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Contents

8980-1, Session 1

Multi-quantum barrier effects on the efficiency droop of GaN-based LEDs *(Invited Paper)*

Joachim Piprek, NUSOD Institute LLC (United States)

The development of high-brightness GaN-based LEDs is handicapped by a significant efficiency reduction with increasing injection current. This efficiency droop phenomenon currently receives great attention and many proposals can be found in the recent literature on how to reduce the efficiency droop, in particular, by design optimization of the AlGaN electron blocking layer (EBL), which is used to limit electron leakage into the p-doped layers. Some of these publications utilize a multi-quantum barrier (MQB) comprising thin alternating layers of GaN and AlGaN. Compared to one thick AlGaN EBL of the same composition, MQBs were demonstrated to improve the performance of nitride-based LEDs and laser diodes. However, the measured performance improvements often deviate from the theoretical expectations, mainly due to MQB deformations typically found in real devices. Using advanced numerical simulation, we analyze recently published measurements on GaN-based LEDs featuring different types of MQBs. Surprisingly, our simulations reveal that the measured efficiency droop reduction is mainly caused by improved hole injection and not by enhanced electron wave reflection, as commonly assumed.

8980-2, Session 1

Monte Carlo-drift-diffusion simulation of electron current transport in III-N LEDs

Pyry Kivisaari, Toufik Sadi, Jani Oksanen, Jukka Tulkki, Aalto Univ. School of Science and Technology (Finland)

Advances in III-N based solid-state lighting are limited by the efficiency droop, the origin of which remains a

subject of open debate. Recent experiments suggest that the single most important factor behind droop would be hot electrons generated by Auger recombination in the active region. To study the contribution of hot electrons in drooping more accurately, simulation methods extending the conventional drift-diffusion model to also include nonequilibrium transport are required. We introduce a coupled Monte Carlo--drift-diffusion (MCDD) simulation method for studying current transport in III-N optoelectronic devices. Our aim is to study computationally the role of hot electrons in leakage currents, overall efficiency, drooping, and emission spectrum of a MQW LED.

In the MCDD method, electron and hole distributions are first simulated by solving the drift-diffusion (DD) equations.

The obtained hole density and recombination rate density are used as inputs in the Monte Carlo (MC) simulation.

The MC simulation is used to solve the Boltzmann transport equation for the electron gas while including recombination events, so that nonequilibrium transport is accurately described. Whenever needed for electrostatic convergence, the electron and hole densities are updated through iterative solutions between DD and MC. We compare the results of plain DD and MCDD models to establish the range of applicability of the DD and also report the importance of hot electron effects in the operation of modern LEDs in the high injection current regime.

8980-4, Session 1

High-voltage LED for general lighting application

Schang-jing Hon, EPISTAR Corp. (Taiwan)

High-Voltage LED for general lighting application

The breakthrough in high power GaN LED's efficiency makes the adoption of these solid state light emitting devices into general lighting application earlier than expected before. However, cost is one of the most important factors for the adoption of the general lighting application. So far, the most popular driving current for 1mm square die is about 350mA. In order to improve the lumen per cost, there is a trend to increase the driving current up to 1.5A or even higher. As well known, the droop effect plays an important roll for LED operating at high current density. Among the many factors affecting the droop effect, current crowding effect has pronouncedly degraded the performance of the LED at high current density.

In the paper we propose a novel high-voltage LED structure to achieve the extreme high power LED with high efficiency and low cost for manufacturing. The design of a series multi-junctions connection is used for high voltage LED chip. The advantages of high-voltage LED are to provide the LED device with high efficiency due to the better current spreading character and to simplify the driving circuit by using high voltage and low current operation condition.

8980-66, Session 1

Study of nano-scale ITO top grating of GaN LED

Travis V. R. Robinson, Gabriel M. Halpin, Xiaomin Jin, California Polytechnic State Univ., San Luis Obispo (United States); Xiang-Ning Kang, Guo-yi Zhang, Peking Univ. (China)

We study the effect of ITO transmission nano-gratings on the light extraction efficiency of GaN LEDs through simulations using the finite difference time domain (FDTD) method. The FDTD method applies Maxwell's equations on a point by point basis throughout the LED model to obtain accurate light extraction data from the CAD models. Our study focus is triangular (or conical) ITO grating. We define a regular spacing between unit cells in a crystal lattice arrangement by employing the following three parameters: grating cell period (?), grating cell height (h), and grating cell width (w). We showed the existence of a standing wave pattern between the multi quantum well (MQW) layer and the LED surface for non grating cases in our previous study. And optimizing the ITO thickness from worst to best case improved the light extraction efficiency by 26.7%. By implementing triangle ITO gratings on the surface of the LED with a filling factor of 0.5 and using a best case ITO thickness we were able to improve the light extraction efficiency by 143% over our conventional LED model. In this research, we use an optimized ITO thickness, but change the grating filling factor over a range of grating sizes. More detailed data with different filling factor ITO grating will be presented at the conference. This allows us to more fully maximize the light extraction efficiency of the GaN LED and deepen our understanding of the filling factor's effect on sub-wavelength gratings on GaN LEDs.

8980-5, Session 2

High-bandwidth, low loss suspended silica splitters

Soheil Soltani, Andrea M. Armani, The Univ. of Southern California (United States)

Optical splitters and couplers are one of the basic elements which comprise an integrated optical circuit, typically used as filters or routers in high bandwidth settings. Thus far, the majority of devices have been fabricated from silicon and silicon nitride due to the advantageous index contrast between the substrate and the waveguide and the low optical loss in the near-IR. However, because these devices rely on evanescent field coupling or Y-branch field splitting, the fabrication process requires high precision alignment or e-beam lithography. Recent work has demonstrated that suspended silica waveguides can achieve improved optical field confinement and lower optical loss from the visible through the near-IR. This advance forms the foundation of the newly developed suspended silica splitter. Because the splitting mechanism relies on transition loss trapping, the gap between the waveguides does not need to be defined with nm-resolution, significantly reducing the fabrication complexity. In this work, we will discuss the theoretical and experimental efforts performed to verify this splitting mechanism. Specifically, 3D FDTD models were developed to determine a predictive model of the device. Additionally, experiments were performed from the visible through the near-IR (765nm-1550nm) to verify the modeling results. Several key parameters of the device are determined, both experimentally and theoretically, with good agreement between the two methods. One of the main features of this device is that the coupling ratio remains almost constant for the entire wavelength range tested which makes it an ideal choice for wideband applications.

8980-6, Session 2

Topology-optimized broadband surface relief transmission grating

Jacob Andkjær, Christian P. Ryder, Peter C. Nielsen, Thomas P. Rasmussen, Kristian J. Buchwald, Ibsen Photonics A/S (Denmark); Ole Sigmund, Technical Univ. of Denmark (Denmark)

During the past 5-10 years dielectric transmission gratings have found widespread use in the ultraviolet, visible and near-infrared spectral ranges. However, it is very challenging to find an efficient grating structure due to the diffraction efficiency having a non-trivial dependency on the material distribution of the grating. In this work we propose a design methodology for systematic design of broad-banded transmission gratings with optimized diffraction efficiency. The physical response for an electromagnetic plane wave incident on a given periodic grating structure is found using the finite element method. The periodic grating structure is modeled using a single “super-cell” with the periodicity imposed by Bloch-Floquet boundaries. The wave enters through a dielectric region before it is scattered/manipulated by the changes in the air-dielectric profile of the grating. The transmitted part of the wave finally exits through an air region. The diffraction efficiency in each of the transmission orders can be found using a near-field to far-field transformation of the transmitted wave. We have used quartz as dielectric material due to its low loss in the ultraviolet region and the Sellmeier equation models its dispersive behavior. The material properties in the grating design region are varied within each element continuously between quartz and air using standard gradient-based topology optimization in order to maximize diffraction efficiency for the -1 transmission order. Results indicate that an optimized polarization independent transmission grating can be designed with a diffraction efficiency of more than 40% in a broad-banded range going from the ultraviolet to the near-infrared region.

8980-7, Session 2

Optical modelling of incoherent substrate light-trapping in silicon thin film multi-junction solar cells with finite elements and domain decomposition

Martin Hammerschmidt, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Daniel Lockau, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany) and Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Lin Zschiedrich, JCMwave GmbH (Germany) and Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Frank Schmidt, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany)

In many experimentally realized applications of photonic crystals, solar cells and light-emitting diodes, nano-photonic systems are coupled to a thick substrate layer, which in certain cases has to be included as a part of the optical system. The finite element method (FEM) yields rigorous, high accuracy solutions of full 3D vectorial Maxwell’s equations [1] and allows for great flexibility and accuracy in the geometrical modelling. Time-harmonic FEM solvers have been combined with Fourier methods in domain decomposition algorithms to compute coherent solutions of these coupled system[2,3]. The basic idea of a domain decomposition approach lies in a decomposition of the domain into smaller subdomains, separate calculations of the solutions and coupling of these solutions on adjacent subdomains.

In experiments light sources are often not perfectly monochromatic and hence a comparision to simulation results might only be justified if the simulation results, which include interference patterns in the substrate, are spectrally averaged.

In this contribution we present a scattering matrix domain decomposition algorithm for Maxwell’s equations based on FEM. We study its convergence and advantages in the context of optical simulations of silicon thin film multi-junction solar cells. This allows for substrate light-trapping to be included in optical simulations and leads to a more realistic estimation of light path enhancement factors in thin-film devices near the band edge. We demonstrate the possibility to compute incoherent averages of derived quantities of the electromagnetic field, like cell absorption, with minimal additional computational effort.

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8980-8, Session 2

Use of a hybrid ray-thin film interference model for the optimization of a FTIR FOEWS

Jeremy R. Godin, Patricia Nieva, Univ. of Waterloo (Canada)

Certain designs for frustrated total internal reflection fiber optic evanescent wave sensors (FTIR FOEWS) include the partial removal of cladding along a finite length of the fiber optic that acts as the sensing region. This paper presents a model for a FTIR FOEWS that has a thin, partial cladding in the sensing region. Because the thickness of the cladding in the sensing region is in the 1 µm range, while the propagating light is on the order of 850 nm, commonly used ray optics modeling techniques fail to properly simulate the thin film interference effects. A modification to the usual ray optics model is therefore performed by including thin film optics modeling at the thin film sensing interface. The

resulting hybrid ray/thin film model maintains the efficiency of previously reported models, but also adds the ability to model the partial cladding of the sensing region. The intensity and angular distributions of light from a point source illumination onto the fiber input face is also derived to discuss the effects of launching conditions on the sensor performance. Investigation of a variety of meridional and skew propagation rays distributions into the fiber are performed by varying the distance and angle of the point source to the fiber input face. Optimal point source distance and angle to fiber input face are also studied for the optimal cladding thickness and used to draw conclusions about FTIR FOEWS performance based on launching conditions.

8980-9, Session 3

Relaxation-oscillation-free semiconductor laser with optical feedback *(Invited Paper)*

Daan Lenstra, Technische Univ. Eindhoven (Netherlands)

Semiconductor lasers often use external optical feedback, or self-injection. The draw-back of such method is that delayed feedback can easily lead to sustained relaxation oscillations (RO), i.e. an intrinsic resonance between laser intensity and population inversion, which for a solitary laser is a damped oscillation. The occurrence of the RO is sensitive, among other things, to the applied settings of the phase of the feedback light [1, 2]. This was studied in [3, 4] with the help of electrically addressable phase shifters. It is known from an early study [5] that, surprisingly, the onset of RO is hampered under resonance conditions, i.e. when the product of RO frequency and external delay time equals an integer. This prediction was based upon certain numerical and analytical considerations, but no simple explanation was given. From a theoretical analysis based on first-order differential-delay equations, as first formulated by Lang and Kobayashi [1] , we will demonstrate the existence of RO-free bias-current intervals of substantial width and for realistic pumping values, irrespective of the feedback phase. We show that for conventional semiconductor lasers with weak optical feedback under RO-resonance condition, i.e. when the product of RO frequency and delay time equals an integer, i.e. 0,1,2,…, the laser with feedback behaves with respect to the RO as if no feedback is present. Therefore, under the above-mentioned conditions the RO is damped and, in fact, will be suppressed. This result is valid in the regime of weak feedback, such that the RO frequency is not deviating substantially from its value in the solitary laser.

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8980-10, Session 3

Rate-equation description of multi-mode semiconductor lasers

Mirvais Yousefi, Photonic Sensing Solutions (Netherlands); Daan Lenstra, Technische Univ. Eindhoven (Netherlands)

In this paper we will derive a set of rate equations that gives a complete description of a semiconductor laser operating in the multi-mode regime. This set of ordinary differential equations for the laser-mode fields and the relevant carrier distribution moments allows for a simple and very convenient analysis of the laser multi-mode dynamics. This is a big advantage over existing theories, which are based on complicated partial-differential and/or integral equations [1-4]. The slowly-dependent amplitudes of the cavity modes can exhibit oscillations with frequencies as high as the intra-mode beating. We will discuss the relevance of these frequency contributions for the dynamics of the cavity modes: contrary to what most conventional rate-equation models describe, the spectral power of each active lasing mode is distributed among different passive Fabry-Pérot modes, through multi-wave mixing processes. The strength of coupling between different modes is regulated by the electron-hole inversion dynamics and in particular by gain gratings in the semiconductor medium. These gratings result from spatial hole-burning in the carrier density and are accounted for by excess-inversion moments. Instead of solving the full PDE which governs the dynamics of the inversion density, we consider only those inversion moments which participate significantly in the dynamics. In this way, the multimode laser is adequately described by a set of ODEs for the modal field-amplitudes and the inversion moments, which facilitates the analytical and numerical evaluation of the modal dynamics considerably.

