is LTE standard according to 3GPP, is optically transmitted through RoF system. Experimental demonstration for the improvement of EVM performance with proposed post-processing is verified.

9772-20, Session 7  
**Multicore fronthaul and backhaul provision in next-generation optical access networks (Invited Paper)**  
Roberto Llorente Sáez, Maria Morant, Andrés Macho Ortiz, Univ. Politècnica de València (Spain)  
Multicore fiber (MCF) supporting space-division multiplexing has been appointed as an interesting solution to increase the fiber density overcoming the capacity limitation of single mode fiber systems reducing cabling size and weight. Next-generation optical access networks are expected to support state-of-the-art 4G cellular wireless systems, and future 5G and Beyond-5G systems. The wireless signals employed impose strict requirements in both fronthaul and backhaul transmission. Fronthaul connectivity, usually implemented in radio-over-fiber (RoF) transmission or digitized-RoF, has to cope with ultra-wideband signals exceeding 400 GHz bandwidth in the case of 5G systems. This requirement is further hardened in the case of Beyond-5G systems, where a massive number of antennas should be optically connected using RoF. MCF-based networks appear as an interesting solution as different signals are transmitted in RoF in different cores supporting simultaneously downstream and upstream operation in fronthaul. In this application, large core-count fibers are perfectly suitable for connecting large antennas sites supporting a large number of radiating elements employing MIMO. Operators employing digitized RoF can benefit for the aggregated bitrate capacity provided by the multicore fiber exploiting space-division multiplexing.

The RoF fronthaul opens up the opportunity of overlaying wireless transmission in next-generation optical access combining wavelength division multiplexing or optical polarization multiplexing. This paper summarizes experimental work in demonstrating the suitability of multicore fronthaul and optical access of fully-standard LTE-Advanced signals using a 4-core MCF. Specific requirements to extend the proposed approach to 5G and Beyond-5G cellular systems are also reported in this paper.
Photonics aided ultra-wideband W-band signal generation and air space transmission (Invited Paper)

Xinying Li, Georgia Institute of Technology (United States); Jianjun Yu, ZTE (TX) Inc. (United States) and Fudan University (China)

Recently, the W-band (75-110GHz), with its inherent advantages of -35-GHz large available bandwidth, relatively small atmospheric loss and good directionality, has become a spotlight in the research community and is promising to provide ultra-wideband long-distance wireless transmission links for emergency backbone-communication services and massive backhauling between wireless macro stations. Photonic millimeter-wave (mm-wave) generation techniques can overcome the bandwidth limitation of existing electrical components and realize high-frequency mm-wave generation. The combination of multiple multi-dimensional multiplexing techniques, including multiple-input multiple-output-based (MIMO-based) optical/antenna polarization multiplexing and multi-band multiplexing, can significantly increase wireless transmission capacity, while the adoption of advanced devices, including high-power/large-gain electrical amplifier (EA) and large-gain small-beamwidth Cassegrain antenna (CA), can effectively extend wireless transmission distance.

In this paper, we overview our several field trial demonstrations of ultra-wideband W-band mm-wave signal generation and its long-distance air space transmission based on the aforementioned enabling technologies and advanced devices. First, we demonstrated the photonics generation and up to 1.7-km wireless delivery of 20-Gb/s polarization-division-multiplexing quadrature-phase-shift-keying (PDM-QPSK) signal at W-band, adopting both optical and antenna polarization multiplexing. Then, we demonstrated the photonics generation and up to 300-m wireless delivery of 80-Gb/s PDM-QPSK signal at W-band, adopting both optical and antenna polarization multiplexing. We also demonstrated the photonics generation and up to 100-m wireless delivery of 100-Gb/s QPSK signal at W-band, adopting antenna polarization multiplexing.

Impact of inter-core crosstalk in radio-over-fiber transmission on multi-core optical media

Andrés Macho Ortiz, Univ. Politécnica de Valencia (Spain); Maria Morant, Roberto Llorente Sáez, Univ. Politécnica de València (Spain)

Multi-core fiber supporting space-division multiplexing is a major focus of recent investigation in optical transmission technology as a good solution to overcome the capacity limitation of single mode fiber systems. In the last two decades, the huge traffic demand capacity has grown by three orders of magnitude, approaching the spectral efficiency limits of single mode fiber systems. Instead of using different optical fibers, multi-core fiber transmission increases the capacity of the system enabling multiple spatial paths over a single fiber.

One of the main physical impairments in multi-core transmissions is the inter-core crosstalk, which presents a stochastic nature due to the random changes of macrobends and structural fluctuations of the multi-core fiber. In linear regime, inter-core crosstalk increases along the multi-core fiber when the fiber is not pre-processed with a phase-matching condition is satisfied. However, in nonlinear regime, Kerr effect detunes the propagation constant of the core modes reducing the number of phase-matching points along the fiber length.

The impact of linear and nonlinear crosstalk is experimentally evaluated in a 4 core fiber with three different radio-over-fiber transmissions using full-standard LTE-A and WiMAX signals in 2x2 MIMO and SISO configurations. The experimental results demonstrate the reduction of the EVM fluctuations in time and wavelength domain when operating in nonlinear regime. In addition, a final in-building transmission is demonstrated along 150 m of 4-core fiber with 20-MHz LTE channels per core using 16-QAM subcarrier modulation. The linear and nonlinear inter-core crosstalk impact is minimized using core interleaving ensuring the EVM standard requirements at the wireless fronthaul.

Integrating free-space optical communication links with existing WiFi (WiFO) network

Spencer Liverman, Qiwei Wang, Yu-Jung Chu, Thai Duong, Duong Nguyen, Songtao Wang, Thinh Nguyen, Alan X. Wang, Oregon State Univ. (United States)

As the demand placed on wireless communication networks increases, existing systems must use bandwidth more efficiently. Free space optical (FSO) systems have recently been investigated in an effort to increase upload and download speeds on wireless networks. FSO systems offer several advantages over WiFi networks such as high bandwidth potentials and a physical layer of protection. However, mobility remains a challenge. We propose a hybrid WiFO system that will take full advantage of the mobility offered by WiFi networks in the uplink, while offering high FSO bandwidths in the downlink. WiFO consists of an array of LED transmitters connected via the Ethernet and deployed directly on ceiling to offer a large coverage area. Downstream data from the Internet will be passed through the wireless access point (AP) which forwards the data on the Ethernet to an appropriate infrared (IR) light emitting diode (LED) FSO transmitter. The FSO transmitter in turn modulates light which is then detected by a PIN photodiode at the receiver. As the receiver moves about, their locations will be determined automatically. This information will be used by the AP to make a decision as to which LED transmitter will provide the best downlink. Additionally, systems that are line of sight can take full advantage of the available transition bandwidth, as one transmitting signal will not interfere with another. This hybrid FSO/WiFi system (WiFO) offers a novel approach to overcoming several of the issues involved with FSO networks.
9772-25, Session 8

**Error performance analysis of FSO links with equal gain diversity receivers over double generalized gamma fading channels**

Mohammadreza Aminikashani, Mohsen Kavehrad, The Pennsylvania State Univ. (United States); Wenjun Gu, The Pennsylvania State University (United States)

Free space optical (FSO) communication has been receiving increasing attention in recent years with its ability to achieve ultra-high data rates over unlicensed optical spectrum. A major performance limiting factor in FSO systems is atmospheric turbulence which severely degrades the system performance. To address this issue, multiple transmit and/or receive apertures can be employed, and the performance can be improved via diversity gain. In this paper, we investigate the bit error rate (BER) performance of FSO systems with transmit diversity or receive diversity with equal gain combining (EGC) over atmospheric turbulence channels described by Double Generalized Gamma (Double GG) distribution. The Double GG distribution, recently proposed, generalizes many existing turbulence models in a closed-form expression and covers all turbulence conditions. Since the distribution function of a sum of Double GG random variables (RVs) appears in BER expression, we first derive a closed-form upper bound for the distribution of the sum of Double GG distributed RVs. A novel union upper bound for the average BER as well as corresponding asymptotic expression is then derived and evaluated in terms of Meijer’s G-functions.

9772-26, Session 8

**A wavelength tunable ONU transmitter based on multi-mode Fabry-Perot laser and micro-ring resonator for bandwidth symmetric TWDM-PON**

Zhensen Gao, Xiao Sun, Kaibin Zhang, Alcatel-Lucent Shanghai Bell Co. Ltd. (China)

Wavelength tunable optical transmitter is an essential component for optical access network, particularly in the newly standardized 40Gb/s time and wavelength division multiplexed passive optical network (TWDM-PON), where tunable ONU is required to transmit at any four upstream wavelength channels, restricting the legacy wavelength fixed ONU transmitter to be used. Besides wavelength tunability, it is also desirable for each ONU to provide a uplink line rate of 10Gb/s in order to realize a 40Gb/s bandwidth symmetric TWDM-PON to support stringent business users and mobile services. In this paper, a novel high speed wavelength tunable optical transmitter is proposed for 10Gb/s colorless ONU by reusing the legacy low speed Fabry-Perot laser based multi-mode optical transmitter, which is connected with an integrated photonic chip consisting of two coupled micro-ring resonators with optimized coupling coefficient and free spectral range to generate a tunable single longitudinal mode optical signal for high speed upstream modulation. The wavelength tuning principle based on Vernier effect across the required four upstream wavelength channels in TWDM-PON with relaxed temperature change requirement is described. The proposed wavelength tunable transmitter will be a very promising candidate for low cost colorless ONU in future bandwidth symmetric TWDM-PON.

9772-27, Session 8

**Demonstration of quantum dot SOA based colorless ONU transmitter for symmetric 40 Gb/s TWDM PON**

Xiao Sun, Qingjiang Chang, Zhensen Gao, Chenhui Ye, Simiao Xiao, Xiaolan Huang, Xiaofeng Hu, Kaibin Zhang, Alcatel-Lucent Shanghai Bell Co. Ltd. (China)

We propose a novel self-seeded colorless ONU transmitter for symmetric 40 Gb/s TWDM-PON. The ONU transmitter consists of a quantum dot (QD) SOA working as the intensity modulator and an injection locked Febry-Perot laser diode (FP-LD) to provide the seed light. The self-seeded broadband light source is generated from the amplified spontaneous emission of the QD SOA. A specially designed multi-mode fiber Bragg grating is placed at the remote node to reflect four TWDM upstream (US) wavelength channels according to ITU-T G989.1. The four reflected wavelengths pass through the QD SOA from the opposite direction and are further injected to the FP-LD. The FP-LD is optimized so that only one of the longitudinal modes is locked and stimulated emission occurs, while other longitudinal modes are strongly attenuated. Providing the seed light, the electrical signal is thus directly added onto the QD-SOA and is intensity modulated. The modulated US signal is then launched into the optical distributed network. The FP-LD can be thermally tuned to be locked by any of the reflected wavelengths to achieve colorless operation.

Detailed numerical investigation of such scheme has been developed. Results show that the QD SOA is able to support a 10 Gb/s OOK signal transmission with an optical extinction ratio of 10 dB. Chromatic dispersion compensation free of 20 km passive transmission has been achieved for a 1:32 split ratio architecture. Moreover, the system performance and power budget have been analyzed for different transmission distance and split ratio.

9772-28, Session 8

**Advanced SDN control for NG-EPON**

Jung-Yeol Oh, Electronics and Telecommunications Research Institute (Korea, Republic of)

In this paper, we propose an advanced SDN control for optical access network. we design a SDN-based reference architecture for wired and wireless converged optical access network and analyze control techniques and their performance for SDN-based optical access networks. Access-SDN is a platform designed to support SDN operations and control mechanisms for NG-EPON. Access-SDN integrates SDN-based managements and PON control architecture exchanging cross-layer information for integration of SDN and access PON. It is described SDN control mechanism and its performance evaluation of dynamic resource scheduling for NG-EPON with wireless base stations. We also evaluate the SDN based NG-EPON architecture as potential backhaul/fronthaul of 5G core networks.

9772-29, Poster Session

**Three-dimensional indoor light positioning algorithm based on nonlinear estimation**

Wenjun Gu, Mohsen Kavehrad, The Pennsylvania State Univ. (United States); Mohammadreza Aminikashani, Pennsylvania State Univ (United States)

With the development of location based services (LBS), indoor positioning has been a popular research topic in recent years. Since global positioning system (GPS) signal suffers from severe attenuation when penetrating through solid walls, other alternatives are proposed to realize indoor
positioning. Visible light communication (VLC) systems offer a practical solution. Light emitting diode (LED) is able to be modulated in high speed as a transmitter, and a photodiode (PD) is commonly a receiver to detect the optical signal strength. In VLC based indoor positioning system, LEDs are applied for both positioning and illumination purposes so that infrastructure cost and power consumption are decreased. In addition, light positioning system provides other advantages such as no electromagnetic interference and better immunity against multipath reflections. Several methods are proposed to realize indoor positioning, such as triangulation, scene analysis and proximity, which are also applicable for a VLC based system. In prior works, the height of receiver is known so that the coordinates on the horizontal plane can be calculated. In this paper, the proposed method includes two stages: the height is presumed in the prediction stage and nonlinear estimation is applied in the correction stage to realize three dimensional coordinate estimation.