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8980-11, Session 3

Dynamics of a semiconductor laser with frequency shifted feedback

Yoann Noblet, Joshua P. Toomey, Deborah M. Kane, Macquarie Univ. (Australia)

Semiconductor laser with optical feedback systems are well known for generating output power that is a complex, nonlinear dynamical state [1]. Their study leads to new knowledge in nonlinear science, and supports their use in potential applications such as secure communications [1]. In this work we contrast frequency shifted feedback (FSF), both resonant and non-resonant with the cavity defined by the external mirror providing optical feedback into the laser, with conventional optical feedback. Results from experimental studies of an 830 nm infrared semiconductor diode laser are reported. The acousto-optic-modulator (AOM), driven by an 80 MHz signal and placed inside the external cavity, causes a frequency shift of 160 MHz for each round trip. The optical frequency spectra of a similar FSF semiconductor diode laser system have been reported in the literature [2, 3]. Both these studies used a resonant condition, in which the frequency shift caused by the AOM exactly matched the resonant frequency of the external cavity length. A feedback level dependent linewidth broadening of up to a few GHz, associated with single longitudinal mode operation, was observed [3]. Further broadening to a bandwidth greater than 1 THz was associated with multiple longitudinal mode operation [3]. In this work we utilize multi-GHz-bandwidth real time data analysis to investigate the temporal and spectral behavior in the optical feedback level, FSF level, and injection current parameter space of the nonlinear system. We use a compilation of system maps, to give a new insight into the dynamics of these systems.

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8980-12, Session 3

Modeling of mode-locked semiconductor lasers with external periodic forcing

Rostislav Arkhipov, Aleksandr Pimenov, Mindaugas Radziunas, Andrei G. Vladimirov, Weierstrass-Institut für Angewandte Analysis und Stochastik (Germany)

Using a delay differential equation model we study the dynamics of a passively mode-locked semiconductor lasers with dual frequency coherent optical injection and hybrid mode-locked lasers with external periodic RF voltage modulation (VM) applied to the saturable absorber section. The width of the locking range, where the output pulse repetition rate is synchronized to the frequency of the external modulation is calculated numerically and asymptotically in the limit of the small external modulation amplitude. The dependence of the locking range on the model parameters and the frequency of the external signal is studied. We demonstrate that locking range increases linearly with the external signal amplitude. Our numerical simulations indicate that hybrid mode-locking can be also achieved in the cases when the frequency of the external modulation is approximately twice larger or twice smaller than the pulse repetition frequency of the free-running passively mode-locked laser fP. When the frequency of the external modulation is close to fP or 2fP the locking range has approximately the same width. However, when the frequency of the external signal is close to fP/2 our analysis predicts and the experiment confirms that the locking range is located within a significantly narrower and strongly asymmetric domain. We demonstrate that this asymmetry is related to the dependence of the pulse repetition frequency fP on the mean value of the absorber relaxation rate, which increases with the modulation amplitude of VM applied to the absorber section.

8980-13, Session 4

Metal-cavity submonolayer quantum-dot surface-emitting microlasers *(Invited Paper)*

Pengfei Qiao, Univ. of Illinois at Urbana-Champaign (United States); Chien-Yao Lu, Princeton Optronics, Inc. (United States); Dieter H. Bimberg, Technische Univ. Berlin (Germany); Shun Lien Chuang, Univ. of Illinois at Urbana-Champaign (United States)

Metal-cavity submonolayer (SML) quantum-dot (QD) microlasers are demonstrated at room temperature under continuous-wave electrical injection for 2-μm-radius devices and pulsed operation for 0.5-μm-radius devices. Size-dependent lasing characteristics are extracted from measurements to investigate the device physics for future size reduction. An optical cavity model using the transfer matrix and the effective index method including metal dispersion is developed and the results agree well with experiments. The active region consists of three groups of SML QDs, and each group consists of 10 stacks of 0.5-monolayer InAs QD layers, separated by 2.2-monolayer GaAs spacers. The cylindrical microcavity is formed by 19/32 pairs of p-doped/n-doped distributed Bragg reflectors (DBRs). The cavity sidewall is passivated by SiNx as an optical buffer layer to reduce the metal loss and as a current blocker. The transverse optical modes are solved using the Maxwell equations, and the resonance condition is determined by round-trip phase matching. Vertically correlated QDs are modeled as quantum disks, and the wave functions and eigenenergies in both conduction and valance bands are solved from Schrodinger equation. Carrier-dependent material gain is calculated using Fermi's golden rule and included in the model. The lasing wavelengths, quality factors, and confinement factors for cavity modes are the inputs for the rate-equation model, which predicts the light output power-vs.-current behavior and has shown excellent agreement with experiments. Size-dependent physical quantities such as leakage current and spontaneous emission coupling factor are extracted and investigated. Further size reduction using only four pairs of DBRs is proposed.

8980-14, Session 4

Nanolasers with 3D Nanocavities *(Invited Paper)*

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

In this paper we will describe design, fabrication and testing of a new family of nanocavities confined in space all three dimensions (3D) . Specific designs of 3-D nanocavities such as composite metal-dielectric-semiconductor composites in various geometries (e.g., cylindrical, coaxial, etc.) will be discussed.

8980-15, Session 4

Recent progress in plasmonic and metallic cavity nanolasers *(Invited Paper)*

Cun-Zheng Ning, K. Ding, M. Hill, Z. C. Liu, L. J. Yin, Arizona State Univ. (United States)

This talk will describe the recent progress towards the demonstration of the first continuous wave operation of metallic cavity nanolasers with sub-wavelength sizes at room temperature under electrical injection. Most recent experimental results as well as theoretical understanding will be presented.

8980-16, Session 4

Electromagnetic modes in nanophotonics *(Invited Paper)*

Philippe Lalanne, Institut d'Optique (France)

Many micro-nanophotonic devices that are exploiting strong field confinements are fundamentally related to electromagnetic modes of translational invariant channels or electromagnetic lossy resonance. We will try to illustrate how important are modal concepts for designing or understanding nanophotonic devices.

For instance we will discuss how a couple-mode surface-plasmon model may elucidate the role played by surface-plasmon in the extraordinary optical transmission - or more generally in Wood anomaly related phenomena - [1]. We will also present a semi-analytical formalism that provides closed-form expressions for light coupling with plasmonic resonance [2-3], leading to a new definition of the mode volume of a resonance mode.

Jean-Paul Hugonin, Haitao Liu and Christophe Sauvan are gratefully acknowledged.

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8980-17, Session 4

Observation of high-Q resonace modes from metal-coated nanocavities and future prospect based on cavity mode simulation

Hiroyuki Kurosawa, Nagisa Ishihara, Ryo Takemoto, Nahid A. Jahan, Hideaki Nakajima, Hidekazu Kumano, Ikuo Suemune, Hokkaido Univ. (Japan)

Metal coated nanocavities have been actively studied mainly for nanolasers with low threshold. However from the viewpoint of resonace quality, observed resonance Q values remained low in the range of 100-300. In this talk we demonstrate the observation of high-Q value of ~9000 from a GaAs nanopillar embedded in Ag. For the study of the resonance modes, we propose to employ broad luminescen from n-GaAs that covers the wavelength range from 800 nm to 1500 nm originating from deep level luminescence. We confirm the cavity resonance modes with excitation power indendent luminescence width which is less than 0.16 meV (0.1 nm). We also confirm it with the temperature dependence of the luminescence peak, which shows much weaker temperature dependence than that of conventional energy gap. We developed a method to well reproduce the temperature dependence of the cavity resonance mode. We also worked on numerical simulations of the cavity resonance modes to investigate the presence of such high-Q resonance modes. What we found is the presence of high-Q whispering gallery modes. We analyzed the wave equation in the cylindrical coordinates and modified the wave equation to 1-D. Shrodinger-type equation, which enables us to discuss the electrodynamics of the fields from the viewpoint of the effective potential. Analyzing the effective potential we found that the dielectric layer between the semiconductor and the embedding metal plays the essential role in the Q value. With the optimization of the metal-coated nanocavity we found the extremely high-Q resonance mode with the Q value exceeding 0.6 million.

8980-18, Session 5

Hybrid metal/semiconductor lasers based on confined Tamm plasmons *(Invited Paper)*

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

Hybrid metal/dielectric structures are very promising for the fabrication of compact and efficient optical sources. Beside the development of micro- and nano-lasers based on surface plasmons, other surface modes presenting less damping than conventional plasmons can be used such as Tamm plasmons. These surface modes appear at the boundary between a distributed Bragg reflector (DBR) and a metallic layer, and present both the advantages of surface plasmons and of microcavities photonic modes. Beside their reduced losses compared to conventional plasmons, they present the great advantage to be easily spatially confined by structuring only the metallic part of the system. This can lead both to a reduction of the mode volume and to various confinement geometries.

Recently, a laser effect has been demonstrated in bidimensional Tamm structures where quantum wells were inserted in the high refractive index layers of the DBR. It has also been demonstrated that a high beta factor could be achieved for confined Tamm modes. We will show here that a laser effect can be obtained in confined Tamm structures under optical pumping, and that the confinement results in a reduced laser threshold. Reducing the structure size increases the beta factor but at the same time decreases the quality factor. These two opposite trends lead to an optimal size for the lasing threshold obtained for a 4 µm disk diameter, in very good agreement with the simulations. We will also show that the angular emission pattern can be tailored by modifying the confined Tamm mode.

8980-19, Session 5

Dye-doped spheres with plasmonic semi-shells: from directional fluorescence to lasing modes

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

A prominent feature of symmetry broken metallic semi-shells (compared to angularly symmetric shells) is their capability to scatter light into certain directions [1]. Recently, we have shown that localized plasmonic modes of semi-shells are apt to direct the fluorescence from fluorophores contained in the dielectric core of the semi-shells into the forward direction [2]. It has also been proposed that the symmetry breaking when full metallic shells become semi-shells might have advantages because a low gain threshold is required [3] , more modes become accessible, and, the coherent emission becomes directional [4]. Up to now, a dispersion-less gain was used in the simulations. In this contribution, we use two Lorentzian lines for the molecular absorption and the Stokes-shifted emission. Adjusting the thickness of the silver caps on dye doped spheres; we tune specific resonances into the emission maximum of the dye molecules. In particular, we focus on the doping concentration, the size of the spheres and the type of gain molecules as given by the commercially available polystyrene spheres. We find that spasing requires gain levels approximately 4 times higher than those achievable in commercially available dye doped spheres. However, commercially available concentrations are already apt to render negative absorption, and to narrow and enhance higher order scattering modes.

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8980-20, Session 5

Epsilon-near-zero-slot waveguides and their applications in ultrafast laser beam steering

Kaifeng Shi, Wangshi Zhao, Zhaolin Lu, Rochester Institute of Technology (United States)

There is increasing research interest in permittivity epsilon-near-zero (or index-near-zero) materials and using them for optoelectronic applications. Recent study of transparent conducting oxides (TCOs) shows that when applying an external voltage, an accumulation layer will be formed at TCO-insulator interface in a plasmonic waveguide. Increasing the applied voltage results in higher carrier concentration at the interface, and this leads to refractive index change in the accumulation layer according to the drude model. At certain carrier concentrations, epsilon-near-zero can be achieved. We explore a novel waveguide structure, namely "epsilon-near-zero-slot waveguide", by utilizing indium tin oxide (ITO) as the active medium, which can be tuned between epsilon-near-zero and epsilon-far-from-zero by accumulation carriers, resulting in sharp effective index change. We propose laser beam steering by taking advantage of this epsilon-near-zero-slot waveguide structure. With periodic grating structure utilized on top of the waveguide, the incident beam can be steered and steering angle is controlled by the waveguide effective index. Preliminary simulation results have been shown in the paper, and we obtain the steering angles ranging from 14° to 75°. By taking advantage of silicon on insulator (SOI) technology and the unique properties of TCOs, the waveguide structure has low loss, compact size, ultra high speed as well as compatibility with standard fabrication methods.

8980-21, Session 5

An electrically driven semiconductor single-photon source working at T = 150 K

Tilmar Kümmell, Wolf A. Quitsch, Oleh M. Fedorych, Univ. Duisburg-Essen (Germany); Carsten Kruse, Arne Gust, Detlef Hommel, Univ. Bremen (Germany); Gerd Bacher, Univ. Duisburg-Essen (Germany)

Solid state single photon sources (SPS) represent central devices for quantum information technology. For future applications, electrically driven SPS working under ambient conditions (room temperature) will represent a key step towards commercially attractive devices. A variety of concepts for SPS has come up during the last years, based e.g. on molecules, color centers in diamond and self organized semiconductor quantum dots (SOQDs). The latter are especially attractive for an easy integration into compact electrically driven devices. However, single photon emission under electrical operation is limited to temperatures below 100 K in SOQDs up to now.