Universal filtered multi-carrier system for asynchronous uplink transmission in optical access network

Soo-Min Kang, Chang-Hun Kim, Sang-Kook Han, Yonsei Univ. (Korea, Republic of)

In passive optical network (PON), orthogonal frequency division multiplexing (OFDM) is being studied actively because it has advantages such as high spectral efficiency (SE), dynamic allocation in time or frequency domain, and strongness in dispersion. For uplink transmission in optical access network, OFDM requires tight synchronization. If time synchronization is broken by short cyclic prefix (CP), orthogonality cannot be maintained. Also its sidelobes cause inter channel interference (ICI) in adjacent channel. To prevent ICI caused by high sidelobes, guard band (GB) is used but it degrades SE. Thus, OFDM is not the best solution for asynchronous uplink transmission in optical access network.

In this paper, we propose intensity modulation/direct detection (IM/DD) based universal filtered multi-carrier (UFMC) which uses subband filtering to subsets of complete band. Since it reduces interference between each channel with suppressed sidelobes by applying subband filtering, we can achieve better performance in synchronization and higher SE compared to OFDM. In experiment, we set two ONUs, each having a different time offset, and one OLT to realize asynchronous uplink transmission. We adaptively modulate OFDM and UFMC in same condition and compare the performance of OFDM and UFMC after 23km transmission. As a result of subband filtering condition optimization, UFMC uplink transmission robustness in time synchronization and enhanced SE were experimentally verified. Therefore, UFMC using subband filtering would be effective for applications in asynchronous environment such as heterogeneous or low latency multiple access services.

Analysis of bend insensitive liquid core optical fiber for broadband network and fiber-to-the-home applications

Vikram Palodiya, Sanjeev K. Raghuwanshi, Indian School of Mines (India)

In this paper we analyze the guided properties of liquid core optical fibers for fiber-to-the-home application. Fibre to the Home is advance technology to give unlimited bandwidth and high speed broadband network for communication. Fibre to the Home technology refers to the installation and use of bend insensitive optical fiber cables. The liquid core optical fiber has a simple core and cladding structure. This fiber achieves high relative refractive index difference among the core and cladding is proved to be bending insensitive. The single mode condition and the group velocity dispersion, mode field diameter and the bending loss of single mode fiber are studied theoretically. Compare with traditional silica optical fiber. Liquid core optical fiber has much smaller bending loss of than traditional silica fibers. Liquid core optical fiber show unique properties, such as more confined guided mode, low bending loss and large non linear parameters in the visible and infrared region. This type of fiber used in fiber -to-the-home applications, Broadband network and also for sensing applications.
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9773-1, Session 3

Multicore erbium doped fiber amplifiers
(Invited Paper)

Koichi Maeda, Yukihiro Tsuchida, Ryuichi Sugizaki, Furukawa Electric Co., Ltd. (Japan); Hiroshi Matsuura, Tohoku Gakuin Univ. (Japan)

No Abstract Available

9773-2, Session 4

100-Gb/s InP DP-IQ modulator for small-form-factor pluggable coherent transceivers
(Invited Paper)

Nobuhiro Kikuchi, Yoshihiro Ogiso, Eiichi Yamada, Nippon Telegraph and Telephone Corp. (Japan)

Nowadays an InP-based dual-polarization in-phase and quadrature (DP-IQ) modulator is attracting a lot of attention as a key device for digital coherent transceivers in small pluggable form factors for metro networks and WDM links between data centers, because it offers great advantages such as its small chip size, low driving voltage, and potential for monolithic integration with semiconductor devices such as laser diodes and photo detectors.

We have developed a compact InP-based DP-IQ modulator. The two IQ modulators and phase shifters to adjust the phase conditions were integrated in one chip whose size was 9.5 mm x 2.5 mm. For high-speed operation, the chip was equipped with four pairs of differential RF electrodes which employed a traveling-wave electrode configuration. A high-frequency interposer was also employed for feeding RF signals into the modulator chip. It helps to maintain the same electrical lengths for all the RF signal lines with a low electrical loss. A 112-Gb/s DP-quadrature phase shift keying (QPSK) modulation with a low driving voltage of 3 Vpp and comparable OSNR performance to that of LN03 (LN)-based modulator were confirmed. A 16-ary quadrature amplitude modulation (QAM) was also successfully demonstrated. Recently, we improved the modulation efficiency by revising the core layer structure of the modulation section. InP-based DP-IQ modulators with a half-wavelength voltage of less than 2.0 V and a DC extinction ratio of over 25 dB for the entire C-band are fabricated stably. And they start to be used in the commercial networks.

9773-3, Session 7

High-speed real-time OFDM transmission based on FPGA
(Invited Paper)

Xin Xiao, ZTE USA (United States); Fan Li, Jianjun Yu, ZTE TX (United States)

We are reviewing our recent research progresses on high-speed real-time OFDM transmission based on FPGA. We designed and manufactured a high-speed real-time OFDM transmission system based on ADCs and FPGAs. Four high-speed ADCs are working at the sample-rate of 41.93 GSa/s, after the ADC sampling, totally 32 FPGAs are used for data organization and DSP processing. The 32 FPGAs are working parallelly to provide huge calculation ability to realize high-speed real-time processing. In the hardware design, the 32 FPGA chips are installed in 4 Printed Circuit Boards (PCB). The first 2 PCBs are data pre-processing (DPP) boards, each one has 2 Altera EP4S100G FPGAs. In the two DPP boards, the ADC outputs will be calibrated to eliminate the random delays caused by ADC sampling, and reorganized before DSP processing. The data pre-processing in DPP boards is essential for DSP processing of next stage. There are two DSP boards following DPP boards, and DSP boards and DPP boards are connected by a high-speed backboard. Each DSP board has 12 Xilinx 6VXS475 FPGAs, and the total 24 Xilinx 6VXS475 FPGAs can fulfill the huge amount of calculations of the OFDM algorithm. Both the Altera EP4S100G FPGAs and the Xilinx 6VXS475 FPGAs have high-speed SERDES interfaces, and the signals transmitted from DPP FPGAs to DSP FPGAs pass through the SERDES interfaces. The transmission speed can be up to 6.5Gb/s. Each FPGA in the DSP boards contains 8 parallel calculation channels, and the calculation clock frequency inside the FPGAs can be up to 296Mhz. The recovered data after the DSP processing and the original transmitted data will be compared by the FPGAs of the DSP boards and the error can be counted. The DSP processing and all processing results can be controlled and monitored by PC through JTAG interface and ChipScope Pro debugging modules.

9773-4, Session 7

Comparison of advanced DSP techniques for spectrally efficiently Nyquist-WDM signal generation using digital FIR filters at transmitters based on higher-order modulation formats

Yi Weng, Univ. of Louisiana at Lafayette (United States); Junyi Wang, Qualcomm Technologies, Inc. (United States); Zhongqi Pan, Univ. of Louisiana at Lafayette (United States)

To support the ever-increasing demand for high-speed optical communications, Nyquist spectral shaping serves as a promising technique to improve spectral efficiency (SE) by generating near-rectangular spectra with negligible crosstalk and inter-symbol interference in wavelength-division-multiplexed (WDM) systems. Compared with specially-designed optical methods, DSP-based electrical filters are more flexible as they can generate different filter shapes and modulation formats. However, such transmitter-side pre-filtering approach is sensitive to the limited taps of finite-impulse-response (FIR) filter, for the complexity of the required DSP and digital-to-analog converter (DAC) is limited by the cost and power consumption of optical transponder. In this paper, we investigate the performance and complexity of transmitter-side FIR-based DSP with polarization-division-multiplexing (PDM) high-order quadrature-amplitude-modulation (QAM) formats. Our results show that Nyquist 64-QAM, 16-QAM and QPSK WDM signals can be sufficiently generated by digital FIR filters with 61, 37, and 17 taps respectively. The root-raised-cosine (RRC) spectrum shape has better performance than raised-cosine (RC) pulses, at the cost of slightly-increased complexity. Then we explore the effects of DAC sampling speeds, as well as the required spectral pre-emphasis, bandwidth and resolution on the performance of Nyquist-WDM systems. To obtain negligible OSNR penalty with a roll-off factor of 0.1, two-channel-interleaved DAC requires a Gaussian electrical filter with the bandwidth of 0.4-0.55 times of the symbol rate for PDM-64QAM, 0.35-0.65 times for PDM-16QAM, and 0.3-0.8 times for PDM-QPSK, with required DAC resolutions as 8, 7, 6 bits correspondingly. As a tradeoff, PDM-64QAM can be a promising candidate for SE improvement in next-generation optical metro networks.
The data traffic pressure to the core network can also be alleviated by utilizing a protocol, which is much faster and cost-effective than traditional methods. Therefore, the inter-eNB traffic can be transponded directly in L2 via PON's own XGEM frame by identifying the downstream XGEM header as normal. The XGEM payload is then processed. Then the OLT creates the corresponding downstream XGEM frame with the target ONU-ID and the corresponding wavelength channel information (e.g., ONU-ID and WLCH-ID). Then the X2-interface IP packet is encapsulated via “MPLS over Ethernet” as normal, however tag the target ONU-ID and the target WLCH-ID. This process is achieved without any dynamic control. This scheme is also proven to extend the power budget up to 41 dB allowing a reach of 40 km and split up to 1:64 using a continuous-mode receiver.

Numerical modeling including SOA rate equations and light propagation equations has been developed. Results show that over 19 dB input dynamic range and up to 16.7 dB compression of the output dynamic range were achieved without any dynamic control. This scheme was also proven to extend the power budget up to 41 dB allowing a reach of 40 km and split up to 1:64 using a continuous-mode receiver.

Efficient eNB inter-communication scheme in converged mobile and NG-PON2 system

Simiao Xiao, Alcatel-Lucent Shanghai Bell Co. Ltd. (China); Xiaojun Sun, Alcatel-Lucent Shanghai Bell Co. Ltd. (China); Kaibin Zhang, Alcatel-Lucent Shanghai Bell Co. Ltd. (China)

In LTE, a new X2-interface is defined to facilitate direct communication between neighboring eNBs. As an all-IP network, the X2-interface traffic needs to be routed and transponded in L3 at the edge router by IP addressing. It is a hot topic to backhaul mobile traffic based on PON, for the economic consideration, also retain the comfort of a secure, scalable, and future-proof evolution path. In such a converged system, the PON in the access part only provides the physical transmission medium for LTE traffic, without any routing or processing function. In this paper, we lower down the inter-eNB control and management function into the OLT. An “Address Table” is built to associate the eNB identifier (e.g., eNB IP address) with the corresponding ONU’s information (e.g., ONU-ID) and the corresponding wavelength channel information (e.g., WLCH-ID). Then the X2-interface IP packet is encapsulated via “MPLS over XGEM” as normal, however tag the target ONU-ID and the target WLCH-ID in the upstream XGEM header. At the OLT, the upstream inter-eNB XGEM frame is recognized by parsing the XGEM header, without processing the XGEM payload. Then the OLT creates the corresponding downstream XGEM frame directly to the target ONU-eNB. The ONU/ONU-eNB filters out its own XGEM frame by identifying the downstream XGEM header as normal. Therefore, the inter-eNB traffic can be transponded directly in L2 via PON’s protocol, which is much faster and cost-effective than traditional method. The data traffic pressure to the core network can also be alleviated.

Photodetector sensitivity improvement for bending loss detection in optical fiber

Jaeyul Lee, Jaewon Song, Jeehyun Kim, Mansik Jeon, Kyungpook National Univ. (Korea, Republic of)

In optical communication and optical systems, bending loss or fault detection is critical problem. Therefore a detection device with high sensitivity and good working distance are the requirements of current system. In this study, we demonstrated a sensitivity improvement of photodetector using a convex lens. The sensitivity enhancement of silicon photodetector is tested with different focal length lenses by employing maximum working distance. The light source with center wavelength of 1625 nm is utilized here with broadband width. The experimental results shows a four times sensitivity improvement in photodetector mounted with lens as compare to no lens detection scheme. Similarly, signal attenuation is done using optical attenuator to measure the sensitivity with decrease in intensity of light. Results show the sensitivity improvement of 6 dB at different working distance with lens as compare to no lens configuration. The sensitivity of 10 dB at a working distance of 20 mm from photodetector is optimized. The convex lens of used for optimized configuration has focal length of 4.51 mm. This study is the first step towards handheld device for the bending loss detection in optical fiber communication.