In this contribution, we report on single photon emission from CdSe-based SOQDs. The SOQDs are embedded between ZnSSe/MgS barriers to provide high quantum efficiency at elevated temperatures. Individual quantum dots are selected by submicron metal apertures. Photon correlation measurements were performed using a Hanbury-Brown-Twiss-Setup. Under optical pumping, we obtain single photon emission up to room temperature.

For electrically driven devices, these CdSe/ZnSSe/MgS SOQDs were embedded into p-i-n diode structures. Using patterned Pd/Au contact layers, we address and detect only a limited number of quantum dots electrically. Single dot electroluminescence (EL) is collected at U=5.6 V by a Micro-EL setup. In these devices, we observe clear antibunching behavior for temperatures up to T = 150 K. This represents the highest temperature ever reported for electrically triggered single photon emission based on a semiconductor quantum dot. Obviously, these SOQDs are highly promising for future single photon sources that can be electrically driven up to room temperature.

8980-22, Session 6

ZnO as a tunable metal: New surface plasmon polaritons at telecommunication wavelengths *(Invited Paper)*

Fritz Henneberger, Humboldt-Univ. zu Berlin (Germany)

ZnO can be heavily doped n-type up to the 1021 cm-3 range without deteriorating material quality. The resultant free-electron gas provides a tunable metallic dielectric function for plasmonic applications in the mid and near infrared spectral range. The shortest wavelength for the cross-over from positive to negative real part reached so far is 1.25 µm. The loss is almost one order of magnitude lower than for Au in this range and the maximum plasmonic figure-of-merit reaches 3.5. Clear signatures for surface-plasmon-polaritons are observed. A particular advantage of using semiconductors in plasmonics is the ability to fabricate multi-layers with low inter- and surface roughness as well as tailored dielectric functions. In this way, we were able to demonstrate surface-plasmon-polaritons at a “metal/metal” interface exhibiting a non-standard dispersion with finite frequency in the long-wavelength limit. We were also able to observe coupling between surface-plasmon-polaritons of adjacent interfaces signifying the potential for plasmonic second-harmonic generation and other novel phenomena.

8980-23, Session 6

Using semiconductors and ceramics as new materials for plasmonic and metamaterials devices *(Invited Paper)*

Alexandra Boltasseva, Purdue Univ. (United States)

In recent years, plasmonics and metamaterials have seen an explosion of novel ideas and device designs. However, transforming these concepts into practical devices requires a significant amount of effort. The constituent materials in these devices play a crucial role in realizing useful and efficient devices. Similar to the way silicon shaped the nanoelectronics field, efforts toward finding the best set of materials for plasmonic and metamaterial devices could revolutionize the field of nanophotonics. As a potential solution, alternative plasmonic materials have recently gained significant attention. Metals, despite being essential components of plasmonic and metamaterial devices, pose many technological challenges toward the realization of practical devices—primarily due to their high optical loss, integration and fabrication limitations. Hence, searching for an alternative to metals is vital to the success of future nanophotonic devices. In this talk, I will provide a brief survey of recent developments in the pursuit of better plasmonic materials, and discuss several classes of materials including doped semiconductor oxides and ceramics as potential alternatives to metals that provide low intrinsic loss, tunability and compatibility with standard semiconductor fabrication processes.

8980-24, Session 6

Development of ZnO films for near-IR plasmonics *(Invited Paper)*

David C. Look, Wright State Univ. (United States)

The interaction of light with plasmons can lead to large changes in the dielectric function ?(?), especially if the real part ??(?) can attain negative values at a frequency ? < ?res, where ?res depends on the carrier concentration n, the mobility µ, the high-frequency dielectric constant ?∞, and the effective mass m*. For metals these parameters are effectively fixed and restrict ?res to the UV and visible regions of the spectrum, leading to, among other things, high losses in the IR region. Semiconductors, on the other hand, have controllable values of n, and can easily support plasmonics in the mid- and far-IR parts of the spectrum. However, the near-IR region, say ?res ~ 1 µm, is more problematic because it requires n ? 1021 cm-3, too low for metals and too high for most semiconductors. Fortunately, ZnO doped with Ga or Al can fulfill this requirement, and thus is a strong candidate for near-IR plasmonic applications. In this work we discuss how to grow and prepare ZnO for plasmonics in the near-, mid- and far-IR spectral regions. For example, we have been able to produce ZnO films with ?res = 1.3 and 1.55 µm, the important telecommunications wavelengths. Another issue is the thickness dependences of mobility and concentration in very thin films, and we show how these can be mitigated by the use of buffer layers.

8980-25, Session 6

Laser processing of conductive oxides for near IR plasmonics *(Invited Paper)*

Alberto Piqué, Heungsoo Kim, Nicholas A. Charipar, Scott A. Mathews, U.S. Naval Research Lab. (United States)

Conventional metals with high carrier concentrations have served to date as the materials of choice for plasmonic and metamaterial devices. However, typical metals are not well suited for near IR (NIR) plasmonic applications because their associated plasma frequencies correspond to the visible and ultraviolet regions of the spectrum. By using instead materials with lower plasma frequencies such as conducting oxides like ZnO and VO2, it is possible to efficiently couple electromagnetic radiation for optical metamaterial and plasmonic applications in the NIR. Furthermore, unlike metals, the electrical transport properties of conductive oxides can be modulated intrinsically by doping or extrinsically by applying heat, light or an electrical bias, thus allowing tuning of their electro-optical behavior. At the Naval Research Laboratory (NRL), we have investigated the use of laser processing techniques for the deposition and processing of various types of conducting oxides, such as Al-doped ZnO and W-doped VO2, which can be optimized over a wide range of optical/electrical properties. This presentation will describe the laser processing of conducting oxide films and their electrical and optical characterization in the NIR. Examples of conducting oxide-based plasmonic structures developed at NRL will be presented together with a discussion of the potential applications of these materials in opto-electronic devices.

8980-26, Session 7

Numerical simulation of deep UV avalanche photodetectors

Enrico Bellotti, Boston Univ. (United States); Francesco Bertazzi, Politecnico di Torino (Italy)

The III-Nitrides material system has become a prominent player in the areas of optoelectronic and electronic devices. The availability of a rich family of ternary and quaternary alloys makes it possible to tailor these semiconductors to work as light emitters and detectors from the near infrared to the deep UV. While LEDs and lasers operating in the UV, including the 250-300nm spectral range, have been fabricated, detectors have not received as much attention. In particular the development of avalanche photodetectors has lagged behind due to the lack of suitable substrates and adequate material quality. Although GaN based APDs have been successfully fabricated, similar devices operating in the solar-blind and deep UV spectral range have not been fully developed yet. In this work we employ our state of the art Monte Carlo simulation model to investigate the performance of UV APD structures based on AlGaN and InAlN. Specifically, we have studied the high field transport properties and impact ionization processes in both AlGaN and InAlN ternary alloys and have used the results to assess the performance of APDs intended to operate in the solar blind and deep UV spectral ranges. We have found that in AlGaN holes dominates the impact ionization process for compositions below 50%, while electrons dominate for larger aluminum contents. The model also predicts that holes impact ionization processes are effectively negligible for aluminum composition above 60%. This may lead to the fabrication of low noise deep UV APDs.

8980-27, Session 7

Simulation of water photo electrolysis with III-nitride semiconductor nanowires

Bernd Witzigmann, Maximilian Bettenhausen, Marvin Mewes, Heiko Fuelle, Friedhard Roemer, Univ. Kassel (Germany)

Hydrogen conversion using water splitting with solar power is an attractive technology for clean energy generation and storage. III-nitrides are resistant to acidic or alkaline aqueous solutions, and have been demonstrated as suitable active materials. In this contribution, both the optical absorption and the carrier and ionic transport properties of GaN/GaInN core-shell nano wire arrays are studied. For the optical absorption of the wires, a three-dimensional finite element method solves the vectorial Helmholtz equation in frequency domain. As main result, it is shown that the nano wire array in aqueous solution acts as optical concentrator element, similar to nano wire array solar cells. With proper design, InGaN shells with only a few tens of nanometers can absorb more than 80% of the respective electromagnetic power at frequencies above the bandgap energy. This way, the strain-imposed critical thickness limit of planar InGaN layers does not impact the optical absorptivity.

The electrolysis process, after optical carrier generation in the semiconductor, consists of transport of photo generated carriers in the semiconductor, ionic diffusion in the aqueous solution and reactive splitting of the water molecules. These processes are simulated by a modified drift-diffusion model, extended by a diffusion equation in the aqueous solution. The validity of this model will be discussed in detail, with a comparison to experimental data. In comparison to a planar structure, the area enhancement of the nano wire array increases the electrolysis rate. As an outlook, the performance of a nano wire array water photo electrolysis cell without external bias voltage will be calculated.

8980-28, Session 7

Numerical simulation of III-nitride lattice-matched structures for THz QC lasers

Sara Shishehchi, Roberto Paiella, Enrico Bellotti, Boston Univ. (United States)

Due to their large optical phonon energies, nitride semiconductors are promising for the development of terahertz quantum cascade lasers (QCLs) with dramatically improved high-temperature performance relative to existing GaAs devices. As we have shown [1], the use of properly designed QC structures based on GaN/AlGaN could enable THz emission with devices operating at room temperature. Unfortunately, as a result of the presence of spontaneous and piezoelectric polarizations, the design of such devices is more complex than in the case of conventional GaAs/AlGaAs QCs. Furthermore, lattice mismatch may also lead to the nucleation of defects and dislocation and even cracking in devices with thick active regions. A possible alternative is to design these devices using lattice matched layers based on ternary (InAlN) or quaternary alloys (InAlGaN). This approach mitigates the effects of the polarization phenomena, since in this case only the spontaneous polarization plays a role. Moreover, employing lattice matched layers significantly improves structural quality of the material and makes it possible to grow thicker devices potentially leading to more efficient emitters. The goal of this work is to provide a rigorous comparison between GaAs/AlGaAs and GaN/InAl(Ga)N terahertz QC structures, in order to properly quantify the potential for improvement offered by lattice matched strucutres. We present a rigorous Monte Carlo study of carrier dynamics in several structures based on the same design scheme for emission at 2 THz, consisting of GaN/InAlN and GaN/AlInGAN, and we compare to similar designs based on GaN/AlGaN and GaAs/AlGaAs quantum wells.

[1] E. Bellotti, K. Driscoll, T.D. Moustakas and R. Paiella, App. Phys. Letters 92, 101112, 2008

8980-29, Session 7

Numerical modeling of improvement in slope sensitivity of InGaN-based ring laser rotation sensor

Hemashilpa Kalagara, Petr G. Eliseev, Marek Osinski, The Univ. of New Mexico (United States)

The slope sensitivity of an active ring laser gyroscope (RLG) is directly proportional to the size of the ring, and inversely proportional to the effective group index and lasing wavelength. The slope sensitivity can be improved by orders of magnitude by decreasing the group index and the wavelength, without having to increase the size of the ring. The nonlinear interactions between a strong driving mode and the neighboring weak probe mode in a semiconductor laser lead to anomalous dispersion. This effect can be used to obtain group index much smaller than unity, corresponding to superluminal propagation of the probe mode. By using

an InGaN-based multiple-quantum-well (MQW) laser, the slope sensitivity can be further improved, because the lasing wavelength is shorter, i.e. 400 nm, and the nonlinear interactions between the modes in this material system are also stronger when compared to GaAs-, InGaAs-, and InGaAsP-based laser systems. InGaN/GaN material system also has a large negative dispersion range, hence we also analyze the static anomalous dispersion to reach the regime of superluminal propagation. Using the finite element method and a realistic waveguide structure, we show that there is a possibility to improve the sensitivity of a RLG using InGaN-based MQW lasers.

8980-30, Session 8

Theoretical and experimental analysis of unidirectionality of asymmetrically-coupled semiconductor ring or disk lasers

Geert Morthier, Pauline Mechet, Univ. Gent (Belgium)

We present analytical, numerical and experimental results about the unidirectional behaviour of semiconductor ring or disk lasers in which the coupling from the clockwise (CW) mode to the counterclockwise (CCW) mode is different from the coupling from the counterclockwise to the clockwise mode. The theoretical and numerical result show different regimes, depending on the gain suppression in the active layer. At very low power, the ratio of the powers of the CW and CCW modes depends mainly on the ratio of the coupling constants, while at high power gain suppression is dominant and the ratio of the powers depends on the ratio of the gain suppression and the weakest coupling coefficient. Our analytical formula for the unidirectionality are in excellent agreement with numerical results obtained using coupled rate equations. Some experimental results are given for a microdisk laser coupled to a bus waveguide, on one side of which an almost 100% reflecting Bragg grating is designed.