Real-time optical path control method that utilizes multiple support vector machines for traffic prediction

Hiroshi Kawase, Yojiro Mori, Hiroshi Hasegawa, Ken-ichi Sato, Nagoya Univ. (Japan)

An effective solution to the continuous Internet traffic expansion is to offload traffic to lower layers such as L2/optical layer. One possible approach is to introduce dynamic optical path operations such as adaptive establishment/tear down according to traffic variation. Path operations cannot be done instantaneously and hence traffic prediction is essential. Conventional prediction techniques need optimal parameter values to be determined in advance by averaging long term variations in the past. However, this does not allow adaptation to the ever-changing short-term variations expected to be common in future networks. In this paper, we propose a real-time optical path control method based on Support Vector Machine (SVM), a machine learning technique. The SVM learns the most recent traffic characteristics, and so enables better adaptation to temporal traffic variations than conventional techniques. The difficulty is how to minimize the time gap between optical path operation and buffer management at the originating points of those paths. The gap makes the necessary learning data set enormous and the learning process costly. To resolve the problem, we propose to adopt multiple SVMs running in parallel, and train them with non-overlapping subsets of the original data set. The maximum value of the outputs of these SVMs will be the estimated number of necessary paths. Numerical experiments prove that our proposal outperforms a conventional prediction method, the Auto-regressive Moving Average with optimal parameter values determined by Akaike's Information Criterion, and reduces packet loss ratio by up to 98%.

Architecture and design of optical path networks utilizing waveband virtual links

Yusaku Ito, Yojiro Mori, Hiroshi Hasegawa, Ken-ichi Sato, Nagoya Univ. (Japan)

We propose a novel optical network architecture that uses waveband virtual
links, each of which can carry several optical paths, to directly bridge distant node pairs. Future photonic networks should not only cover extended areas transparently but also expand fiber capacity. However, the traversal of many ROADM nodes impairs the optical signal due to spectrum narrowing. To suppress the degradation, guard bands need to be increased, which degrades fiber frequency utilization. Waveband granular switching allows us to apply broader pass band filtering at ROADM nodes to insert sufficient guard bands between wavebands with minimum frequency utilization offset. The scheme resolves the severe spectrum narrowing effect. Moreover, the guard band between optical channels in a waveband can be minimized, which increases the number of paths that can be accommodated per fiber. In the network, wavelength path granular routing is done except for utilizing waveband virtual links, and it still suffers from the spectrum narrowing. A novel network design algorithm that can bound the spectrum narrowing effect by limiting the number of hops (traversed nodes that need wavelength path level routing) is proposed in this paper. This algorithm dynamically changes the waveband virtual link configuration according to the traffic distribution variation, where optical paths that need many node hops are effectively carried by virtual links. Numerical experiments demonstrate that the number of necessary fibers is reduced by 23% compared with conventional optical path networks.

9773-20, Poster Session

Physical layer one-time-pad data encryption through synchronized semiconductor laser networks

Apostolos Argyris, Evangelos Pikasis, Dimitris Syvridis, National and Kapodistrian Univ. of Athens (Greece)

Semiconductor lasers (SL) have been proven to be a key device in the generation of ultrafast true random bit streams. Their potential to emit chaotic signals under conditions, with desirable statistics, establish them as a low cost solution to cover various needs, from large volume key generation to real-time encrypted communications. Usually, only undermanding post-processing is needed to convert the acquired analog timeseries to digital sequences that pass all established tests of randomness. A novel architecture that can generate and exploit these true random sequences is through a fiber network in which the nodes are semiconductor lasers that are coupled and synchronized to central hub laser. In this work we show experimentally that laser nodes in such a star network topology can synchronize with each other through complex broadband signals that are the seed to true random bit sequences (TRBS) at several Gb/s. The potential for each node to access real-time generated and synchronized with the rest of the nodes random bit streams, through the fiber optic network, allows to implement an one-time-pad encryption protocol that mixes the synchronized true random bit sequence with real data at Gb/s rates. Forward-error correction methods are used to reduce the errors in the TRBS and the final error rate at the data decoding level. An appropriate selection in the sampling methodology and properties, as well as in the physical properties of the chaotic seed signal through which network locks in synchronization, allows an error free performance.

9773-21, Poster Session

Automated and comprehensive link engineering supporting branched, ring, and mesh network topologies

Jim Farina, VPIphotonics (United States); Dmitry Khomchenko, Dmitry Yevseyenko, VPI Development Ctr. (Belarus); Judith Meester, VPIphotonics (United States); André Richter, VPIphotonics GmbH (Germany)

Link design, while relatively easy in the past, can become quite cumbersome with complex channel plans and equipment configurations. The task of designing optical transport systems and selecting equipment is often performed by an applications or sales engineer using simple tools, such as custom Excel spreadsheets. Eventually, every individual has their own version of the spreadsheet as well as their own methodology for building the network. This approach becomes unmanageable very quickly and leads to mistakes, bending of the engineering rules and installations that do not perform as expected.

We demonstrate a comprehensive planning environment, which offers an efficient approach to unify, control and expedite the design process by controlling libraries of equipment and engineering methodologies, automating the process and providing the analysis tools necessary to predict system performance throughout the system and for all channels. In addition to the placement of EDFAs and DCEs, performance analysis metrics are provided at every step of the way. Metrics that can be tracked include power, CD and OSNR, SPM, XPM, FWM and SBS. Automated routine steps assist in design aspects such as equalization, padding and gain setting for EDFAs, the placement of ROADM and transceivers, and creating regeneration points. DWDM networks consisting of a large number of nodes and repeater huts, interconnected in linear, branched, mesh and ring network topologies, can be designed much faster when compared with conventional design methods. Using flexible templates for all major optical components, our technology-agnostic planning approach supports the constant advances in optical communications.

9773-22, Poster Session

An FPGA design of generalized low-density parity-check codes for rate-adaptive optical transport networks

Ding Zou, Ivan B. Djordjevic, The Univ. of Arizona (United States)

In state-of-the-art fiber-optics communication systems the fixed forward error correction (FEC) and constellation size are employed. While it is important to closely approach the Shannon limit by using turbo product codes (TPC) and low-density parity-check (LDPC) codes with soft-decision decoding (SDD) algorithms, rate-adaptive techniques, which enable increased information rates over short links and reliable transmission over long links, are likely to become more important with ever-increasing network traffic demands. In the literature, serial concatenated of two Reed-Solomon (RS) codes can provide rate variation by using shortening and puncturing techniques [1]. As continuing evolution, employing different code rates of LDPC codes have been demonstrated as an alternative solution for rate adaptation [2], by adjusting the field size and the code rate of non-binary LDPC coded. This approach has been shown to bring more flexibility [3]. While combined coding and modulation can bring additional flexibility, in this paper, we only focus on adaptive FEC code rates, and the proposed rate-adaptive scheme is based on generalized LDPC (GLDPC) codes, which utilize Hamming codes as component code. We show that with carefully design of GLDPC code, larger minimum distance and larger girth can be achieved as compared to conventional LDPC codes. Then by FPGA emulation, we demonstrate that a single designed GLDPC can achieve a large NCG exhibiting no error floor at BER down to 10-15 and thus require no outer code or post-processing method. In the implementation, we have optimized the bit-width of input log-likelihood ratios (LLRs), check-to-variable messages and variable-to-check messages. By employing the layered decoding algorithm we have been able to achieve a good compromise between processing complexity and decoding performance. At last, we show that by replacing the rows in parity-check matrix with local Hamming codes, wide range of NCGs can be achieved with the proposed unified GLDPC decoder architecture.

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Junwen Zhang, Fudan Univ. (China); jianjun yu, ZTE (Tx) Paper)
(Invited short-haul and access network
Advanced digital signal processing for optical packet and circuit integrated networks (Invited Paper)
Hideaki Furukawa, Takaya Miyazawa, National Institute of Information and Communications Technology (Japan)
We have been developing an optical packet and circuit integrated (OPCI) network, which realizes dynamic optical path, high-density packet multiplexing, and flexible wavelength resource allocation. In the OPCI networks, a best-effort service and a QoS-guaranteed service are provided by employing optical packet switching (OPS) and optical circuit switching (OCS) respectively, and users can select these services. Different wavelength resources are assigned for OPS and OCS links, and the amount of their wavelength resources are dynamically changed in accordance with the service usage conditions. To apply OPCI networks into wide-area (core/metro) networks, we have developed an OPCI node with a distributed control mechanism. Moreover, our OPCI node works with a centralized control mechanism as well as a distributed one. It is therefore possible to realize SDN-based OPCI networks, where resource requests and a centralized configuration are carried out. In this paper, we show our SDN architecture for an OPS system that configures mapping tables between IP addresses and optical packet addresses and switching tables according to the requests from multiple users via a web interface. While OpenFlow-based centralized control protocol is coming into widespread use especially for single-administrative, small-area (LAN/data-center) networks. Here, we also show a interworking mechanism between OpenFlow-based networks (OFNs) and the OPCI network for constructing a wide-area network and a control method of wavelength resource selection to automatically transfer diversified flows from OFNs to the OPCI network.

SDN architecture for optical packet and circuit integrated networks (Invited Paper)
Hideaki Furukawa, Takaya Miyazawa, National Institute of Information and Communications Technology (Japan)

FPGA implementation of advanced FEC schemes for intelligent aggregation networks (Invited Paper)
Ding Zou, Ivan B. Djordjevic, The Univ. of Arizona (United States)
Forward error correction (FEC) codes have been extensively studied and widely adopted in remarkably many communication systems such as space communication links, digital subscriber lines, as well as wireless systems. Due to ever increasing demands for high capacity in optical core and access network, the high-speed low-power implementations of FEC decoder are desirable. Several FEC codes, including Reed Solomon (RS) codes, concatenated codes, product codes, and low-density parity-check (LDPC) codes, are recommended by ITU-T [1-3]. They differ in terms of transmission overhead (redundancy), implementation complexity, net coding gain (NGC), burst error correction ability, to mention few. In this invited paper, we describe and compare various LDPC coding schemes, including binary LDPC codes and concatenated non-binary LDPC codes, and a rate adaptation technique for both cases. By computer simulation, we first optimize the bit-width of input log-likelihood ratios (LLRs), check-to-variable messages in variable-to-check messages. Then we show via FPGA emulation that the large-girth LDPC coding schemes can achieve large NGCs exhibiting no error floor at BER down to 10^-15, when layered decoding algorithm is employed. Meanwhile, we demonstrate a flexible rate adaptation technique with the proposed unified decoder architecture. At last, by comparing the implementation complexity of RS codes and concatenated codes, we conclude that the proposed flexible LDPC coding schemes represent one of the promising candidates for next-generation intelligent optical aggregation networks.

Advanced digital signal processing for short-haul and access network (Invited Paper)
Junwen Zhang, Fudan Univ. (China); jianjun yu, ZTE (Tx)
(United States); nan chi, Fudan Univ. (China)
Digital signal processing (DSP) has been proved to be a successful technology recently in optical short-haul and access network, which enables high performances with high speed and high spectrum-efficiency based on digital equalizations and compensations. In this paper, we investigate advanced DSP at both transmitter and receiver side for signal pre-equalization and post-equalization in the optical access network. A novel DSP-based digital and optical pre-equalization scheme has been proposed for bandwidth-limited high speed short-distance communication system, which is based on the feedback of receiver-side adaptive equalizers, such as least-mean-squares (LMS) algorithm and constant or multi-modulus algorithms (CMA, MRA). Using this scheme, we experimentally demonstrate 400GE on a single optical carrier based on the highest ETDM 120-Gbaud PDM-PAM-4 signal. A line rate of 480-Gb/s is achieved, which enables 20% forward-error correction (FEC) overhead to keep the 400-Gb/s net information rate. The performance of the PDM-PAM-4 signal with a record symbol-rate of 120-Gbaud after fiber transmission shows large margin for both short range and metro/regional networks. We also extend the advanced DSP for short haul optical access networks with high order modulation formats. We propose and demonstrate a high speed multi-band CAP-WDM-PON system using intensity modulation with direct detection and digital equalizations. A hybrid modified cascaded MAA with decision-directed LMS post-equalization schemes are used to equalize the multi-band CAP-QAM signals. Using this scheme, we successfully demonstrates 550Gb/s high capacity WDM-PON system with 11 WDM channels, 55 sub-bands, and 10-Gb/s per user in the downstream over 40-km SMF.


Spatial and planar optical circuit for flexible ROADM (Invited Paper)

Kota Shikama, Yuichiro Ikuma, Nippon Telegraph and Telephone Corp. (Japan); Kenya Suzuki, NTT Photonics Labs. (Japan); Tetsuo Takahashi, NTT Network Innovation Labs. (Japan)

Reconfigurable optical add/drop multiplexing (ROADM) systems with colorless, directionless, and contentionless (CDC) capabilities are attracting attention because they can provide flexible wavelength routing and wavelength assignment for “software-defined network” operations. To construct such systems, a high port-count wavelength selective switch (HPC-WSS) is the key component because it can handle a large number of wavelength channels with a simple configuration. In this context, we have been developing an HPC-WSS for ROADM systems by combining a waveguide-based device and free-space optics (FSO), which we call a spatial and planar optical circuit (SPOC) platform.

Based on the SPOC platform, we recently demonstrated an ultra-high port count WSS (UHPC-WSS) and a novel WSS-type transponder aggregator (TPA). Both are composed of an optical front-end based on a planar lightwave circuit (PLC), which is incorporated with the FSO, and a liquid crystal on silicon (LCOS) phase modulator as a switching engine for flexible-grid wavelength channels. The results showed that our UHPC-WSS and TPA are capable of dealing with high port count channels with good optical characteristics. Here, to put them to practical use, the devices used in the WSS configuration such as the PLC front-end must offer high reliability as well as good optical performance.

In this paper, we present the SPOC applications for HPC-WSS and low-loss TPA, and also describe the reliability of the PLC front-end, which is a key enabler for the SPOC platform.

Lossless photonic switched networks for metro-access

Yara Martins, LGE Corp. (Brazil); Felipe Rudge Barbosa, Indayara B. Martins, Univ. Estadual de Campinas (Brazil); Edson Moschim, University of Campinas - Unicamp (Brazil)

Based on the fact that Metro-Access presently tend to be the bottlenecks of high-capacity networks, we propose photonic switching as a means of speeding up client traffic with transparency to rate and format. In this way, we have evaluated through computer simulation the performance of OPS/ OBS photonic networks with different sizes and configurations, based on a lossless (SOA-amplified) photonic switching node experimentally demonstrated previously [1]. We choose the Manhattan St. topology, with unidirectional links, because it fits best the dynamics of our optical switching node. Two different routing protocols (SF and DR) are used to evaluate several parameters, such as average number of hops (ANH), network latency (delay) and packet loss fraction. Physical constraints are also considered. The network performance results that have been obtained, and will be presented, are very encouraging, especially on ANH and delay. Such extended investigation (networks with 16, 25 and 36 nodes) could not be performed without the aid of our newly developed simulation platform. Presently we are preparing to assemble a small prototype network with a few nodes to try and validate our network model.

Beam steering by computer generated hologram for optical switches (Invited Paper)

Keita Yamaguchi, Kenya Suzuki, NTT Device Technology Labs. (Japan); Joji Yamaguchi, NTT Device Innovation Center. (Japan)

We describe a computer generated hologram (CGH) method for application to a multiple input and multiple output (MxN) optical switch based on liquid crystal on silicon (LCOS). LCOS is a spatial light modulator that can modulate a wavefront by employing pixels arranged in two dimensions and control the diffraction angle of the signal light. The CGH method is a technique for designing phase modulation patterns by means of diffraction simulations. With this method, we can realize the complex control of signal lights, such as beam splitting.

The conventional MxN optical switch needs multiple spatial light modulations. However, the proposed CGH method realizes an MxN optical switch simply with a one-time spatial light modulation by using the LCOS, leading to fewer optical elements and improved cost efficiency. In this MxN optical switch, holographic interferometry splits all the input lights and controls the diffraction angle of each split light to connect arbitrary input ports and arbitrary output ports.

We also describe a 5x5 wavelength selective switch (WSS) realized with the above CGH method. In the proposed 5x5 WSS, the worst port crosstalk was -14.9 dB. The maximum and average increases in the insertion loss from its original value for 1xN WSS operation with these optics were 3.5 and 1.3 dB, respectively, with the exception of an intrinsic broadcast loss of 7 dB. These experimental results indicate that the proposed 5x5 WSS works well.
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9774-1, Session 1
Recent advances in silicon photonic integrated circuits (Invited Paper)
John E Bowers, Tin Komljenovic, Mike Davenport, Jared Hulme, Alan Y Liu, Christos Santis, Alex Spott, Sudharsanan Srinivasan, Eric J. Stanton, Chong Zhang, Univ. of California, Santa Barbara (United States)

A number of important breakthroughs in the past decade have focused attention on Si as a photonic platform. Recent progress in this field is described with a focus on research to make lasers, amplifiers, modulators and photodetectors on or in silicon. Progress in silicon photonic integrated circuits and the impact active silicon photonic integrated circuits could have on interconnects, telecommunications and on silicon electronics is reviewed.

9774-2, Session 2
Multidimensional modulation formats for coherent optical communications (Invited Paper)
Tobias A. Eriksson, Erik Agrell, Magnus Karlsson, Chalmers Univ. of Technology (Sweden)

The coherent receiver in combination with digital signal processing (DSP) has enabled the use of spectrally efficient modulation formats such as polarization multiplexed (PM) quadrature phase shift keying (QPSK) and PM 16-ary quadrature amplitude modulation (16QAM). Conventional modulation formats utilize the amplitude and phase of the signal, making them two-dimensional (2D), and the two orthogonal polarizations are considered as separate independent channels. By considering the four-dimensional space (4D) spanned by the amplitude, phase and polarization, more sensitive modulation formats can be found due to the more degree of freedom. Higher-dimensional formats can be achieved by considering modulation over several time-slots, wavelength channels, modes or cores of multicore-fibers (MCF).

In this invited contribution, 4D and eight-dimensional (8D), as well as higher-dimensional modulation formats are investigated and compared to conventional formats. The modulation formats are studied for systems without and without forward-error correction (FEC) coding. Examples for such uncoded, or low-complexity FEC, systems can for example be short-range and metro coherent links, while transoceanic links are assumed to apply strong FEC coding. The specific case of modulation over spatial super-channels for MCF-systems is also reviewed. The modulation formats are investigated in terms of spectral efficiency, asymptotic power efficiency and achievable rate with FEC coding. Experimental verifications for some formats are also presented where achievable transmission distances are examined and compared to conventional formats.

9774-3, Session 2
Comparison of cost and complexity for various 16-QAM transmitter structures in coherent optical systems
Ali M. Al-Bermani, Memorial Univ. of Newfoundland (Canada); Reinhold Noé, Univ. Paderborn (Germany)

Combination of quadrature amplitude modulation with coherent detection is attractive for optical transmission systems, since it allows an increase of data rate without increasing the symbol rate or the required bandwidth. 16-point Quadrature Amplitude Modulation (16-QAM) is most interesting in this context. In-phase (I) and quadrature (Q) signals transmit 2 bit each. Together with polarization division multiplex this amounts to 8 bit/symbol.

In this article the effect of laser-linewidth-times-symbol-rate product for different square 16-QAM transmission structures is analyzed and compared with each. These structures can be categorized according to electrical driving signals to the optical modulator. A blind phase search carrier phase estimation with feedback structure have been used to present the influence of laser phase noise. The carrier recovery does not contain any feedback loop and is therefore highly tolerant against laser phase noise. Several structures of square 16-QAM with electrical multilevel drive signals are compared with electrical binary drive signals techniques with combination of multiple optical modulators. The simulation showed conventional IQ transmitter is the best choice for square 16-QAM. Based on that scheme we present later the results of conventional IQ transmitter in a real-time transmission experiment with a synchronous digital detection for 16-QAM constellations. Signals were digitally processed in real-time on a field-programmable gate array (FPGA). 2.5 Gb/s 16-QAM data was transmitted over 100 km of fiber in a heterodyne receiver. The averaged BER was below the threshold of a state-of-the-art FEC for receiver input powers above 730 dBm.

9774-4, Session 3
New fibers for high-density space-division-multiplexed transmissions (Invited Paper)
Pierre Sillard, Prysmian Group (France)

Space-Division Multiplexing (SDM), introduced more than 3 decades ago, is currently subject to intense research in order to increase by more than tenfold the current 10s of Tbit/s capacity of single-core, single-mode systems and thus avoid the foreseen capacity crunch.

Fibers play a central role in this renewed research field, and significant efforts have recently been spent to develop new fibers for SDM. These fibers can be classified into 3 categories depending on the way the inherent cross-talk issue of SDM is addressed. In the first weakly-coupled category, the cross-talk is minimized so that each SDM channel is separately detected without using complex Multiple-Input-Multiple-Output Digital Signal Processing (MIMO-DSP). In the second low-Differential-Group-Delay (low-DGD) category, the DGDs between all the SDM channels are minimized so that they can be simultaneously detected at reception and that MIMO-DSP can efficiently compensate for cross-talk. The third category is a hybrid category in which low-DGD SDM channels are arranged in weakly-coupled groups.

In this paper, we will review the most recent advances on these different SDM fibers. We will also compare their performances and evaluate their respective potentials using the normalized spatial density that is a measure of the space efficiency.

9774-5, Session 3
Four-mode semiconductor optical amplifier (Invited Paper)
He Wen, Tianjin Univ. (China); Yousef Alahmadi, Patrick L. LiKamWa, Cen Xia, Christian Carboni, Guifang Li, CREOL,
The College of Optics and Photonics, Univ. of Central Florida (United States)

Mode-division multiplexing (MDM) can significantly increase per fiber transmission capacity by exploiting the new dimension of fiber modes. Few-mode amplifiers are one of the most important technologies utilized in MDM. While most research interests are focused on few-mode Erbium-doped fiber amplifiers (FM-EDFA), a complicated design, necessitating intricate ion doping concentration and refractive index profile, as well as precise pump modal power control, to equalize the gain between different modes. Few-mode semiconductor optical amplifiers (FM-SOA) have not been investigated so far. FM-SOAs have some of the same attractive attributes such as compactness, energy efficiency and low-cost as single-mode SOAs. For MDM applications, FM-SOAs have potential advantages over FM-EDFAs because they are electrically pumped, which provides an identical carrier distribution for all modes, as opposed to optical pumped, which produces modal-dependent carrier distributions. In addition, the doping concentration profile in FM-SOAs can be precisely controlled to nanometer resolutions. Therefore, FM-SOAs can provide easy modal-dependent gain control that is not possible with FM-EDFAs.

In this paper, we report the first demonstration of the FM SOA, to our best knowledge. The FM-SOA features layered quantum well structures strategically placed to provide high gain for high-order waveguide modes. The measured mode intensity profiles agree well with simulation. The on-off mode gain can reach 13 dB and the difference between each mode is kept within 4 dB.

9774-6, Session 4

On-chip mode division multiplexing technologies (Invited Paper)

Yunhong Ding, Louise F. Frellsen, Xiaowei Guan, Technical Univ. of Denmark (Denmark); Jing Xu, Huazhong Univ. of Science and Technology (China); Francesco Da Ros, DTU Fotonik (Denmark); Haiyan Ou, Technical Univ. of Denmark (Denmark); Christophe Peucheret, Univ. de Rennes 1 (France); Lars H. Frandsen, Leif K. Oxenløwe, Technical Univ. of Denmark (Denmark); Kresten Yvind, DTU Fotonik (Denmark)

Space division multiplexing (SDM) has recently been considered a promising technology to meet the ever increasing capacity demand in future optical fiber communication networks. In particular, mode division multiplexing (MDM), which utilizes spatial modes of few-mode fibers (FMFs), has been demonstrated to efficiently increase the throughput of optical links. As one of the critical components for MDM, efficient mode (de)multiplexers are under investigation.

Recently, on-chip interconnects using MDM technologies have gained significant attention. In on-chip interconnects, optical technologies are considered promising in order to satisfy the increasing bandwidth requirements in multiple-core processor architectures with relatively low power consumption. In this context, optical networks on chip (ONOCs) are therefore foreseen to be one critical technology. Currently, ONOCs are mainly based on wavelength division multiplexing (WDM). The main limitation of the WDM approach is the current difficulty to integrate light sources on the silicon platform. On the other hand, MDM offers another possible mean to route the multiplexed optical signals, and the footprint of the circuit could potentially be reduced. Critical building blocks such as mode (de)multiplexers, mode converters, mode filters etc. have been the objects of investigations.