From the theoretical analysis, it is also possible to determine the external feedback sensitivity of unidirectional ring or disk lasers and to compare the feedback sensitivity (normalized to facet loss) to other laser structures. At low power levels, highly unidirectional ring or disk lasers are more sensitive to external reflections than edge-emitting lasers such as Fabry-Perot or DFB lasers. At high enough power levels though, the gain suppression makes these lasers potentially less sensitive to external feedback.

8980-31, Session 8

Simulation of III-V strained quantum-well lasers with coupled concentric racetrack resonators

Jaime Viegas, Peng Xing, Solomon M. Serunjogi, Masdar Institute of Science & Technology (United Arab Emirates)

The simulation of the lasing behavior of semiconductor quantum well structures with accurate description of transport phenomena and optical propagation poses great challenges when complex epitaxial layers are coupled with optical cavities in the transverse direction that are more complex than the well know Fabry-Pérot and distributed feedback-reflector based resonators. In this work, we present an approximate approach for the simulation of an electrically-pumped III-V strained quantum well laser with coupled concentric racetrack resonators. The electrical, thermal and optical behavior of an epitaxial stack with at least one quantum well is obtained from a physics based simulator for a reduced dimensionality problem, and this solution is coupled with the cold cavity analysis of the resonator using either finite difference time domain simulation or coupled-mode analysis. The effects of gain and charge transport on the active resonator are then taken into account as a perturbation and the approximate solution derived. Comparison with actual devices based on InGaAlAs/InGaAs/InP and InGaSb/AlGaAsSb/GaSb shows reasonable agreement. The concentric racetrack resonator exhibits complex dispersive behavior, with possible applications in sensing, nonlinear phenomena and optical signal processing.

8980-33, Session 8

Modeling of optical gain in GaInNAs quantum wells by using 8-band and 10-band models

Marta Gladysiewicz, Marek S. Wartak, Wilfrid Laurier Univ. (Canada) and Wroclaw Univ. of Technology (Poland)

With the fabrication of novel III-V-N semiconductor materials like GaNAsSb/GaAs or GaNPSb/GaAs and creation of quantum well structures involving those materials there is a need for theoretical analysis and numerical simulations of their optical properties. Typical simulations are performed by applying 10-band model. However, input parameters for numerical simulations in this model, mostly based on experimental data are limited or not available. For example, reliable optical gain calculations with BAC (i.e., 10-band kp model calculations) have been rather impossible to perform at present for such QWs, despite the fact that the band structure parameters like energy gaps, effective masses, band offsets are known from experimental studies. In such situation, the usual 8-band kp model can be applied, but it is unclear how accurate such an approach can be.

In an effort to eliminate, at least partially, the parameter's problem we have compared 10-band and 8-band models for GaInNAs/GaAs QWs to high indium concentration (In~35%) where BAC parameters are parameterized by simple formulas. We compared those two approaches by calculating band structure and optical gain. The role of conduction band nonparabolicity in optical gain calculations and the validity of application of 8-band kp model to calculate the band structure and optical gain in other dilute nitride QWs have been explored. We have shown that reasonable and fruitful approach to calculate the band structure and optical gain in dilute nitride QWs is by using the 8-band kp model with energy gap and electron effective mass as the only input material parameters.

8980-81, Session 8

Temperature Dependences of Metal-Clad Subwavelength Semiconductor Lasers (MCSELs): Geometric Invariance and the Spontaneous Emission Factor

Joseph S. T. Smalley, Qing Gu, Matthew Puckett, Yeshaiahu Fainman, Univ. of California, San Diego (United States)

We analyze several temperature dependences of subwavelength metal-clad semiconductor lasers. Firstly, we optimize the threshold gain for cylindrical composite (semiconductor-dielectric-metal) waveguides with various metal claddings. The cladding are distinguished by different complex permittivities, which may represent different metals or identical metals at different temperatures. We show that the optimal dielectric width is invariant with respect to the imaginary part of the permittivity of the metal, $\varepsilon M''$, and weakly dependent on the real part, $\varepsilon M'$. To explain this behavior, we compare optimal geometries of waveguides with different semiconductor permittivities, $\varepsilon G'$. Secondly, we perform a rigorous analysis of the temperature dependence of the spontaneous emission factor, β, in subwavelength semiconductor lasers. The study combines a recent formulation of the Purcell effect in semiconductor nanolasers with finite-element modeling and established theoretical models for temperature-dependent material gain spectra. While the method is general, we apply it to a subwavelength metallo-dielectric InGaAsP laser whose shield layer is optimized for minimal threshold gain. We find that β of the dominant mode decreases sharply below a transition temperature, and that this result holds for both positive and effectively negative thermo-optic coefficients of the semiconductor. Our

analyses contribute to the understanding of the temperature dependence of nanolaser dynamics, and are useful for the design and characterization of high-β semiconductor nanolasers.

8980-34, Session 9

Plasmonic enhancement and losses in light-emitting quantum-well structures incorporating metallic gratings

Toufik Sadi, Jani Oksanen, Jukka Tulkki, Aalto Univ. (Finland)

Recent experimental work has shown significant luminescence enhancement from quantum-well (QW) light-emitting devices (LEDs) exploiting metallic gratings to convert surface plasmon (SP) modes into radiative modes. However, details regarding the origin of the enhancement and plasmonic losses have not been fully investigated. We analyze the exact physical role of SPs in improving light extraction from GaN-based multilayer QW LED structures using first-principle theory based on Maxwell's equations and fluctuational electrodynamics. The method is employed for the prediction of optical properties including reflectivity, luminescence and plasmonic losses, but also for the localization of the SPs in the grated structures. We explain experimental results demonstrating the enhancement of spontaneous emission from an InGaN QW located at the vicinity of periodically-grated silver layer in structures with and without a polymer (PVA) coating. Results show significant enhancement in the blue/green wavelength range, as compared to structures without grating, with emission being increased by a factor of up to four in our test geometry. However, the enhancement decreases dramatically as the distance between the grating and the QW is increased; when the distance is greater than 50nm, the enhancement figure is below unity and the grating is detrimental to the luminescence due to the added absorption. Results also show considerable optical losses introduced by the metallic grating. Albeit, it is concluded that while the losses may be a significant obstacle for plasmonic enhancement, careful engineering allows reducing such losses so that the benefits outweigh the increased losses.

8980-35, Session 9

Analysis of hybridized surface plasmon resonance sensor with metallic nanoparticles for high sensitivity

Byeong-Hyeon Lee, Geum-Yoon Oh, Hong-Seung Kim, Tae-Kyeong Lee, Chung-Ang Univ. (Korea, Republic of); Doo-Gun Kim, Korea Photonics Technology Institute (Korea, Republic of); Young-Wan Choi, Chung-Ang Univ. (Korea, Republic of)

Kretschmann configuration is one of the most well-known structures for surface plasmon resonance (SPR) sensor. It has been employed as sensors with benefits of non-labeling, real-time detection and high sensitivity. Moreover, because Kretschmann configuration facilitates measurement by angle variation, it is very easy to detect a target material in bulk optics. On the other hand, the sensitivity of a localized surface plasmon resonance (LSPR) sensor with metallic nano-particles is 24 times greater than that of Kretschmann SPR sensor. However, precision measurement equipment is essentially required for LSPR sensor, because, the electric field is highly localized around the nano particles on the subwavelength scale.

Many researches have been done for enhancement the sensitivity and ease measurement in bulk optics such like blending localized surface plasmon resonance with SPR. Metallic nano-grating structure has been designed as an example of it. Because it is based on Kretschmann configuration, very easy to measure with very high sensitivity resulted from highly localized field around the grating structure. However, the dimensional factors such as pitch, period, and duty cycle of the structure are very important to the metallic grating, and therefore, E-beam lithography is essential to its fabrication.

In this paper, we have analyzed and optimized the hybridized SPR sensor which can be fabricated very simple fabrication. We optimized the dimensional parameters and appropriate wavelength for the proposed structure using 3D-FDTD simulation. More detailed results will be presented.

8980-36, Session 9

Enhancement of Goos-Hänchen effect in a prism-waveguide coupling system with magneto-optic material

Tingting Tang, Univ. of Electronic Science and Technology of China (China) and Chengdu Univ. of Information Technology (China); Longjiang Deng, Jun Qin, Lei Bi, Univ. of Electronic Science and Technology of China (China)

We study the Goos-Hänchen (GH) effect enhanced by magneto-optic (MO) material in a prism-waveguide coupling system which consists of Prism/Au/Ce:YIG/SiO2. Theoretical analysis about the proposed system inluding expression of GH shift is derived. Simulation results illustrate that GH shift is dramatically enlarged with the increase of thickness of Au layer and by choosing proper parameters the largest GH shift can be as large as 5.898 μm. Meanwhile the corresponding incident angle has a very small amount of change, and incident angle range of the GH shift peak is narrowed and thus the discrimination capacity of incident angle is increased to 0.001 degree when it used as a sensor. As GH shift only appears in a very small range of incident angle, the extinction ratio can be close to 1 when it works as a switch. In addition, as the increase of intensity of longitudinal magnetization, the largest GH shift increases from 0.42 μm to 3.8 μm while the corresponding incident angle decreases from 39.8 to 38.85 degree. We also notice when the direction of magnetization reverses, the sign of GH shift also reverses which further improves the sensitivity if the prism-waveguide system works as a detector. In order to verify these results, spectroscopic ellipsometry is used to measure and characterize the proposed structure. Simulation and experimental results show that the enhancement of GH effect in a prism-waveguide system has potential applications in MO switches or modulators as well as sensors for its dramatically enhanced discrimination capacity and sensitivity.

8980-37, Session 9

Tunable plasmonic metamaterial based on transparent conducting oxide

Kaifeng Shi, Riaz R. Haque, Wangshi Zhao, Runchen Zhao, Zhaolin Lu, Rochester Institute of Technology (United States)

We propose active plasmonic metamaterial for electro-optic (EO) modulator applications, which, in this paper, is an indium tin oxide (ITO)-based multilayer structure. The high carrier concentration of transparent conducting oxides such as ITO enables guiding the surface mode at the interface of ITO and dielectric materials. We have investigated two different structures: ITO/electrolyte gel/doped Si and ITO/electrolyte gel/ITO. ITO films were deposited on a glass substrate by the DC sputtering method. We used a commercially available electrolyte on top of the ITO layer. When employing electrolyte gel, electric double layers are formed at the interfaces of ITO and electrolyte gel. The modulation performance is investigated with an attenuated-total-reflection (ATR) setup. The measured reflectance of the ITO modulator is numerically fitted by transfer matrix method (TMM). The relative permittivity of electrolyte gel is found to be around 1.8 at 1520 nm wavelength. At the same wavelength, applying +10V and -10V across the ITO layer and doped Si in ITO/electrolyte gel/doped Si on BK7 glass substrate structure, the dielectric

constant is found to be 4.23+j*0.5 and -0.47+j*4.9, respectively, and that result without applying voltage is 3.7 +j*1.0. The modulation depth is around 21.7% with one ITO active layer. This result can be further enhanced to 38.8% by employing two ITO active layers. The switching speed of the modulator is dependent on the relaxation of the ions in the electrolyte gel. Our immediate next plan is to replace the electrolyte gel with high-K material which has a high dielectric constant. Such complex ferroelectric oxides are known to have desirable optical properties and high electro-optic coefficients, and will enhance the switching speed of our EO modulators.

8980-38, Session 10

Optimizing light absorption in a thin film p-i-n solar cell using a quasi-periodic grating

Mahmoud Atalla, The Pennsylvania State Univ. (United States)

A p-i-n solar cell is best suited for strong absorbers with poor collection capabilities. However, the absorption naturally decreases at photon energies close to the electronic bandgap of the semiconductor. We hypothesized that a quasi-periodic surface textures in the role of diffraction gratings at the back contact can efficiently scatter light increasing the optical path length inside the absorber layer and the generation rate of charge carriers. In such structures, sunlight is coupled from the nanostructures into the waveguide modes of the semiconductor, as well as to surface-plasmon-polariton (SPP) waves that may be supported at the semiconductor/back metal interface. To help optimizing the design of the quasi periodic grating, a canonical problem consisting of a planar interface between semi-infinite expanses of metal and a multilayered semiconductor has to be considered. A cascade dielectric grating on the top of the solar cell is used to improve the light coupling efficiency into guided modes. The effect of quasi-periodic corrugated backing metallic contact of various types was studied theoretically on the light absorption in a single-junction thin-film p-i-n solar cell for an AM1.5 solar irradiance spectrum for a wavelength range of 400-1100 nm. The rigorous coupled-wave approach is used to describe the wave propagation in the solar cell. The n- and i-layers consist of isotropic nonhomogeneous multilayered semiconductor. The absorptance of the solar cell with quasi-periodic grating was found to be higher than the solar cell with a conventional periodic grating.