In this paper, we present building blocks on the silicon-on-insulator (SOI) platform, including fabrication tolerant wideband (de)multiplexers, ultra-compact mode converters and (de)multiplexers designed by topology optimization, and mode filters using 1D photonic crystal silicon waveguides. We demonstrate point-to-point MDM transmission, and all-optical signal processing by mode-selective wavelength conversion. Finally, we report efficient silicon photonic integrated circuit mode (de)multiplexers for FMFs.

9774-7, Session 5

Ultra-long-haul optical transmissions based on coded modulation (Invited Paper)

Jin-Xing Cai, TE SubCom (United States)

Coded modulation formats offer an effective approach to maximize capacity, increase reach and performance in long-haul transmission systems. Recently the records in spectral efficiency and capacity in a single core and single mode fiber over transoceanic distances were achieved using coded modulation with variable spectral efficiency which resulted in the most efficient transmission bandwidth utilization. We discuss the transmission performance of coded modulation formats based on Nyquist spectrally shaped QPSK, 16QAM, and 64QAM constellations in a range of spectral efficiencies from 2.4 to 8.0 bits/s/Hz with a fixed symbol rate (32 GBd). We review a record 54 Tb/s capacity experiment over transpacific distance of 9,150 km using coded modulation based on 16QAM constellation. We also review 63.5 Tb/s transmission over 5,380 km and 61.9 Tb/s over 5,920 km using 64QAM based coded modulation where 7.1 b/s/Hz spectral efficiency was achieved.

9774-8, Session 5

Massive eigenvalue modulated optical transmission systems

Akihiro Maruta, Osaka Univ. (Japan)

The nonlinear Schrödinger equation (NLSE) which describes behavior of the complex envelope of electric field propagating in a nonlinear dispersive fiber, can be solved analytically by using the inverse scattering transform (IST). In the IST, the eigenvalues of the Dirac-type eigenvalue equation associated to NLSE are invariables even though the temporal waveforms and frequency spectra dynamically change during propagation in fiber. Therefore the eigenvalue is more ideal information carrier than the pulse’s amplitude, frequency, and/or phase which are modulated in conventional formats. In this paper, we introduce massive transmission technologies for eigenvalue modulated system based on the digital coherent technology. After briefly explaining the principle of modulation and demodulation of the eigenvalue modulated signal, we numerically and experimentally demonstrate the eigenvalue modulated system. We also introduce eigenvalue multiplexing, wavelength division multiplexing, polarization division multiplexing for the eigenvalue modulated system to achieve massive transmission.

9774-9, Session 5

Smoothly clipped root raised cosine waveforms for an effective loading of a coherent optical M-QAM modulator (Invited Paper)

Bishara Shamee, Morteza Ziyadi, Amirhossein Mohajerin-Ariaei, Ahmed Almaiman, Yinwen Cao, Nisar Ahmed, The Univ. of Southern California (United States); Steven R. Wilkinson, Raytheon Space and Airborne Systems (United States); Alan E. Willner, The Univ. of Southern California (United States)

Higher order modulation formats increase the peak to average power limiting the spectral efficiency due to the non-linearity of the optical modulator and the RF drivers. Hard clipping broadens the spectrum of the waveform beyond the desired excess bandwidth of the root raised cosine and by smoothly controlling waveform clipping, the bandwidth growth can be optimized to load the optical front end consisting of the optical i-Q MZM modulator and the corresponding RF drivers. We present a simulation...
9774-10, Session 6

Performance analysis of low-complexity adaptive frequency-domain equalization and MIMO signal processing for compensation of differential mode group delay in mode-division multiplexing communication systems using few-mode fibers

Yi Weng, Xuan He, Zhongqi Pan, Univ. of Louisiana at Lafayette (United States)

Mode-division multiplexing (MDM) transmission systems utilizing few-mode fibers (FMF) have been intensively explored to sustain continuous traffic growth. The key challenges of MDM systems are inter-modal crosstalk due to random mode coupling (RMC), and largely-accumulated differential mode group delay (DMGD), whilst hinders mode-demultiplexer implementation. The adaptive multi-input multi-output (MIMO) frequency-domain equalization (FDE) can dynamically compensate DMGD using digital signal processing (DSP) algorithms. The frequency-domain least-square means (FD-LMS) algorithm has been universally adopted for high-speed MDM communications, mainly for its relatively low computational complexity. However, longer training sequence is appended for FD-LMS to achieve faster convergence, which incurs prohibitively higher system overhead and reduces overall throughput. In this paper, we propose a fast-convergent single-stage adaptive frequency-domain recursive least-squares (FD-RLS) algorithm with reduced complexity for DMGD compensation at MDM coherent receivers. The performance and complexity comparison of FD-RLS, with signal-PSD-dependent FD-LMS method and conventional FD-LMS approach, are performed in a 3000 km 6x6 transmission system with 40 ps/km DMGD. We explore the convergence speed of three adaptive algorithms, including the normalized mean-square-error (NMSE) per fast Fourier transform (FFT) block at 14-30 dB OSNR. The channel matrix is estimated, and RMC in FMF is discussed. The fast convergence of FD-RLS is exploited at the expense of slightly-increased necessary tap numbers for MIMO equalizers, and it can partially save the overhead of training sequence. Furthermore, we demonstrate adaptive FD-RLS can also be used for chromatic dispersion (CD) compensation without increasing the filter tap length, thus prominently reducing the DSP implementation complexity for MDM systems.

9774-11, Session 6

20-Gb/s QPSK transmission over 4km-long holey fiber using a wavelength tunable quantum dot light laser in T-band

Akiihoro Murano, Shoko Yamada, Aoyama Gakuin Univ. (Japan); Atsushi Kanno, Naokatsu Yamamoto, National Institute of Information and Communications Technology (Japan); Hideyuki Sobotabayashi, Aoyama Gakuin Univ. (Japan)

Pioneering and developing advanced new wavebands directly increase the capacity of photonic transport network because conventional C and L bands have the optical bandwidth of 4.39 and 7.1 THz, respectively; up to 100 optical channels by wavelength-division-multiplexing (WDM) technology. Now, a novel waveband of T band (Thousand-band: 1000-1260 nm, 61.9-THz) is being developed for application not only to industry but also to communication. Broad-bandwidth feature of the T band promises drastic increase of the channels and finally the capacity of the transport system, however, the broad waveband requires a wide-wavelength-tunable laser source. In addition, to optimize spectral efficiency, multilevel modulation and demodulation using a coherent detection technique are also indispensable. In the study, we demonstrates 20-Gb/s quadrature phase-shift keying (QPSK) signal over endlessly single-mode holey fiber using a wavelength-tunable semiconductor quantum-dot (QD) laser operated at the wavelengths of 1040-1070 nm, which corresponds to an optical frequency of 8.09-THz that is wider than the L band. We employed the QD laser developed for the T band as ultra-broadband wavelength-tunable and narrow-linewidth coherent light sources. The transmission system is based on a homodyne coherent detection with offline digital signal processing including a carrier phase and IQ data recovery, which is configured with similar manner to the conventional optical digital coherent detection. The obtained bit error rates were within a forward error correction limit of 270-3. As the endlessly single-mode holey fiber is capable for the C and L bands, the WDM technology with the entire wavebands will realize the huge capacity photonic transport systems.

9774-12, Session 6

Improved pilot-tone technique for inter- and intra-channel nonlinearity compensation in long-haul CO-OFDM systems

Ali M. Al-Bermani, Memorial Univ. of Newfoundland (Canada)

Coherent optical orthogonal frequency division multiplexing (CO-OFDM) has become a promising modulation formats to overcome the limitation due to linear transmission impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD) in addition to crosstalk limitation. Fiber nonlinearity is one of the major hurdle in long-haul transmission which can limits the maximum transmission reach and the spectral efficiency. Therefore mitigation of fiber nonlinearities is essential to enable higher launch powers in the optical fiber to improve the optical signal to noise ratio. This will enhance the spectral efficiency and the transmission capacity by sending high order modulation formats.

In this work we studied fiber nonlinearity mitigation in CO-OFDM by combining RF pilot (RFP) technique with various subcarrier filling schemes and compare it with various RFP guard band frame structure. The technique is effective to combat the SPM effects, for mitigation of both SPM and XPM enhanced pilot-tone technique for inter- and intra-channel nonlinearity compensation in long-haul CO-OFDM systems. The simulated result show the ability of using commercial lasers over 10, 20 and 30 spans of SSMF with QPSK and 16-QAM CO-OFDM systems. The technique shows clearly higher tolerance due to laser phase noise and fiber nonlinearity compared to standard RFP tone technique. Although this technique can lower the spectral efficiency compared to the conventional CO-OFDM system, it is a good candidate that can mitigate fiber nonlinearity in long-haul CO-OFDM system. The technique is simple without any additional hardware complexity. The results shows CO-OFDM can be used for long-haul transmission when fiber nonlinearities are dominated.

9774-13, Session 7

Detection and alignment of XY skew for dual-polarization optical quadrature amplitude transmitter using reconfigurable interference

Yang Yue, Bo Zhang, Qiang Wang, Rob Lofland, Jason O’Neil, Jon Anderson, Juniper Networks, Inc. (United States)

To meet the ever-growing requirement for data-carrying capacity, a few degrees of freedom of photon (amplitude, phase, polarization, etc.) have
been used to multiplex low speed electrical data streams. Dual-polarization quadrature phase-shift keying (DP-QPSK) modulation format has been adopted by the optical communications industry for its efforts with 100G line-side coherent solutions. Dual-polarization quadrature amplitude modulation (QAM) is also the feasible path towards 400Gbps and 1Tbps systems.

For DP-QAM transmitter, the time mismatch between the IQ or XY tributary channels is known as the IQ or XY skew. Large uncompensated IQ or XY skew can significantly degrade the system performance in the coherent system. Sometimes, for long-haul transmission, time-interleaved return-to-zero DP signal is preferred with lower nonlinear polarization scattering induced penalty. Recently, we have demonstrated a simple scheme for IQ skew detection using reconfigurable interference, potentially with an integrated photodiode. A laudable goal would be to detect XY skew and align all tributary channels for DP-QAM transmitter with a simple, sensitive, and fast method.

In this work, we experimentally demonstrate XY skew detection and alignment of optical quadrature amplitude transmitter using reconfigurable interference of two tributary channels, one from each polarization. By reconfigurably interfering time-skewed identical BPSK channels, periodic power transfer function with >23dB dynamic range is obtained to determine sub-unit-intervals (UI) or multi-UI XY skew. ~1.5-dB power change is achieved for 1-ps XY skew. The scheme is compatible with different modulation formats, flexible data sequences, and variable waveforms. Potential fast detecting scheme for arbitrary skew measurement is experimentally verified.

9774-14, Session 7
Secured optical fiber communication using polarization restoration technique and channel characterization
Nikhil V. Punekar, Bhagyashri A. Darunkar, Pramode K. Verma, The Univ. of Oklahoma - Tulsa (United States)

Optical fiber channels are used as media to transfer the information globally. This paper presents an implementation of a novel procedure using which a secured communication between two parties can be carried out using polarized beam of light over an optical fiber. The paper presents the experimental results obtained of the procedure in the lab environment and a security analysis of the same. It is observed that polarization state of a light pulse cannot be retained as it travels over an optical fiber because of the birefringence phenomenon. Multiple environmental factors such as pressure, vibration, temperature, etc. also add a non-linearity to the birefringence of an optical fiber leading towards an un-predictable polarization state changes over the course of an optical fiber. The proposed procedure helps the receiving party to successfully retrieve the data in the form of a polarization state transmitted by the sending party without having any knowledge about the state of polarization at the transmitting end. The paper also explains an added layer of security the procedure provides to the communicating parties to make it difficult for an adversary to fetch the data being transferred. The proposed system does not depend on the wavelength of the light being used, nor does it depend upon the type of the optical fiber used for the communication. Using this procedure, multiple bits of secured information can be sent over an optical fiber in a single polarized pulse and retrieved at the receiving end, also known as Polarization Shift Keying.

9774-15, Session 8
High-speed coherent transceiver technologies enabled by silicon photonic integrated circuits (Invited Paper)
Benny Mikkelsen, Acacia Communications Inc. (United States)

The paper discusses high speed coherent transceiver designs enabled by silicon photonic integrated circuits (PICs). In particular we discuss the implementation of a silicon photonic PIC that contains all the optics for a high speed coherent transceiver, except the laser. The PIC is co-packaged with linear drivers and TIA and consumes only 4.5W. Operating together with a coherent ASIC, the PIC supports transmission speeds up to 200Gb/s by 16QAM. The OSNR performance is comparable to the performance of discrete optics, and supports a wide variety of applications including Data Center Interconnects, Metro and Long-haul. We also consider different pluggable coherent form-factors enabled by silicon photonic PICs.