8980-40, Session 11

Rate equation analysis of frequency chirp in optically injection-locked quantum cascade lasers

Cheng Wang, Institut National des Sciences Appliquées de Rennes (France); Frédéric Grillot, Télécom ParisTech (France); Vassilios I. Kovanis, The Ohio State Univ. (United States); Joshua Bodyfelt, Massey Univ. Albany (New Zealand); Jacky Even, Institut National des Sciences Appliquées de Rennes (France)

Optical injection locking is a favourable technique for improving the dynamics of semiconductor lasers [1], which allows the residual amplitude-modulation suppression, reduction of frequency noise and spectral linewidth as experimentally demonstrated in quantum cascade (QC) lasers [2,3]. It was also theoretically proved that the intensity modulation performance can be enhanced as well [4,5]. This work aims to theoretically study the frequency chirp properties of an injection-locked QC laser via the chirp-to-power ratio (CPR). The rate equation model takes into account the carrier dynamics including the upper and lower laser subbands, the bottom state and the multi-cascade scheme. Following the standard approach of linearizing rate equations, an analytical expression for the CPR is derived. Simulations show that the CPR is remarkably influenced by the optical injection, especially for modulation frequencies less than 10 GHz. For the free running QC laser, the CPR remains almost constant in the modulation range 0.01~0.1GHz, where the adiabatic chirp dominates. In higher frequency regime, the CPR increases linearly with the modulation frequency, and the slope is proportional to the linewidth enhancement factor. Under zero detuning, the optical injection decreases the free-running CPR from 480 MHz/mW down to 30 MHz/mW at the modulation frequency 1.0 GHz. While for frequencies higher than 10 GHz, more than half of the CPR is reduced. In contrast to interband lasers, both positive and negative detunings increase the CPR value. Since the detunings also enhance the modulation bandwidth, a compromise between the bandwidth enhancement and the frequency chirp suppression is required.

8980-41, Session 11

Effect of light backscattering on high-speed modulation performance in strongly injection-locked unidirectional semiconductor ring lasers

Gennady A. Smolyakov, Marek Osinski, The Univ. of New Mexico (United States)

Optical injection locking has been actively researched for its potential to improve ultrahigh frequency performance of semiconductor lasers and to reach beyond the record values of modulation bandwidth achieved for free-running devices. Improved microwave performance has been observed in edge-emitting lasers with Fabry-Perot cavity, DFB lasers, and VCSELs. Strong optical injection is crucial for reaching the ultimate limits of modulation bandwidth enhancement in injection-locked lasers. The smallest possible values for both cavity roundtrip time and reflectivity of the mirror used for injection are desirable in injection-locked lasers. However, the inherent design trade-off between these parameters makes further optimization of both edge-emitting lasers and VCSELs for enhanced high-speed performance very problematic.

We have recently proposed a novel injection-locking scheme involving a DBR master laser monolithically integrated with a unidirectional whistle-geometry microring laser (WRL). The novel scheme is expected to allow for strong coupling of the master laser output into the ring laser. Greatly enhanced resonance frequency of up to ~160 GHz was predicted in numerical calculations for the strongly injection-locked WRL. In this paper, we investigate the effect of backscattering between the two counterpropagating modes on high-speed modulation performance of strongly injection-locked WRL.

8980-42, Session 11

Experimental and simulation analysis of stimulated Brillouin scattering in continuous wave regime

Rafael Sanchez-Lara, José A. Alvarez-Chávez, Ctr. de Investigación e Innovación Tecnológica (Mexico); Lelio de la Cruz May, Francisco Méndez Martinez, Univ. Autónoma del Carmen (Mexico)

There are basically five nonlinear phenomena that occur in the optical fiber which limits the power or distort the signal in the data transmission. One of the most important is the phenomenon called Stimulated Brillouin Scattering (SBS) as it only requires relatively low pump power for affecting signal power in single and multi-wavelength transmission in DWDM systems, for instance. There are numerous studies of this phenomenon that deal with power threshold determination which represents the limit on the transmit power but many of them are very complex and not very clear. In this work we propose an experimental setup for the spectral analysis of the reflected power (Brillouin and Raleigh) and transmitted power (residual pump at the end of the fiber), for the determination of Brillouin power threshold under two criteria. Similarly

by simulation of the phenomenon, we found that with a SBS power at the end of the fiber equal to 1EXP (-6) the pumping power is shown a clear approximation between experiment and simulation. Interesting results are displayed between the curves of evolution of powers of forward and backward power to determine the power threshold under two criteria. The criteria used for obtaining Brillouin threshold is the inflexion point of the backward SBS Vs Pump power, and when the forward signal (residual pump) is equal to the backward SBS. Also, we observed that the first criterio can be found with the Raleigh curve. The results are validated by analytical solutions of traditional coupled equations.

The experimental setup consists of two laser (980 and 1550 nm), MUX, EDFA amplifier, Circulator, 25 Km SMF-28, Optical Spectrum analyzer, and a power meter.

8980-43, Session 11

Reflective semiconductor optical amplifier submitted to strong optical feedback and coupled to long external cavity

Myke Rolan Ruiz Prado, Pascal Besnard, Thierry Chartier, CNRS-Fonctions Optiques pour les Technologeis de l'information (France); Fabienne Saliou, Sy Dat Le, Qian Deniel, Philippe Chanclou, Orange SA (France)

Dense wavelength division multiplexing (DWDM) metropolitan networks are currently being extensively deployed with distances ranging from a couple of ten's kilometers to several hundred kilometers. 40 DWDM channels are commonly used; each of them is carrying today Ethernet or Fibre Channel traffics ranging from 1 to 10 Gb/s. This type of network requires achromatic components, for which the provider can fix the operating wavelength in order to have the same type of components in the consumer's home. The DWDM sources could be based on a tunable laser source or on a self-seeded- reflective semiconductor optical amplifier (RSOA) as recently proposed [1]. In this last case, the RSOA is coupled to a mirror, located at a few kilometers in a central office. A frequency filter fixes the wavelength. The RSOA is then directly modulated at a few GHz. However even if a 100 GHz-wide filter is used, a much narrower slot of wavelengths are selected on the "red" side of the transmission window of the filter. This communication gives from a Green function approach [2], the modal structure of an RSOA coupled to a long cavity with strong optical feedback and explains how such coupled structure is operating.

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8980-44, Session 11

Numerical analysis of frequency chirp in strongly injection-locked semiconductor ring lasers

Fei-Hung Chu, Gennady A. Smolyakov, Marek Osinski, The Univ. of New Mexico (United States)

One of the performance issues with directly modulated semiconductor lasers is the frequency chirping due to refractive index variations caused by changes in carrier densities under high-speed modulation of the injection current. In optical fiber links, frequency chirping coupled with fiber dispersion leads to pulse broadening after transmission through optical fibers and hence limits the bit rates and distance. Optical injection locking has been shown theoretically and experimentally for semiconductor lasers of various structures to greatly reduce the frequency chirp.

In our previous work, strongly injection-locked semiconductor ring lasers monolithically integrated with DBR master lasers were demonstrated numerically to exhibit a wide locking range of more than 150 GHz for positive detuning and 160 GHz for negative detuning, and an enhanced modulation response with resonance frequency of up to 160 GHz. The rate-equation-based simulations are extended in this work to provide the information on frequency chirping across the locking range and for different modulation frequencies. The results are then compared to the case of weak injection locking of the ring lasers and the advantages of strong injection locking are identified.

8980-3, Session PWed

Carrier transport in dichromatic color-coded semipolar (20-2-1) and (20-21) III-N LEDs

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

We present, to the best of our knowledge, the first successful simulation of color-coded III-nitride LED structures. As an experimental benchmark, we use the UCSB dichromatic violet-aquamarine semipolar LEDs grown both in Ga-polar and N-polar crystallographic orientations and in violet-aquamarine or aquamarine-violet active region layouts (Y. Kawaguchi et.al., APL 100, 231110, 2012). Different QW depths and opposite interface polarization charges in Ga-polar and N-polar structures provide different conditions for carrier transport across the active region and account for strongly different emission spectra in such color-coded LEDs.

Combination of several effects was crucial for reproducing experimentally observed output optical spectra in color-coded LEDs. To reproduce spectra in LEDs with violet-aquamarine QW layout, standard drift-diffusion transport model had to be completed with rate equations for nonequilibrium QW populations which appeared severely off-balanced from corresponding mobile carrier subsystems. Nonequilibrium effects were noticeably stronger in deeper Aquamarine-emitting QWs. In Ga-polar LEDs, interface polarization charges facilitate QW overshooting by mobile carriers. In N-polar structures, the carrier transport across the MQW active region was limited by thermionic emission.

To reproduce experimental spectra in color-coded LEDs with aquamarine-violet QW layout, drift-diffusion transport and QW kinetic models had to be completed with Auger-assisted QW depopulation process which enhances the nonequilibrium character of QW populations and supports the mobile carrier transport across the LED active region. Carrier transport in semipolar dichromatic LEDs was severely affected both by polarization barriers and by intra-QW recombination rates. Hole transport is most sensitive to the interface potential barriers whereas the electron transport was more susceptible to the balance between QW carrier capture and intra-QW recombination rates.

8980-59, Session PWed

Generation of pulse trains with high-repetition-rate in anomalous dispersion decreasing fibers

Dmitry A. Korobko, Ulyanovsk State Univ. (Russian Federation); Oleg G. Okhotnikov, Tampere Univ. of Technology (Finland); Alex A Sysoliatin, General Physics Institute of the Russian Academy of Sciences (Russian Federation); Igor O. Zolotovskii, Ulyanovsk State Univ. (Russian Federation)

Anomalous DDF are proposed for applications in optical pulse compressors and generators. We have identified two stages in self-similar dynamics of these pulses in this case. The initial stage of quasi-

linear pulse compression is significantly affected by the initial pulse chirp. For pulses with shorter duration, the quasi-linear stage is almost suppressed by nonlinear factors providing an effective compression of pulses without initial chirp.

For anomalous DDF waveguides we have distinguished an advanced stage of modulation instability (MI), which causes pulse train generation. We have proposed a new method for increasing the pulse train repetition rate through frequency modulation of long amplitude modulated pulse. It has been shown that the pulses generated in anomalous DDF due to nonlinear MI effects are asymptotically similar to the chirped soliton pulses.

The effect of Raman self-scattering on pulse generation in anomalous DDF has been studied. In the important regime of nonuniform amplitude modulation of long pulses, this mechanism causes pulse train generation with high peak powers and formation of the pulses with giant peak power, i.e. an optical rogue wave. This effect is of interest for many applications in opto-electronics, in particular, in modulators, decoders, delay lines, etc. It is found that initial pulse chirp enhances self-Raman scattering at early stages of pulse propagation and improves compression of the generated pulses.

8980-60, Session PWed

Adaptive sampling strategies for efficient parameter scans in nano-photonic device simulations

Martin Hammerschmidt, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Jan Pomplun, Sven Burger, Frank Schmidt, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany) and JCMwave GmbH (Germany)

Rigorous optical simulations are an important tool in optimizing scattering properties of nano-photonic devices and are used, for example, in solar cell optimization. The finite element method (FEM) yields rigorous, time-harmonic, high accuracy solutions of the full 3D vectorial Maxwell's equations [1] and furthermore allows for great flexibility and accuracy in the geometrical modeling of these often complex shaped 3D nano-structures. A major drawback of frequency domain methods is the limitation of single frequency evaluations. For example the accurate computation of the short circuit current density of an amorphous silicon/micro-crystalline multi-junction thin film solar cell may require the solution of Maxwell's equation for over a hundred different wavelengths on an equidistant, predetermined grid. Also in optical critical dimension (OCD) metrology, wavelength scans are frequently used to reconstruct unknown geometrical and material properties of optical systems numerically from measured scatterometric data.

In our contribution we present adaptive numerical integration and sampling routines and study their efficiency in the context of the determination of short circuit current densities of solar cells. We show that these strategies lead to a reduction in the computational effort without loss of accuracy. We discuss the employment of tangential information in a Hermite interpolation scheme to achieve similar accuracy on coarser grids. Besides solar cells, we also explore the usability of these strategies for parameter dependent target quantities in other photonic application areas like scatterometry.

[1] S. Burger et al in Integrated Photonics and Nanophotonics Research and Applications, p. ITuE4, Optical Society of America, 2008, doi: 10.1364

[2] S. Burger et al in Proc. SPIE 8166, Photomask Technology 2011, 81661Q, doi:10.1117/12.896839

8980-61, Session PWed

Modeling of opto-electronics in complex photonic integrated circuits

Cristina Arellano, VPIphotonics GmbH (Germany); Sergei Mingaleev, Eugene Sokolov, VPI Development Ctr. (Belarus); Igor Koltchanov, Andre Richter, VPIphotonics GmbH (Germany)

Circuit level modeling of photonic integrated circuits (PICs) encompassing electronic-photonic co-design is one of the main requirements for enabling rapid functional design of CMOS-silicon devices as well as InP-based structures. The circuit modeling approach employed for this work covers the design of PICs that comprise elements of versatile nature as active semiconductor-based structures, passive waveguide elements and electric elements.