9774-16, Session 8
Ultra-compact integrated silicon photonics balanced coherent photodetector
Jason T. Meyer, Mahmoud Fallahi, College of Optical Sciences, The Univ. of Arizona (United States)

The rapid expansion of the internet in recent years has placed increasing demand on the telecommunications infrastructure. This has driven the need to develop novel silicon photonics devices, which are capable of delivering high-speed, low-cost device solutions while also being compatible with standard CMOS technology. We have investigated a novel ultra-compact balanced coherent photodetector device capable of meeting these demands. This device consists of a silicon 2x2 multimode interference (MMI) device that takes a signal of interest and mixes it with a local oscillator. The two outputs from the MMI each have a 50%/50% split of the mixed signal and are evanescently coupled into a germanium photodetector layer. The balanced coherent nature of the device allows for extraction of phase information from the detected signal. Furthermore, we propose utilizing liquid capillary bonding to wafer bond the germanium detection layer directly to the silicon output waveguides from the MMI device. Utilizing this fabrication approach will avoid epitaxial growth issues arising from the lattice mismatch between germanium and silicon. In this presentation, I will discuss the theoretical foundation of our device and present several simulations we have performed to model its effectiveness. I will conclude by discussing the challenges that need to be overcome in fabrication in order to realize this device.

9774-17, Session 8
Spatial-mode conversion using random diffuser and spatial light modulator for reduction of modal crosstalk
Koki Ishii, Atsushi Okamoto, Hokkaido Univ. (Japan); Takehiro Tsuritani, Yuta Wakayama, KDDI R&D Labs., Inc. (Japan); Yuta Goto, Akihisa Tomita, Hokkaido Univ. (Japan)

The mode-division multiplexing (MDM) technique enables the transmission of multiple signals within a multi-mode fiber (MMF) or a few-mode fiber (FMF). To construct an efficient and flexible MDM network in the same way as a wavelength-division multiplexing network, a mode conversion method with low modal crosstalk is required for switching between arbitrary spatial modes. However, in general, modal crosstalk is strongly dependent on the intensity pattern before mode conversion, and it is increased particularly for higher order modes. In order to reduce modal crosstalk, we propose a method using a random diffuser and a spatial light modulator (SLM). In the proposed method, firstly, the input spatial mode is dispersed uniformly by the random diffuser. Subsequently, the diffused phase distribution is canceled and converted into the desired spatial mode by the SLM, which displays phase difference between desired and diffused modes. Consequently, every spatial mode can be evenly converted into a desired mode. Here, we numerically simulate and confirm that the proposed method can reduce modal crosstalk compared to the conversion method without the random diffuser.
Frequency noise of quantum-dash DFB laser

Omar M. Sahni, Stéphane Trebaol, Yohann Léguiillon, Christelle Pareige, Pascal Besnard, CNRS-Fonctions Optiques pour les Technologes de l’information (France); Liam Barry, Dublin City Univ. (Ireland) and The RINCE Institute (Ireland)

We present recent results of noise intensity (RIN) and phase noise measurements on DFB quantum-dash lasers. We show that the noise at low frequencies is much lower than that of commercial quantum-well DFB lasers. These noise measurements will be important in understanding the performance of these quantum dash devices in coherent systems.

Highly accurate spatial mode generation using spatial cross modulation method for mode division multiplexing

Hiroki Sakuma, Atsushi Okamoto, Hokkaido Univ. (Japan); Atsushi Shibukawa, California Institute of Technology (United States); Yuta Goto, Akihisa Tomita, Hokkaido Univ. (Japan)

Mode division multiplexing (MDM) has been actively studied to overcome the capacity crunch caused by the rapid growth of the Internet traffic. In the MDM systems, independent time series signal is modulated to each of a plurality of spatial modes. The most well-known technique for generation of the complex amplitude distribution is a computer-generated hologram using a spatial light modulator (SLM). In this method, however, its spatial resolution and light utilization efficiency are very limited. Specifically, the distortion of the generated spatial mode causes the modal cross-talk. In this study, we propose a spatial mode generation technique using a spatial cross modulation (SCM) method. In the SCM, both the phase and the amplitude of the spatial mode is computationally encoded into phase-only image by the light diffusing with the virtual random diffuser based on the fact the phase distribution in a homogeneous scattered wavefront contains most of the important features of the original complex amplitude. Then, the phase conjugated image of the diffused image is displayed onto a phase-type SLM (PSLM). After incident light falls on the PSLM, the spatial mode is reconstructed by making the modulated light pass through an actual random diffuser in order to cancel added phase modulation with the virtual random diffuser. We experimentally performed a spatial mode generation included LP01, LP11, LP21, LP51 and LP101 using the SCM technology. The results showed the SCM has great potential to realize the spatial mode generation with high accuracy and enough light utilization efficiency for MDM.

SDM transmission using FMF with large number of modes (Invited Paper)

Chigo Okonkwo, Eindhoven University of Technology (Netherlands)

Due to the increase in bandwidth requirements from emerging applications, there have been rapid developments in space division multiplexing. Increasing the number of spatial channels is crucial to the cost-effective deployment of such systems. In this work, we address some of the challenges in scaling the number of channels, particularly in single core mode-multiplexed transmission systems and/or few-mode multi-core SDM transmission systems, where low mode dependent losses and low differential mode group delays could yield much lower digital signal processing efforts.

Low insertion loss highly-mode-selective spatial multiplexers using multi-plane light conversion (Invited Paper)

Jean-François Morizur, Nicolas Barré, Olivier Pinel, Kevin Lenglé, Lionel Garcia, Lionel Jaffres, Pu Jian, Guillaume Labroille, CAILabs (France)

Multi-Plane Light Conversion enables novel beam shaping devices, including spatial multiplexers. After a presentation of the achievable performances of these spatial multiplexers, which can combine 10 spatial modes with average -21 dB cross-talk and 4.4 dB insertion loss, we review the performances of multi-plane light conversion in multiple application cases. These application cases include mode-multiplexed optical amplification, high-power beam shaping and combining and LAN fiber capacity upgrade.

Advanced S2 imaging spatial mode analysis: furthering modal characterization (Invited Paper)

Benoit Sevigny, Guillaume Le Cocq, Lab. de Physique des Lasers, Atomes et Molécules (France); Géraud Bouwmans, Univ. des Sciences et Technologies de Lille (France); Yves Quicquempois, Lab. de Physique des Lasers, Atomes et Molécules (France); Carmen C. Castiñeiras Carrero, Lab. de Physique des Lasers, Atomes et Molécules (France) and Prysman Group (France); Pierre Sillard, Prysman Group (France)

In recent years, multimode fibers have become more common, motivated by the needs of the fiber laser industry to move to larger effective mode areas and by a keen interest in space division multiplexing (SDM) for telecommunications. In parallel, it became necessary to develop methods to quantify single-mode operation in fiber lasers by measuring modal content, giving rise to several ingenious characterization techniques such as spatially and spectrally resolved imaging (S2) and cross-correlated imaging (C2) to name a few. Amongst those, S2 imaging is easy to implement, but relies on hypothesis (such as quasi-single mode operation), which make it somewhat unsatisfactory for characterization of heavily multimode operation. Indeed, for applications like SDM, the mode power distribution can be uniform, thus making the standard S2 data analysis difficult to use if not useless. What we outline in this paper is an approach we developed that allows one to extract a lot more information from interferometric datasets, while preserving the simple nature of the S2 setup. Based on multivariate statistical analysis, this method can isolate all the terms in a modal interferometer, both spatially and spectrally, and retrieve the corresponding amplitude of the interference. Furthermore, information on vector mode effects and mode coupling dynamics can be obtained by using this method and the differential group delay diagrams can be modally resolved. Ultimately, such a method, coupled with simple sets of rules for the interpretation of the solutions, could be used to automatically characterize the dispersion and mode structure of arbitrary optical fibers.
9774-23, Session 9

Ultrafast laser inscription of 3D components for spatial multiplexing (Invited Paper)

Robert R. Thomson, Heriot-Watt Univ. (United Kingdom)

When an ultrashort laser pulse of sub-bandgap radiation is focused inside a transparent material, the peak electric field intensity can be sufficiently high to deposit optical energy through processes such as multiphoton absorption, tunnelling ionisation and avalanche ionisation. This deposition of energy can result in a permanent modification to the material lattice, which can then manifest itself through changes in the material properties e.g. refractive index [1] and chemical etch rate [2]. Using these manifestations, the technique of Ultrafast Laser Inscription (ULI) enables the direct-write fabrication of 3D photonic components, such as optical waveguides [3] and Bragg gratings [4], inside the material. I will present some of the work that myself and others have carried out on developing components such as integrated photonic lanterns [5] and 3D integrated waveguide fan-outs [6] using ULI – components that are now finding applications in the field of spatially multiplexed telecommunications for coupling light to and from few-mode and multicore fibres respectively.


9774-24, Session 9

Gain-controlled erbium-doped fiber amplifier using mode-selective photonic lantern

Gisela López-Galmiche, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico) and CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Zeinab Sanjabi Eznaveh, J. E. Antonio Lopez, Amado M. Velazquez Benitez, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Jorge Rodríguez Asomoza, Univ. de las Américas Puebla (Mexico); Luís A. Herrera Piad, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and Univ. de Guanajuato (Mexico); Jose J. Sánchez-Mondragón, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); C. Gonent, Pierre Sillard, Prysmian Group (France); Guifang Li, Axel Schuizgen, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Chigo Okonkwo, Technische Univ. Eindhoven (Netherlands); Rodrigo Amezcua Correa, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

In optical communication, for long distance data transfer fiber amplifiers are required in order to increase the data transmission capability. In space division multiplexing systems, few modes erbium-doped fiber amplifiers (FM-EDFAs) are getting much attention due to its low differential modal gain between all supported modes by using a configurable pumping scheme. Traditionally, the signal modes and pumping modes are generated using a system conformed by a collection of phase plates and beam splitters. However, this approach, which is based mainly on bulky free-space optics, can result in severe limitations when high efficiency optical systems are required. One method to overcome this limitation is to replace the mode multiplexer by an all-fiber mode selective photonic lantern (MSPL). This device can be straightforwardly incorporated in an EDFA system offering scale up to support a large mode number, high mode conversion efficiency and the possibility of reconfigurable pump. Here, we demonstrate for the first time the performance of an MSPL as an all-fiber spatial mode multiplexer, which is integrated in a FM-EDFA system. We individually amplify the first six modes of the EDFA with relatively low differential modal gain by pumping the LP21 mode.

9774-25, Session 9

Connectivity technologies of MCF: readiness for field deployment (Invited Paper)

Kengo Watanabe, Furukawa Electric Co., Ltd. (Japan)

I was invited to talk on Connectivity for multicore fiber by Dr. Guifang Li, conference Co-Chair. So, I enter the above 100-word abstract as follow: Multicore fiber (MCF) is a promising candidate of an optical fiber for next generation large capacity transmission and high density optical wiring in data center application. To construct optical network based on MCF, a fan-out for connecting independent single core fibers and MCF is a key component. In addition, an optical connector for simultaneously connecting all cores of MCF is also a key component. In this paper, we report the recent progress in fan-out and optical connectors for MCF.

9774-26, Session 9

Photochromic glass optical fiber

Bilal A. Alvi, Hamdard Univ. (Pakistan); Amber Israr, Muhammad Asif, Muhammad Aamir, Muhammad Rehan, Sir Syed Univ. of Engineering & Technology (Pakistan)

The photochromic glass has interesting adaptive properties which can unfortunately not be conveniently exploited in single core propagation because of excessive attenuation even in the undarkened state. This paper describes the fabrication and analysis of novel twin cored fiber which contains a transparent and silver halide doped photochromic core in same cladding. The Photochromic core fibers were fabricated in twin cored structure by rod and tube method. The fiber design permitted the incorporation of photochromic core close to the transparent core during the preform fabrication. The diameter of photochromic core and transparent core is around 15 µm. The distance between two cores is 1.5µm. The transparent core was used to guide the probe beam and photochromic core was excited by U.V. source. The interaction of the probe beam with the excited photochromic core showed the photochromic behavior of the fiber.
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9775-1, Session 1

Silicon-photonics-based optical transceivers for high-speed interconnect applications (Invited Paper)
Peter M. De Dobbeleare, Luxtera, Inc. (United States)

In this paper we address some key aspects of design, manufacturing and application of silicon photonics transceivers. We will start with the silicon wafer process, next comes the development and performance of essential photonic devices within that process, including: low-loss coupling elements, low-loss single and multimode waveguides, efficient high-speed phase modulators, high-speed photo-detectors. The aspects and trade-offs concerning light source and electronic circuit integration will be reviewed followed by the architecture considerations for a transceiver system, including transmitter and receiver design, control loops and built-in self-test. This will be followed by a short review of packaging, manufacturing, reliability and supply chain for silicon photonics transceivers. Finally we will address some applications of silicon photonics transceivers.