In previous works we have addressed the modeling of fully passive PICs, based on the description of PIC elements in terms of frequency-dependent scattering-matrices. Lately, we presented a new method for efficient modeling of hybrid large-scale PICs containing active sections as well that aids inefficiencies of pure time-domain simulations. We named it time-and-frequency domain modeling (TFDM). In this contribution we present another functionality extension of our modeling environment that allows the design of complex PICs comprising linear electric and optical sub-elements in a single simulation setup.

We connect electrical elements with each other via bidirectional ports representing forward and backward propagating electrical waves. The calculation of linear electric circuits (ECs) is natively performed using an S-matrix approach. For this, we extended our previously developed S-matrix modeling approach for passive clusters in PICs to support the modeling of linear ECs for both, low- and high-frequency conditions.

We illustrate the functionalities of our approach using several application examples. For instance, we present a model of the electrical driver for a monolithically-integrated InP transmitter developed in frame of the European research project MIRTHE and the analysis of the driver and the EA-Modulator interplay.

8980-62, Session PWed

Toward bound-to-continuum photon absorption with quantum tunneling in type-II nanostructures: a source-radiation scheme using perfectly-matched layers

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

Electrons and holes in type-II nanostructures are spatially separated. Therefore, both the radiative and nonradiative recombination rates are reduced. Although the photon conversion efficiency is hence decreased, the lowered nonradiative recombination such as Auger process benefits photovoltaic applications. Furthermore, if generated carriers can be rapidly removed from nanostructures through quasi-bound states, the photon absorption may be designed and enhanced regardless of the concern on nonradiative mechanisms. Here, we model the bound-to-continuum absorption of type-II nanostructures in the presence of tunneling using the density-matrix formalism and convert it into a radiation problem in the multiband space with band mixing. An effective source is derived from the eight-band momentum operator, and the corresponding field is expressed in terms of the source and retarded Green's function of the eight-band Luttinger-Kohn Hamiltonian. On the other hand, the response is actually calculated without the Green's function. Perfectly-matched layers in the multiband space are introduced to model the effect of quasi-bound states in open regions. In this way, the interplay between photon absorption and tunneling is fully taken into account. We present both the transverse-electric and transverse-magnetic absorption spectra of type-II GaAs_{0.65}Sb_{0.35}/GaAs coupled quantum wells. The corresponding lineshape broadening

near the resonant energy can be divided into two parts. One comes from various incoherent relaxation mechanisms, and another well-fitted by the Fano resonance originates from the coherent tunneling. For a 2-nm potential barrier, the tunneling times of metastable states in nanostructures are around 20 fs, and their degrees of mixing to the continuum are high.

8980-63, Session PWed

Modified metal-dielectric-metal plasmonic waveguide with enhanced figure-of-merit

Chang Y. Jeong, Myunghwan Kim, Sangin Kim, Ajou Univ. (Korea, Republic of)

We report an investigation on a modified metal-dielectric-metal (MDM) plasmonic waveguide structure in which a thin low-index dielectric layer is inserted in the middle of the dielectric layer. Modal properties of the modified MDM plasmonic waveguide are investigated systematically and compared to those of the MDM waveguide. In the modified MDM plasmonic waveguide, most of electromagnetic wave is confined in the central low-index dielectric region, this enables the stronger modal confinement and lower propagation loss at the same time, and thus, overall performance is improved as compared to the MDM plasmonic waveguide. The modified MDM waveguide can be a good alternative to the MDM for various applications.

8980-64, Session PWed

Low-loss plasmonic waveguide on SOI platform

Chang Y. Jeong, Myunghwan Kim, Sangin Kim, Ajou Univ. (Korea, Republic of)

We propose a novel hybrid plasmonic waveguide formed on a silicon-on-insulator (SOI) platform. The proposed plasmonic waveguide is formed by inserting a thin metal layer in the middle of a dielectric slot waveguide, which shows a remarkably enhanced propagation distance and reduced mode area beyond the diffraction limit compared to a simple metal stripe waveguide. Our systematic investigation reveals that the mode area of the proposed plasmonic waveguide can be reduced by a factor of 4 as compared to the bare metal strip waveguide and the propagation distance can be widely varied by changing the thickness of the metal layer, which can range from a few tens of micrometers to millimeter scales. Reducing the metal layer thickness to a few nanometers enables the figure-of-merit, propagation distance to mode size ratio, to exceed 10^4. It is also shown that the mode area and the propagation loss can be simultaneously reduced by decreasing the height of the waveguide, which results in a rapid increase of the figure-of-merit.

8980-65, Session PWed

Design and simulation of an optical waveguide for its integration with a light source based on SRO

Jesús Alarcón Salazar, Ignacio Enrique Zaldívar Huerta, Mariano Aceves-Mijares, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

It has been demonstrated that Silicon Rich Oxide (SRO) deposited by Low Pressure Chemical Vapor Deposition (LPCVD) and annealed for 180 minutes at 1100 °C has emission of light in the visible range. Different spectra can be obtained with SRO by varying the pressure gas ratio (PSiH4/PNH3) during the deposition process. Also, electroluminescent devices have been demonstrated using SRO. However, to our knowledge there are not optoelectronic circuits integrating the emission light source and the waveguide. In this work an optical waveguide is designed and simulated with the purpose to be integrated with a SRO device on a silicon substrate. We describe the methodology followed for the design of the optical waveguide able to transmit light emitted in the wavelength range from 400 to 800 nm. Due to its optical properties and the compatibility with silicon technology, the core material selected for the waveguide is silicon nitride (Si3N4) covered with silicon oxide (SiO2). This work also compares between a rectangular waveguide with other waveguides compatible with MOS technology reported in the literature. The optimal dimensions and geometry that reduce the losses and confine more light into the core zone are obtained by simulation. The final design contemplates the fabrication limits like maximum thickness, minimum length and optical properties depending on the fabrication technique. The results of this work will be used for the design and fabrication of the mask as well as the fabrication of the integrated devices.

8980-67, Session PWed

Optical property tuning of gold-nanocap-coated dielectric nanoparticles

Sunghwan Kim, Taehyeong Kim, Joonhan Park, Ajou Univ. (Korea, Republic of)

Dielectric nanoparticles such as polystyrene, zinc oxide, and quantum dots have been attractive for bio-photonic application (imaging, photo-induced diagnosis and therapy). These applications are based on the photon-generation phenomena. So tuning the emission and extinction properties of nanoparticles would open new possible applications (e. g. directional fluorescence, fluorescence enhancement, and amplifying second harmonic generation). This means we might have to integrate photonic structures to individual nanoparticle. Plasmonics can be a solution since coating or deposition of metal onto the nanoparticle are relatively ease to be fabricated. Here we computationally investigate the optical properties revealed in dielectric nanoparticles with a gold semi-cap. Strong localizations with a sharp spectral peak can be found at the gold/particle boundary. The resonance frequency is dependent on the size, shape, and surrounding medium. The plasmonic localization can induce the enhancement of absorption and emission which may be shown in the dielectric material. Along with those, the gold semi-cap act as a concaved metal mirror, thereby inducing the concentrated field inside the particle. Simulation results reveal that the directional reshaping of emitting light is the result to the mirror effect and the edge plasmonic localized mode. The simulated results and other possible optical properties would open the way to numerous additional bioapplications.

8980-68, Session PWed

GPGPU-based parallel computing of PIC-FDTD simulation for the development of novel terahertz radiation devices

Tsuyoshi Iwata, Akiko Okajima, Tatsunosuke Matsui, Mie Univ. (Japan)

Since Urata et al. reported on the superradiance of Smith Purcell radiation (SPR), numerous studies have been carried out to develop novel type of terahertz (THz) radiation source known as THz free electron lasers (THz-FELs). It is believed that the bunching of the electron beam (e-beam) due to the interaction with the surface waves on the metallic grating plays a crucial role to obtain the SP superradiance. In order to numerically study the SPR, particle-in-cell finite-difference time-domain (PIC-FDTD) method has been widely employed. In the PIC-FDTD simulation, the behavior of a huge number of electrons (typically millions) has to be monitored and it requires a lot of computational time and memory.

Recently, many studies on the usage of the graphic processing unit

(GPU) for a general purpose computation such as scientific simulations, which is known as the general purpose computation on GPU (GPGPU), have been reported. The GPU has a lot of processing unit, which is suitable for a parallel computing. Here we show our studies on the GPGPU computation of our homemade PIC-FDTD simulation code. We have used Geforce GTX680 for the computation and employed the compute unified device architecture (CUDA) for the development of the parallel computational code. We have successfully reproduced the SP superradiance and the computational time has been reduced to the quarter of that required for the same simulation using CPU.

8980-70, Session PWed

Graphical computational method for active materials in simulation of optical electromagnetics

Mary J. Potasek, Evgueni Parilov, Karl Beeson, Simphotek Inc. (United States)

Traditional numerical analyses of laser beam transmission through "active" nonlinear materials have involved many assumptions that narrow their general applicability. As optical phenomena become more complex, it is necessary to expand the use of numerical simulation methods. Historically, laser-matter interactions have involved calculations of "classical" wave propagation by Maxwell's equations and photon absorption through rate equations using numerous approximations.

We describe a novel numerical simulation method in computational electromagnetics that combines classical electric field propagation with "active" photon absorption kinetics using computational optical building blocks. It allows investigating a plane electromagnetic wave propagating through generic organic or inorganic photoactive materials while "active" photo-transitions are implemented without rewriting the numerical code.

To date we have used the method in multiphoton absorbers, upconversion, semiconductor quantum dots, rare earth ions, organic chromophores, singlet oxygen formation, energy transfer, and optically-induced chemical reactions. We will demonstrate the method with applications in measurements of two-photon absorbers, energy transfer between different rare-earth ions, singlet oxygen formation in photodynamic therapy and multiphoton processes in semiconductor quantum dots.

8980-71, Session PWed

Impact of the gain model on the stability assessment in semiconductor DFB lasers

Ivan A. Aldaya-Garde, Gabriel Campuzano, Tecnológico de Monterrey (Mexico); Christophe Gosset, Frédéric Grillot, Télécom ParisTech (France); Cheng Wang, Télécom ParisTech (France) and Univ. Européenne de Bretagne (France); Gerardo A. Castañón, Tecnológico de Monterrey (Mexico)

Optical injection locking has been extensively applied to analyze the physics of semiconductor lasers [1], as well as to enhance their modulation characteristics [2], or to generate nonlinear dynamics [3]. Since the accuracy of the numerical analysis on injection locking stability assessment is highly depending on the laser model, it is important to properly model the optical gain compression induced by hole-burning and carrier heating at high photon densities. The simplest gain model is linear in terms of carrier density; it considers only the carrier differential gain, , the carrier density, , and the transparency carrier density, , and is given by . Different gain models accounting for the gain compression effect have been proposed in the literature [4, 5]: (a) , (b) , and (c) , with , the gain compression coefficients and the photon density. We part from the well-known Kobayashi-Lang rate equations and perform the stability analysis of the linealized rate equation using the different gain models.

This study is not limited to weak or strong-injection regimes but covers power-injection ratios ranging from –50 to 10 dB. Numerical analysis of DFB lasers reveals that under weak-injection regime, the stability boundary (in the power-injection ratio vs. frequency-detuning plane) calculated from the linear gain model differs from those considering gain compression, in accordance with experiments reported in [4]. However, the latter models result in similar boundaries. For higher power-injection ratios, the difference between the linear and the compressed-gain models becomes smaller and therefore the gain compression models do not imply a significant improvement.

8980-72, Session PWed

Plasmonic gap-mode nanocavities at telecommunication wavelengths

PiJu Cheng, Academia Sinica (Taiwan); Chen-Ya Weng, National Taiwan Ocean Univ. (Taiwan) and Academia Sinica (Taiwan); Shu-Wei Chang, Academia Sinica (Taiwan) and National Chiao Tung Univ. (Taiwan); Tzy-Rong Lin, National Taiwan Ocean Univ. (Taiwan); Chung-Hao Tien, National Chiao Tung University (Taiwan)

We have analyzed a plasmonic Fabry-Perot nanocavity with a metallic nanowire embedded in a thick cladding layer. First, three cladding refractive indices of unity (ambience), 2.1 (silicon nitride), and 3.455 (silicon) are considered. We investigate the effect of dielectric claddings around the nanowire on the fundamental and first-order plasmonic gap modes. Using the finite-element method, we numerically solve guided modes of the plasmonic waveguide at a wavelength of 1.55 µm. After that, the waveguide confinement factors and modal losses of the fundamental and first-order modes are explored as a function of the cladding indices at various gap heights and wire radii. We utilize standing wave patterns from interferences of the incident and reflected fields and the orthogonality theorem of waveguide modes to calculate modal reflection coefficients and reflectivities at cavity ends. The result shows that both the field confinement and reflectivity can be improved with adequate choices of cladding materials. To improve the mirror loss, we additionally consider silver coatings at two end facets as reflectors. Using silver coatings within a decent thickness range, we show that the reflectivity is substantially enhanced above 95 %. The corresponding cavity performance is evaluated based on the threshold gain and Q factor of Fabry-Perot cavities. At a coating thickness of 50 nm and cavity length of 1.51 µm, the quality factor is about 150, and the threshold gain can be lower than 1500 1/cm.