9775-2, Session 1

Economics of data center optics (Invited Paper)
Lisa Huff, Discerning Analytics, LLC (United States)

Traffic to and from data centers is now reaching Zettabytes/year. Even the smallest of businesses now rely on data centers for revenue generation. And, the largest data centers today are orders of magnitude larger than the supercomputing centers of a few years ago. Until quite recently, for most data center managers, optical data centers were nice to dream about, but not really essential. Today, the all-optical data center – perhaps even an all-single mode fiber (SMF) data center is something that even managers of medium-sized data centers should be considering. Economical transceivers are the key to increased adoption of data center optics. An analysis of current and near future data center optics economics will be discussed in this paper. The following technologies will be presented:

• Next-generation Ethernet. We discuss how the transition from GigE to 10G, 40G and 100G will lead to significant new networking opportunities for firms with Ethernet products of all types and what the likely roadmap, economics and timetables for optical Ethernet in the data center will look like.
• InfiniBand (IB) and Fibre Channel. These standards are often declared dead, murdered by Ethernet. But they continue to find large addressable markets and have aggressive roadmaps promoted by their trade associations. This paper will show how these standards will profitably fit into the optical data center that is expected to emerge over the next few years.
• Novel networking architectures. The paper will examine how SDN and virtualization will affect physical infrastructure deployment in the coming optical data center.

9775-3, Session 3

Next-generation wideband multimode fiber for data centers (Invited Paper)
Kasyapa Balemarthy, OFS (India)

Short-reach optical links such as those used in data centers pre-dominantly employ VCSELs together with laser-optimized OM4 and OM3 multimode fiber (MMF), mainly due to their reliability, energy-efficiency and low end-to-end system cost. The IEEE 802.3bm specification for 100Gbps Ethernet utilizes four parallel MMFs each operating at a serial data rate of 25Gbps. Due to the rapidly increasing internet traffic, the IEEE P802.3bs Task Force is working towards a 400Gbps Ethernet standard requiring a commensurate increase in the number of parallel fibers deployed. Using 16 parallel lanes, while feasible, is not the most efficient use of cabling.

One solution to the data rate - cable density problem is the use of coarse wavelength division multiplexing (CWDM) near 850nm. For example, employing four wavelengths separated by ~30nm (with an operational window of 840-950nm) results in a four-fold increase in the per-fiber data rate. Furthermore, CWDM can be combined with the parallel solution to support 400Gbps with the same cable density as the current 100Gbps Ethernet solution using OM4 fiber.

Conventional laser-optimized OM4 gives diminished performance at the longer wavelengths compared to 850nm. Shifting the OM4 optimization wavelength to longer wavelengths sacrifices the 850nm performance. In this paper, we present a next-generation wideband multimode fiber (NG-WBMMF) that is optimized for CWDM operation using a novel design approach employing multiple dopants. We also demonstrate system performance results for optical links using this next-generation wideband multimode fiber.

9775-4, Session 5

Short-haul transmission links based on 25- and 50-Gbaud PAM4 modulation (Invited Paper)
Winston I. Way, NeoPhotonics Corp. (United States)

PAM4 has been considered as a practical modulation format for 100Gb/s, 200Gb/s, 400Gb/s, and even DWDM short-haul links, and the transmission distance can range from 500m to 80km. In this talk, we will review (1) technical considerations of the recently ratified IEEE802.3bs 400GbE FR8 and LR8 standards, (2) technical feasibility of next-generation 4x100G PAM4 transmission over 2km, and (3) technical and economical considerations of 80- wavelength of 50Gb/s PAM4 or 40-wavelength 100Gb/s PAM4 DWDM transmission systems over 40-80km.

9775-5, Session 5

Scaling single-wavelength optical interconnects to 180 Gb/s with PAM-M and pulse shaping
Stefanos Dris, Paraskevas Bakopoulos, Nikolaos Argyris, Christos Spatharakis, Hercules Avramopoulos, National Technical Univ. of Athens (Greece)

Faced with surging datacenter traffic demand, system designers are turning to multi-level optical modulation with direct detection as the means of reaching 100 Gb/s in a single optical lane; a further upgrade to 400 Gb/s is envisaged through wavelength-multiplexing of multiple 100 Gb/s strands. In terms of modulation formats, PAM-4 and PAM-8 are considered the front-runners, striking a good balance between bandwidth-efficiency and implementation complexity. In addition, the emergence of energy-efficient, high-speed CMOS digital-to-analog converters (DACs) opens up new possibilities: Spectral shaping through digital filtering will allow squeezing
even more data through low-cost, low-bandwidth electro-optic components. In this work we demonstrate an optical interconnect based on an EAM that is driven directly with sub-volt electrical swing by a 65 GSa/s arbitrary waveform generator (AWG). Low-voltage drive is particularly attractive since it allows direct interfacing with the switch/server ASIC, eliminating the need for dedicated, power-hungry and expensive electrical drivers. Single-wavelength throughputs of 180 and 120 Gb/s are experimentally demonstrated with 60 Gbaud optical PAM-8 and PAM-4 respectively. Successful transmission over 1250 m SMF is achieved with direct-detection, using linear equalization via offline digital signal processing in order to overcome the strong bandwidth limitation of the overall link (~20 GHz). The suitability of Nyquist pulse shaping for optical interconnects is also investigated experimentally with PAM-4 and PAM-8, at a lower symbol rate of 40 Gbaud (limited by the sampling rate of the AWG). To the best of our knowledge, the rates achieved are the highest ever using optical PAM-M formats.

9775-6, Session 6

Recent advances of emerging PAM4 signaling with real-time processing for 100/400Gbps intra data center connectivity (Invited Paper)

Frank Chang, Inphi Corp. (United States)

It’s obvious that the demand for bandwidth will continue to rise rapidly in the data center and server segment. Just recently the IEEE 400Gbe P802.3bs Task Force has adopted Pulse Amplitude Four Level Modulation or PAM4 signaling as the only viable technology standard of data center interconnect for 2km and above distances as well as for low end of 500m and below. To implement the PAM4 architecture over transition from NRZ, the key IC building blocks include the PAM4 DSP engine with real time DSP processing as well as high linearity, low power transimpedance amplifiers (TIA) and drivers.

In this talk, we will review various emerging PAM4 applications covering scenarios operating at ~25Gbaud rates: 1) single lambda 40-50Gbps PAM4; 2) dual lambda 100Gbps with PIN ROSA; 3) dual lambda 100Gbps with APD ROSA and 4) its implications to 400Gbps. Various commercial TOSA devices for either DML or EML, and ROSA devices with either PIN or APD are extensively examined targeting lower cost & power alternatives to the existing implementations. By leverage the newly developed PAM4 IC chipset, link Performance with real-time DSP realized in miniaturized silicon format are extensively studied for distance of standard single mode fiber from 2km, and it shows error free transmission with great margin under KR4 FEC threshold at 1310nm wavelength(s) for up to 40km distance.

9775-7, Session 6

Power penalties for multi-level PAM modulation formats at arbitrary bit error rates

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There is considerable interest in combining multi-level pulsed amplitude modulation formats (PAM L) and forward error correction (FEC) in next-generation, short-range optical communications links for increased capacity. In this paper we derive new formulas for the optical power penalties due to modulation format complexity relative to PAM-2 and due to inter-symbol interference (ISI). We show for the first time that these penalties depend on the required system bit-error rate (BER) and that the conventional formulas overestimate link penalties. Our corrections to the standard formulas are very small at conventional BER levels (typically 1E-12) but become significant at the higher BER levels enabled by FEC technology, especially for signal distortions due to ISI.

The standard formula for format complexity, P = 10log(L-1), is shown to overestimate the actual penalty for PAM-4 and PAM-8 by approximately 0.1 and 0.25 dB respectively at 1E-3 BER. Then we extend the well-known PAM-2 ISI penalty estimation formula from the IEEE 802.3 standard 10G link modeling spreadsheet to the large BER case and generalize it for arbitrary PAM-L formats. To demonstrate and verify the BER dependence of the ISI penalty, a set of PAM-2 experiments and Monte-Carlo modeling simulations are reported. The experimental results and simulations confirm that the conventional formulas can significantly overestimate ISI penalties at relatively high BER levels. In the experiments, overestimates up to 2 dB are observed at 1E-3 BER.

9775-8, Session 7

High-capacity modulation for data center applications using silicon photonic integrated circuits (Invited Paper)

Po Dong, Jeffrey Lee, Alcatel-Lucent Bell Labs. (United States)

The emerging applications for inter- and intra-data center communications demand low-cost and small-from-factor optical transceivers with 100G/400G capacity and beyond. Various techniques, such as wavelength-division multiplexing (WDM), multi-level pulse-amplitude modulation (PAM), and discrete multi-tone (DMT), are heavily investigated in this field. Among these techniques, DMT can offer 100-G capacity with 20-260G optical devices using direction detection, which provides a very promising low-cost 100G/400G solution. In this talk, we review silicon photonics multiple-channel DMT integrated circuits, which demonstrate channel rates of 80-100 Gb/s. For one circuit, the silicon photonic chip integrates four silicon Mach-Zehnder modulators (MZMs) and WDM multiplexers using thermally-tuned second-order microring filters. Besides the wavelength multiplexing functionality, we also demonstrate that these microrings can serve as vestigial sideband (VSB) filters to enhance the transmission performance in 20-40 kilometer ranges. For the second circuit, we demonstrate DMT using microring modulator array. These demonstrations indicate the promise of using low-cost and high-integrated silicon photonic circuits in high capacity 100G/400G applications.

9775-9, Session 7

112 Gb/s sub-cycle 16-QAM Nyquist-SCM for intra-datacenter connectivity

Paraskevas Bakopoulos, Stefanos Dris, Nikolaos Argyris, Christos Spatharakis, Hercules Avramopoulos, National Technical Univ. of Athens (Greece)

Datacenter traffic is exploding. Ongoing advancements in network infrastructure that ride on Moore’s law are unable to keep up, necessitating the introduction of multiplexing and advanced modulation formats for optical interconnects in order to overcome bandwidth limitations, and scale lane speeds with energy- and cost-efficiency to 100 Gb/s and beyond. While the jury is still out as to how this will be achieved, schemes relying on intensity modulation with direct detection (IM/DD) are regarded as particularly attractive, due to their inherent implementation simplicity. Moreover, the scaling-out of datacenters calls for longer transmission reach exceeding 300m, requiring single-mode solutions. In this work we advocate using 16-QAM sub-cycle Nyquist-SCM as a simpler alternative to discrete multitone (DMT), but which is still more bandwidth-efficient than PAM-4. The proposed optical interconnect is demonstrated at 112 Gb/s, which, to the best of our knowledge, is the highest rate achieved in a single-polarization implementation of SCM. Off-the-shelf components
Recent standardization directions for high-speed client and line side components (Invited Paper)

Hideki Isono, Fujitsu Optical Components Ltd. (Japan)

Triggered by the recent vast demands of the information bandwidth, high speed transmission networking system, such as 100G/400G, have been developed and installed with extremely high speed. In order to lead the proper concept/design of the leading edge optical components which is applied for these high speed networking equipment, de-fact standardization bodies such as IEEE802.3/OIF have made important roles in the industry. Focusing on optical transceivers/devices, IEEE802.3 has standardized 100G and 400G Ethernet transceivers with suitable new electrical/optical interfaces, and OIF has standardized high-speed digital coherent transceivers and its built-in devices for long-haul and metro networking application fields. It seems that these standardization activities have reached the tentative plateau from the existing industry demand. However the demands of the bandwidth will still continue to increase with endless degree, and therefore the future migration towards higher speed and smaller form factor transceivers/components is absolutely inevitable, and one of which is mainly due to data-center configuration progress, such as new demand for IDC (Inter Data Center) and mobile backhaul networking applications. At this point, the technical review of the directions of the future improvement for higher bandwidth and lower profile transceivers/components is considered to be extremely important and it should be made from the view point of components.