8980-73, Session PWed

Influence of the nonlinear gain on the stability limit of a semiconductor laser with optical feedback

Yuanlong Fan, Yanguang Yu, Jiangtao Xi, Qinghua Guo, Univ. of Wollongong (Australia); Zhao Wang, Xi'an Jiaotong Univ. (China)

Dynamical stability analysis of a single mode semiconductor laser (SL) under external optical feedback (EOF) system has been being attracted extensive research activities due to the broad applications of an SL with EOF, such as optical communication, data recording and sensing. The system of an SL with EOF is described by the Lang and Kobayashi (L-K) equations. If the system determinant has no zeros in the right side of the S-plane, the system is thought as stable. For a DC biased SL system, the stability limit of the system is reached when the constant laser output just transits into periodic oscillation followed by other instabilities, including quasi-periodic oscillation, low frequency fluctuations (LFFs) and chaos. To determine the stability limit, the condition of the transition should be studied. Many relevant works have been conducted in the past decades.

However, the influence of the nonlinear gain effect on the stability limit has escaped attention. Nonlinear gain effect is an important factor for describing the dynamic behaviors of an SL with EOF. The inclusion of nonlinear gain can provide a good agreement between numerical results and experimental results. In this paper, starting from the L-K equations, two coupling equations for describing the stability limit of the system are derived. Based on the coupling equations, the stable region of an SL with EOF is obtained. The result presented in the paper is more accurate in contrast to the one reported previously in literature. The correctness of our results is verified by numerical calculations.

8980-74, Session PWed

Occurrence of Talbot effect in time domain in a dual-mode coaxial optical fiber

Jyoti Anand, Enakshi K. Sharma, Univ. of Delhi South Campus (India)

Coaxial fibers have been widely studied as dispersion compensating fibers assuming the excitation and the propagation of only the LP01 supermode which offers a large negative dispersion. However, we note that the coaxial fiber supports both the LP01 and LP02 supermodes and in general both are excited. At a certain wavelength, ?, both the supermodes have the same group velocity and almost equal and opposite group velocity dispersion (GVD). When the coaxial fiber is excited by a periodic sequence of Gaussian temporal pulses of spectral spread ~2.5nm and pulse width (?=1"ps"), from a single mode fiber identical to the rod waveguide of the coaxial fiber, both supermodes are almost equally excited. In each mode each spectral component propagates with its own propagation constant. Due to opposite GVD, the ?±∆? components of the LP02 mode and ??∆? components of the LP01 mode have the same group delay and hence arrive at any distance, z, at the same time. The temporal interference between these components can produce pulses at the beat frequency ∆?. The two modes also interfere spatially due to which power oscillates between the rod and tube waveguides of the coaxial fiber. Due to the spatial as well as the temporal interference between the supermodes, each Gaussian pulse in the sequence splits into a series of narrow pulses within the broadened Gaussian envelope. However, for chosen repetition rate and propagation lengths, the original Gaussian pulse sequence reappears-occurrence of "Talbot Effect" in time domain.

8980-75, Session PWed

Characteristics of microwave frequency combs generated by a semiconductor laser under dynamical dual-beam injection

Cheng-Ting Lin, Yu-Shan Juan, Yuan Ze Univ. (Taiwan)

We demonstrate and characterize the microwave frequency combs utilizing both the dynamical single-beam and dual-beam injection schemes numerically. The dynamical single-beam injection scheme is realized by optical pulse injection to the slave laser (SL) from a pulsed laser. When the SL subjected to only the optical pulse injection from the pulsed laser, microwave frequency combs are generated by the nonlinear dynamics of the frequency-locked states with different locking ratios. The amplitude variation of ±18 dB in a 30 GHz range is obtained by precisely varying the operational parameters, injection strength, repetition frequency, and detuning frequency. In this paper, we propose the dynamical dual-beam injection scheme to strongly improve the amplitude variation of the microwave frequency comb generated. The dynamical dual-beam injection is realized by both optical pulse injection and optical cw injection to the slave laser. By utilizing the hybrid scheme consists of double optical injections, the advantages of each individual dynamical system are added and enhanced. As the result, the amplitude variation of the microwave frequency comb of ±3 dB in a 30 GHz range is achieved when operating the cw injection system in a stable locking state. In addition, the bandwidth enhancement over 25 GHz is also observed.

8980-76, Session PWed

Physical modeling of RF source generation based on electro-optic modulation and laser injection locking

Shouyuan Shi, Garrett J. Schneider, Dennis W. Prather, Univ. of Delaware (United States)

In this paper we present both time and frequency domain methods to model the behavior of widely tunable RF source, i.e., 1-100GHz, generated by down-mixing of two coherent DFB lasers with a desired RF frequency offset. The coherence is established through laser injection locking from a seed laser, and high frequency response is achieved by efficient electro-optic modulation driven by a local oscillator with low phase noise. Therefore, The generated RF source will not only preserve the phase characteristics of the local oscillator, but also provide wide RF tunability by thermally tuning laser wavelengths.

To model the system, we employ rate equations to simulate time evolution of master and injection lasers. The parametric variables, extracted from each component, such as lasers, modulator, filter, RF amplifier, and local oscillator, are incorporated. Potential phase noise sources, i.e., driving currents, local oscillator phase noise, and spontaneous emission in lasers, are included in the model. The phase noise, relative intensity noise, and RF linewidth are extracted to evaluate overall system performance.

Due to computational complexity of the time domain method, low frequency response, i.e., < 10KHz, becomes extremely challenging. To alleviate this, we use a frequency approach to enhance modeling capability. A linearization process is employed to approximate the coupled nonlinear rate equations. Based on the calculation of power density of noise in the system, the corresponding performance parameters can be extracted.

The proposed modeling tools provide numerical approaches to understand the physical origin of system phase noise, predict the system performance, and ready for future design and optimization.

8980-77, Session PWed

Analysis of evanescent fiber optic sensors using Meep as a simulation tool

Liliana Zdravkova, Patricia Nieva, Univ. of Waterloo (Canada)

Optical fibers are commonly used as evanescent wave sensors. Many factors affect the performance of fiber optic-based evanescent sensors, including, but not limited to, cladding thickness and the refractive index of the external medium. A lot has been done on analytical and numerical models to predict the effects of these factors in order to aid sensor design, however these models are often complicated and difficult to solve. Here, the free open source finite-difference time-domain (FDTD) simulation software called Meep (MIT Electromagnetic Equation Propagation) is used to investigate to the performance of a fiber optic evanescent wave sensor. The software simulates Maxwell's equations and is used due to the simplicity of setting up the simulation and the reasonable running time. Electromagnetic flux is calculated at various points along the structure to determine the power loss based on the physical dimensions and refractive indices of the structure. The dimensions used in the simulation are relative and therefore the results are mainly qualitative, however they are still useful in guiding the design of fiber optic sensors. To validate the accuracy of the simulation results experimentally, optical fibers are etched to various cladding thicknesses. The change in transmitted power is then measured when an external medium, of refractive index up to 1.5, is applied to the sensing region. The results are used to explore the advantages and limitations of this free and open source software in the modelling and simulation of this type of photonic sensors.

8980-78, Session PWed

Highly-strained InxGa1-xAs1-ySby/GaSb for mid-infrared devices

Charles R. Meyer II, Justin S. Grayer, Dan Paterson, Emily Cheng, Gregory E. Triplett, Univ. of Missouri-Columbia (United States)

InxGa1-xAs1-ySby is an important semiconductor material for mid-infrared photonic devices. Because of conduction and valence band alignment with other zinc-blende compounds (AlSb, GaSb, InAs), InxGa1-xAs1-ySby has been exploited as higher efficiency gain mediums in ~3 ?m sources and thermophotovoltaics. Unfortunately, the ability to pseudomorphically synthesize InxGa1-xAs1-ySby across the compositional range has been limited by the substrate availability. Because of the lattice mismatch with GaSb, an ability to take advantage of the entire wavelength tuning range that InxGa1-xAs1-ySby offers remains somewhat elusive. In an effort to optimize the gain medium in mid-infrared InxGa1-xAs1-ySby VCSELs and active region in thermophotovoltaic structures, we examine the structural, morphological, and optical properties in InxGa1-xAs1-ySby/GaSb structures produced by solid-source molecular beam epitaxy (MBE) with varying indium and arsenic mole fractions and thicknesses. There has been considerable effort to exploit high-indium content InxGa1-xAs1-ySby for longer wavelength operation, yet high misfit dislocation densities are inevitable and the miscibility gap is a formidable barrier. To date, the ability to cover the compositional range of InxGa1-xAs1-ySby as well as its range of properties remains unresolved. In this work, we report on InxGa1-xAs1-ySby/GaSb structures, where the measured indium mole fraction (x) varies from x=0 to x>0.50. In addition to atomically smooth structures, we observed three-dimensional networks of quantum dashes and results reveal a self-organized composition modulation. Some physical features of the quantum dashes include near one-micron lengths, 90° flip in orientation, and uniformity across a 20 x 20 µm area. We also observe network formation up to a film thickness of 10-nm.

8980-79, Session PWed

Analysis of quantum cascade lasers using an equivalent circuit model

Saba Soltani, Islamic Azad Univ. of Tabriz (Iran, Islamic Republic of); K. Abedi, Shahid Beheshti Univ. (Iran, Islamic Republic of)

A large-signal circuit model based on a set of rate equations which govern the dynamics of carrier and photon densities in the active region of Quantum Cascade Lasers (QCLs), is described. Making use of this equivalent-circuit model, the static and dynamic responses of QCL for some affecting parameters are extracted by using HSPICE circuit simulator. There is no relaxation oscillation in the pulse response characteristics. A large modulation bandwidth is obtained with no resonance peak in the frequency responses. Dependency of the laser characteristics on the injection efficiency into the upper lasing state, relaxation lifetime of carriers from the lower lasing state and photon lifetime inside the optical cavity are analyzed. Our simulation results agree favorably with the analytical evaluations of the rate equations.

8980-80, Session PWed

Study on K2Te solar blind ultraviolet cathode

Xiaofeng Li, North Night Vision Technology Co., Ltd. (China); Gui Lin Zeng, North Night Vision Technology Group Co., Ltd. (China) and Kunming Institue of Physics (China)

In this paper, the processing technology of K2Te solar blind ultraviolet cathode is described and samples of K2Te solar blind ultraviolet cathode were produced. The spectral response, spectral reflectance and the fluorescence spectra under the excitation condition of 250nm wavelength of K2Te solar blind ultraviolet cathode samples were measured. The findings suggest that under the existing technological condition, the sensitivity of K2Te solar blind ultraviolet cathode is less than of Cs2Te, however compared with Cs2Te solar blind ultraviolet cathode, the peak wavelength in spectral response is shorter at 250nm, while the cutoff wavelength of long wave is at 315nm; in addition, K2Te solar blind ultraviolet cathode has better solar blind property; the spectral sensitivity at 633nm is ranked at the order of magnitude of 10-6mA/W, two order of magnitudes lower than that of Cs2Te solar blind ultraviolet cathode. In terms of spectral reflectance, the findings show that the spectral reflectance of K2Te solar blind ultraviolet cathode is higher than that of Cs2Te solar blind ultraviolet cathode within the scope of 200~400nm wavelength, and is lowered than that of Cs2Te solar blind ultraviolet cathode within the scope of 400~600nm wavelength. The spectral reflectance curves of K2Te solar blind ultraviolet cathode and Cs2Te solar blind ultraviolet cathode are similar in shape, and the peaks in spectral reflectance curve of K2Te solar blind ultraviolet cathode are basically same to the peaks in spectral reflectance curve of Cs2Te solar blind ultraviolet cathode. It is concluded that the refractive index of K2Te solar blind ultraviolet cathode is basically same as that of Cs2Te solar blind ultraviolet cathode, only small difference in the range of longer wavelength. The findings on fluorescence spectra indicate that under the same condition and within the scope of 200~450nm wavelength, the fluorescence of K2Te ultraviolet cathode is more weak than that of Cs2Te ultraviolet cathode, as the reflectance of K2Te cathode is higher than that of Cs2Te ultraviolet cathode, the more the photo absorption, the more intense the fluorescence. Thus, the properties of K2Te solar blind ultraviolet cathode are similar to those of Cs2Te solar blind ultraviolet cathode, and both cathodes can be applied to image device for solar blind ultraviolet detection.