Optical interconnect technologies for high-bandwidth ICT systems

Norio Chubo, Naoki Matsushima, Toshiaki Takai, Hideo Arimoto, Yasunobu Matsuoka, Hiroki Yamashita, Akiko Mizushima, Hitachi, Ltd. (Japan)

The bandwidth of information and communication technologies (ICT) systems such as servers and routers doubles every two years and it will be above 10 Tbps within several years. Interconnect requires more high-density, lower loss, lower power and lower crosstalk. So optical interconnect will be introduced.

To realize optical interconnect such as high bandwidth apparatus, we developed three component.

First is small footprint and low power embedded optical module (EOM). By introducing a dual inline electrical connector, the module can straddle optical fibers, so it can be arranged tile-like on a PCB. ICs are directly attached to cooling fin, so it gets high cooling efficiency. The bandwidth is 100 Gb/s (25 Gb/s × 4 ch), density is 45 Gb/s/cm².

Second is high density optical wiring. By introducing optical fiber tray which is integrated multi fiber connectors, compact optical backplane was realized. The fiber tray can be removed from or be installed to apparatus's PCB easily. Therefore it can inspect separately from electrical parts.

Third is high density optical connector. By integrating 8 MT ferrules in a housing, it can connect 384 fibers at a time. Moreover, to reduce insertion force and to improve reliability, we prototyped a lensed connector.

We realized 9.6 Tbps optical interconnect system using the EOM, the optical backplane and the optical connector in a network apparatus chassis. We demonstrated 25 Gb/s transmission between FPGAs via optical backplane.

Optoelectronic specifications of emerging coherent optical solutions for data center interconnect (Invited Paper)

André Souza, CPqD (Brazil); Valery N Rozental, CPqD Foundation (Brazil); Andrea Chiuchiarelli, CPqD Foundation (Brazil); Tatiani Pivem, CPqD Foundation (Brazil); Jacklyn D. Reis, Juliano Oliveira, CPqD (Brazil)

Emerging short-reach data center interconnect is a scenario wherein the capacity has to be maximized over point-to-point optical links without intermediate optical amplification, i.e. unrepeated links. Most of the transceiver solutions are based on 100G modules with direct detection modulation. Although these legacy solutions are cost-efficient in a short-term, they are not scalable in a long-term where the capacity times distance product will be more and more stringent.

This paper addresses coherent optical solutions for emerging data center interconnect wherein the optical transmission reach is limited to around unrepeated 100 km. The main advantage of coherent solutions when compared to legacy direct detection technologies is the inherently improved spectral efficiency (e.g. 400 Gb/s channels in a 50 GHz) and receiver sensitivity provided with high baud (>40 Gb/s) rate transceiver modules. In this paper, two technological options for single-carrier optical 400 Gb/s modules are exploited for high capacity links over short reach scenarios, i.e. 42 Gbd – PDM – 64 QAM in 50 GHz grids and 64 Gbd – PDM – 16 QAM in 75 GHz grids. These two solutions are compared in terms of capacity allocated in C band (~4 THz bandwidth), when considering 50 GHz (80 channels at 400 Gb/s × 2 Tbps in 50 GHz grid) and 75 GHz (53 channels with 21.2 Tbps) grid, back-to-back requirements in terms of optoelectronics (digital-to-analog and analog-to-digital converters, modulators, receivers etc) and transmission performance in terms of power budget (OSNR and receiver sensitivity) and fiber effects (CD compensation and fiber nonlinearities).
100 Gb/s optical discrete multi-tone transceivers for intra- and inter-datacenter networks

Kazuhito Ikeda, Keijiro Suzuki, Ken Tanizawa, G. W. Cong, and Ken-ichi Sato, Nagoya Univ. (Japan); Shu Namiki, National Institute of Advanced Industrial Science and Technology (Japan)

Owing to broadband mobile communication systems and cloud services being widely used, demands to increase the capacity of optical communication systems in intra- and inter-datacenter networks have been growing continuously. 100-Gb/s Ethernet (100GbE) systems have been commercialized, and 400GbE standardization in short reach applications has finished. Moreover, enhancing reach more than 40 km is strongly demanded. We thus propose discrete multi-tone (DMT) technology using a simple configuration to achieve high capacity at low cost. DMT technology is an orthogonal frequency division multiplexing based modulation format. DMT signals are modulated into the intensity domain of lightwaves. Cost-effective devices such as directly modulated lasers and direct detectors can be used for DMT technology. For an intra-datacenter network at the distance of several kilometers, transceivers require not only high capacity but also low cost, size, latency, and power consumption. In inter-datacenter networks more than 40 km, technical issues such as transmission loss and fiber dispersion must be considered. Fiber dispersion causes power fading at photodetectors. SNR degradation due to power fading degrades the capacity and transmission distance of DMT signal. Vestigial sideband (VSB) optical shaping is one possible candidate to reduce power fading at low cost. Nonlinear compensation (NLC) by using digital signal processing effectively compensates for not only nonlinearities of devices but also transmission distortion. We experimentally demonstrated 100-Gb/s DMT transmission up to 100 km using VSB and NLC. In this paper, we will discuss suitable technology for DMT transceivers in intra- and inter-datacenter networks, respectively.

Silicon photonics for high-data-rate link applications

Jonathan Luff, Mehdi Asghari, Dazeng Feng, Mellanox Technologies, Inc. (United States)

Silicon Photonics has become one of the most promising technologies to address connectivity bottlenecks in data center and optical networks. We have focused on the development of a manufacturable micron-scale silicon photonics platform to demonstrate the practical realization of this technology for high speed optical links. In this paper, we will review the latest progress in the development of key photonic components such as hybrid lasers, WDM multiplexers, electro-absorption modulators, and germanium detectors. We will also review recent advances in the development of highly integrated N750 Gbps transceiver circuits and discuss the path to 1Tb/s transceivers.

Silicon photonics switches for energy-efficient flexible networking

Kazuhiro Ikeda, Keijiro Suzuki, Ken Tanizawa, G. W. Cong, and Ken-ichi Sato, Nagoya Univ. (Japan); Shu Namiki, National Institute of Advanced Industrial Science and Technology (Japan)

Large-scale optical switches are the essential building block for the energy-efficient Dynamic Optical Path Network that will fundamentally resolve the limitation in energy and capacity of the current packet-switching-based networks, and in sustainability of the emerging SDN/NFV technologies based on electrical switches. It also enables Ebps-class optical interconnects that substantially the “Exascale” high-performance computing in the future datacenters and supercomputers. In this presentation, we review the basics and our recent results of ultra-compact, low-cost, and highly reliable large-port-count silicon photonics switches fabricated with the CMOS-compatible fabrication process.

Isipp-200: a silicon photonics platform supporting optical data rates beyond 50Gb/s (Invited Paper)

Philippe P. Absil, Peter De Heyn, IMEC (Belgium); Hongtao Chen, Ashwyn Srinivasan, IMEC (Belgium) and Univ. Gent (Belgium); Peter Verheyen, Sadhishkumar Balakrishnan, Guy Lepage, Marianna Pantouvaki, Jeroen De Coster, IMEC (Belgium); Gunther Roelkens, Dries Van Thourhout, IMEC (Belgium) and Univ. Gent (Belgium); Joris Van Campenhout, IMEC (Belgium)

Silicon photonics has been selected by a growing number of industrial players to develop their next generation transceivers, typically towards 100GbE based on various 4x25Gb/s architectures. Future systems will aim at 400GbE relying on 8x50Gb/s architectures for instance. To support this bandwidth scaling imec has developed a single-chip silicon photonics solution capable of data rates at 50Gb/s and beyond. In this paper we will review the key building blocks of imec’s 200mm silicon photonics platform (ISIPP200) technology that enable modulation and detection at such data rates. These functionalities are enabled by silicon and silicon-germanium based devices that are co-integrated on standard photonics silicon-on-insulator substrates. The modulators operate with peak-to-peak voltages below 3V and extinction ratios of at least 3dB. The detectors exhibit bandwidth greater than 50GHz with dark current below 30nA and responsivities greater than 0.8A/W.

Demonstration of 720x720 optical fast circuit switch for intra-datacenter networks

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Intra-datacenter traffic is growing more than 20% a year. In typical datacenters, many racks/pods including servers are interconnected via multi-layer electrical switches. The electrical switches necessitate power-consuming optical-to-electrical (OE) and electrical-to-optical (EO) conversion, the power consumption of which increases with traffic. To overcome this problem, optical switches that eliminate costly OE and EO conversion and enable low power consumption switching are being investigated. There are two major requirements for the optical switch. First, it must have a high port count to construct reduced tier intra-datacenter networks. Second, switching speed must be short enough that most of the traffic load can be offloaded from electrical switches. Among various optical switches, we focus on those based on arrayed-waveguide gratings (AWGs),...
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since the AWG is a passive device with minimal power consumption. We previously proposed a high-port-count optical switch architecture that utilizes tunable lasers, route-and-combine switches, and wavelength-routing switches comprised of couplers, erbium-doped fiber amplifiers (EDFAs), and AWGs. We employed conventional external cavity lasers whose wavelength-tuning speed was slower than 100 ms. In this paper, we demonstrate a large-scale optical switch that offers fast wavelength routing. We construct a 720x720 optical switch using recently developed lasers whose wavelength-tuning period is below 460 ?s. We evaluate the switching time via bit-error-ratio measurements and achieve 470-?s switching time (includes 10-?s guard time to handle EDFA surge). To the best of our knowledge, this is the first demonstration of such a large-scale optical switch with practical switching time.

9775-19, Session 9
Adaptive gain, equalization, and wavelength stabilization techniques for silicon photonic microring resonator-based optical receivers

Samuel Palermo, Texas A&M Univ. (United States); Patrick Chiang, Oregon State Univ. (United States) and Fudan Univ. (China); Kunzhi Yu, Texas A&M Univ. (United States); Rui Bai, Oregon State Univ. (United States); Cheng Li, Chin-Hui Chen, Marco Fiorentino, Raymond G. Beausoleil, Hewlett-Packard Co. (United States); Hao Li, Oregon State Univ. (United States); Binhao Wang, Ayman Shafik, Alex Titriku, Texas A&M Univ. (United States)

Interconnect architectures based on high-Q silicon photonic microring resonator devices offer a promising solution to address the dramatic increase in datacenter I/O bandwidth demands due to their ability to realize wavelength-division multiplexing (WDM) in a compact and energy efficient manner. However, challenges exist in realizing efficient receivers for these systems due to varying per-channel link budgets, sensitivity requirements, and ring resonance wavelength shifts. This presentation discusses adaptive optical receiver design techniques which address these issues. A 10Gb/s power-scalable architecture is presented where the supply of a three inverter-stage transimpedance amplifier (TIA) is adapted with an eye-monitor control loop to yield the necessary sensitivity for a given channel. As reduction of TIA input-referred noise is more critical at higher data rates, a 25Gb/s design is detailed with a large input-stage feedback resistor TIA cascaded with a continuous-time linear equalizer (CTLE) that compensates for the increased input pole. When tested with a waveguide Ge PD with 0.45A/W responsivity, this topology achieves 25Gb/s operation with -8.2dBm sensitivity at a BER=10^-12. In order to address microring drop filters sensitivity to fabrication tolerances and thermal variations, efficient wavelength-stabilization control loops are necessary. A peak-power-based monitoring loop which locks the drop filter to the input wavelength, while achieving compatibility with the high-speed TIA offset-correction feedback loop, is described.

9775-20, Session 9
Hybrid optical amplifier in high-speed duo-binary modulated hybrid DWDM-OTDM system

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The Raman and Erbium Doped Fiber Amplifier (Raman-EDFA) hybrid optical amplifier (HOA) is studied in 16x40 Gbps DWDM-OTDM hybrid system with duo-binary modulated signals. It is reported that the Hybrid Optical Amplifier provides better gain, acceptable output power and signal quality even when 640 Gbps duo-binary signals are transmitted over maximum single span of 119 km of pumped single mode fiber (PSMF). With no costly dispersion controlling components and no special system design, the Raman-EDFA HOA reports an average gain of 11.375 dB with uniform received output power level across all the channels spread in 3.2 nm bandwidth. It is observed that acceptable quality factor is obtained even at higher input power > 5 dBm with duo-binary signaling. The duo-binary hybrid system performance is compared with the standard binary transmission and it is reported that the Q factor value of 16.20 dB is obtained at +6 dBm input/ channel for duo-binary transmission as against 13.94 dB obtained at +4 dBm input/channel for binary transmission after which the performance falls of rapidly to unacceptable levels. This indicates that in the scenario of high speed hybrid 640 Gbps DWDM/OTDM system with HOA, the uncompensated and repeaterless transmission of 119 km is possible for which the “Maximum Nonlinear Duobinary Limit (MNDL = 6dBm)” is required. Further the current investigation is compared with current state-of-the art schemes.