8980-82, Session PWed

Thermal considerations in electrically-pumped metallo-dielectric nanolasers

Janelle C. Shane, Qing Gu, Univ. of California, San Diego (United States); Felipe Vallini, Univ. Estadual de Campinas (Brazil); Brett Wingad, Joseph S. T. Smalley, Univ. of California, San Diego (United States); Newton C. Frateschi, Univ. Estadual de Campinas (Brazil); Yeshaiahu Fainman, Univ. of California, San Diego (United States)

Metal nanocavity-based lasers show promise for dense integration in nanophotonic devices, thanks to their compact size and lack of crosstalk. However, self-heating of these devices is believed to be one of the primary factors limiting their stability and performance. Despite their importance to the design of metallo-dielectric nanolasers, thermal considerations have been largely overlooked. We discuss the interplay of thermal, material, electrical, and optical considerations in analysis of a fabricated and characterized electrically-pumped device, as well as in the design of a higher-performance room-temperature laser. We also show the effects that choice of shield material can have on a nanolaser's ability to dissipate heat, and explore the use of amorphous Al2O3 (α-Al2O3) as a thick thermally-conductive shield layer. By allowing a metallo-dielectric nanolaser to dissipate heat through its shield, the use of α-Al2O3 improves device thermal performance, and may enable the design of laser cavities with new functionality, which till now have proven too prone to self-heating for practical consideration. The design analysis we demonstrate, which considers the interconnectedness of a nanolaser's thermal, material, electrical, and optical properties, should aid in the design of these new metal-clad nanolasers.

8980-45, Session 12

Graphene-based transverse epsilon-near-zero metamaterial

Mohamed A. K. Othman, Caner Guclu, Filippo Capolino, Univ. of California, Irvine (United States)

It has been shown in the literature that isotropic epsilon-near-zero metamaterials possess many interesting features such as the ability to tunnel electromagnetic waves in small channels or nonlinear phenomena such as second harmonic generation. In uniaxail electric metamaterial realized using graphene-dielectric multilayers, hyperbolic or elliptic dispersion regimes can be observed under certain conditions on the permittivity tensor, moreover, phenomenological transition between both regimes corresponds to vanishing transverse permittivity. We focus our discussion on the realization of this kind of metamaterial at terahertz and far-infrared frequencies, where tunability using electrostatic bias demonstrates superior properties over other implementations. At near-zero transverse permittivity, flat iso-frequency wavevector dispersion characteristics are obtained where the phase constant normal to the layers is slowly varying over a wide spatial spectrum. Based on this phenomena, not only transmission and reflection are stable with respect to incidence angle, but also we report tunable and almost complete tunneling of TM plane waves in the multilayer at that condition, in contrast to the extremely narrow angular transmission in conventional ENZ materials. In addition, by introducing external magnetostatic bias, in plane anisotropy in graphene is excited and the multilayer behaves as a gyrotropic material. In such case, non-reciprocal transmission is achieved for circularly polarized waves. This property can be utilized in designing novel tunable isolators.

8980-46, Session 12

Difference frequency generation of terahertz surface plasmons in graphene and topological insulators

Xianghan Yao, Alexey A. Belyanin, Texas A&M Univ. (United States); Mikhail Tokman, Russian Academy of Science (Russian Federation)

Surface plasmons in graphene/TI may provide an attractive alternative to noble-metal plasmons due to their tighter confinement, peculiar dispersion, and longer propagation distance, which is believed to exhibit promising applications in nanophotonics and quantum information processing. Direct excitation of THz or infrared surface plasmons by an incident electromagnetic wave is inefficient and requires grating in order to satisfy frequency and phase matching conditions. Here we theoretically propose difference frequency generation (DFG) in 2D layers of massless Dirac electrons, e.g. graphene and TI, as an efficient and controllable way of generating surface plasmons over a broad range of THz frequencies. Stemming from unique bandstructure of Dirac electrons and efficient interband resonances, the magnitude of the 2D second-order susceptibility $|chi^{(2)}|$ for graphene is in the order of $10^{-6} esu$, much higher than $|chi^{(2)}|$ measured in similar wavelengths in asymmetric coupled quantum-well structures. We also demonstrate this nonlinear process is broadly tunable according to incident angle, doping and gating. Our result proves that the generated plasmon frequency can be tuned from 1THz to several THz while still maintaining high efficiency. The intensity conversion ratio reaches $10^{-4} cm^2/W$ when relaxation rate is around $1 meV$. In conclusion, 2D layers of massless Dirac electrons provide an ideal platform for highly efficient light-matter interaction, offering promising interesting applications in nanophotonics for sensing, imaging, information processing etc.

8980-47, Session 12

Electronic band structure and photo-emission spectra of graphene on silicon substrate

Brahmanandam Javvaji, Abhilash Ravikumar, Bhamy Shenoy, D. Roy Mahapatra, Gopalkrishna M. Hegde, Indian Institute of Science (India)

Free-standing graphene is a two dimensional honey-comb lattice with exceptional electrical conductivity and zero band gap. Band gap engineering is possible by placing graphene on metallic and silicon substrates. The effect of substrate leads to band gap widening by chemical or physical interactions between carbon and silicon atoms. For such systems, optical, electrical and opto-electronic characteristics are identified. Current study discusses about the photoelectric characteristics like photoemission spectrum where electrons are excited and extracted from the surface of graphene on silicon substrate by the excitation of incident electromagnetic radiation. Equilibrium geometry of graphene-silicon system is obtained from molecular dynamics simulations where the interactions between the atoms are modeled using Tersoff inter-atomic potential. The system is equilibrated at 300 K using Nose-Hoover thermostat. The electronic band structure of the equilibrated system is calculated using density functional theory in its local density approximation. The real and imaginary parts of dielectric constant as a function of frequency are obtained by using the calculated band structure along with random phase approximation. The photoemission spectrum measures the kinetic energy of the emitted electrons which is to plotted for a range of frequencies of incident carrier wave on the system. This study is useful in understanding graphene based design of photodetectors and photodiodes and quantum information processing.

8980-48, Session 12

Novel approaches to enhance graphene absorption and electro-optic property

Kaifeng Shi, Wangshi Zhao, Binying Zhao, Zhaolin Lu, Rochester Institute of Technology (United States)

There is an increasing interest in using graphene for optoelectronic applications. However, due to its single atom thickness, graphene is an inherently weak optical absorber, so novel concepts need to be developed to increase the absorption and take full advantage of its unique optical properties. We demonstrate greatly enhanced light absorption by monolayer graphene over a broad spectral range, from visible to near infrared, based on attenuated total reflection (ATR). In the experiment, graphene is sandwiched between two dielectric media referred as superstrate and substrate. Based on analytical calculation and experimental result, great light absorption can be achieved at the incident critical angle for TE polarized light. It is also verified that the closer the refractive indices of the superstrate and substrate, the higher the absorption of graphene will be. The maximum light absorption of 42.7% has been obtained through our experiment. Moreover, based on the ATR setup, we propose a graphene-based multilayer electro-optical modulator, by which light absorption of graphene can be tuned by an external applied voltage. The main approach here is the utilization of electrolyte gel between graphene layer and conducting substrate (i.e. metal or doped silicon). When given external voltage, electric double layers are formed at the graphene-gel interface, which changes the surface conductivity of graphene. Since the dielectric constant (or refractive index) of graphene is directly related to its surface conductivity, we can finally modulate light absorption of graphene. The modulator has potential application in building optoelectronic interconnections.

8980-49, Session 12

Broadband high photoresponse graphene photodetector

Yongzhe Zhang, Nanyang Technological Univ. (Singapore) and North China Electric Power Univ. (China); Tao Liu, Bo Meng, Xiaohui Li, Guozhen Liang, Xiaonan Hu, Qijie Wang, Nanyang Technological Univ. (Singapore)

Graphene, a two dimensional allotrope of carbon atoms on a honeycomb lattice with unique band struceure, has attracted significant interest in photonic applications. Here, by introducing a Titanium sacrificial layer fabrication approach, we provide an improved graphene photodetector with photoresponse as high as 8.61A/W in the range from visible (532 nm) to mid-infrared (around 10 um). The process was performed by evaporating one thin Ti layer on graphene and followed by an etching away process. The results show that defects and a bandgap are formed in the resulted graphene nanostructure after this process. The physical picture of the mechanism is like this: when the graphene photodetector is excited by light illumination, electron-hole pairs are formed. Then a multicarrier excitation process occurs where multiple carriers are generated in the graphene photodetector. After that, when those photo-generated and secondary-generated electrons are trapped in the defect states, the related holes can be re-circulated many times through the hopping effect within the lifetime of the trapped electrons. Owning to the relatively long trapping lifetime of electrons in the defect states and the fast transport of holes in the graphene nanostructures, a photoconductive gain is achieved by our graphene photodetector and the gain increased with the increase of the illumination photo energy. Finally, a high photoresponse of 8.61A/W has been realized by our simple approach. The concept would find important applications in graphene photonics and optoelectronics.

8980-50, Session 13

Non-reciprocal optical devices based on linear silicon photonic crystals

Davi Franco Rego, Vitaly Felix Rodriguez-Esquerre, Univ. Federal da Bahia (Brazil)

Due to the promises of ultrahigh speed computation realized in the optical domain, great interest towards all-optical integrated systems has been shown. A great number of different types of optical logic gates have been proposed during the last years and the optical diode effect based on photonic crystal is of crucial importance in optical logic gates and computing integrated optical systems. The diode effect can be achieved by breaking the spatial inversion symmetry by various ways. Many different linear passive structures that exhibits optical isolation and unidirectional transmission behavior have been proposed, which exploit the properties of point defects, mode conversion and filtering, chirped structures or heterojunction slabs (two different 2D Photonic Crystals structures). Further improvements of these structures are here proposed and enhanced unidirectional behavior was achieved by optimization of the originally proposed structures where with good optical isolation has been achieved. The results were obtained by efficient numerical simulations and it is shown that these devices are good candidates for building blocks of integrated optical systems.

8980-51, Session 13

Supersymmetric optical waveguides

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

We show that the concept of supersymmetry (SUSY) can be utilized as a versatile tool to design integrated optical structures with desirable properties and functionalities. Our approach makes use of the fact that SUSY provides a systematic way to construct a so-called "superpartner" for any given one-dimensional optical waveguide. The refractive index distribution of this partner waveguide shares all of its effective indices with the original waveguide, except for that of the fundamental mode which is absent from the spectrum. Therefore SUSY establishes perfect phase matching condition between an, in principle, arbitrarily large number of guided modes. Moreover, the respective field distributions are related through intervening SUSY transformations. The peculiar properties of coupled superpartner arrangements make them an ideal platform for integrated mode filtering applications. The key idea behind this is that global phase matching allows each mode from the original waveguide to interact freely with the neighboring guides, while the fundamental mode remains isolated. Here, this whole set of modes can be simultaneously manipulated, removed or amplified. Along similar lines, supersymmetric waveguides can also be used for mode extraction and multiplexing in hierarchical ladders of SUSY structures. By iteratively applying supersymmetric transformations to a fundamental waveguide, each individual mode can be populated selectively. In the reverse direction, such a ladder of multimode structures naturally converts the higher order modes of the original multimode structure to fundamental modes of specific partner waveguides.

8980-52, Session 13

Multimode interferometers based on non conventional waveguides

Ana Julia R. F. de Oliveira, Univ. Federal da Bahia (Brazil) and Univ. Federal do Vale do São Francisco (Brazil); Vitaly Felix Rodriguez-Esquerre, Univ. Federal da Bahia (Brazil)

For advanced photonics networks all kind of optical devices are being developed with the aim of routing and manipulating high speed optical signals without conversion to electric ones. Many techniques have been proposed to achieve this demand and the multimode interference MMI principle is becoming very important because these devices have a simple configuration, compactness and are suitable for integration. MMI couplers based on subwavelength periodical gratings and silicon nanowires are here analyzed based on the self-imaging principle and on the coupled-mode formulation. Several geometrical configurations were analyzed as a function of the operating wavelength, covering the O, E, S, C, L and U optical communication bands, for both types of MMIs by varying the width/radius, the period, the segment length (duty cycle) and the nanowires radius. The spatial distribution of the electric and magnetic fields, the dispersion relations for two first TE and TM modes for both type of waveguides are also calculated for an interval of wavelengths as well as the modal phase error for the first modes. It was observed that for some specific configurations the coupling distance is almost flat in a wide wavelength interval, suggesting the existence of a wavelength independent behavior as well as high quality imaging. Additionally, shorter devices length can be obtained if compared with the conventional ones.

8980-53, Session 13

Ultra-thin low loss Si_3N_4 optical waveguides at 1310 nm

Soon Thor Lim, Ching Eng Png, Alagappan Gandhi, A*STAR Institute of High Performance Computing (Singapore)

Recent advances in optical waveguides have brought long-awaited technologies closer to practical realization. Although the concept of a single-mode (SM) waveguide has been around for a while, SM condition usually posed very stringent conditions in fabrication for small

waveguides. Researchers have developed low loss silicon nitride (Si3N4) at 1550nm wavelength, the developments in specific application have down converted to 1310nm (O-band) so they do not have to compete with internet data for bandwidth and could share the existing optical fiber infrastructure. However, wavelength-demultiplexer technology at this band is not readily commercial available. Custom-made O-band optical devices for wavelength-demultiplexing have typical losses. Such high losses deplete more than 75% of the already-scarce photons. We studied Si3N4 channel waveguide with ultra-thin slab for (SM) condition at 1310nm wavelength using finite element method (FEM). We have shown that SM condition is possible for ultra-thin slab with wide waveguide width; such condition can ease the constraint of photolithography, allowing deposition of thin Si3N4 layer to be accomplished in minutes. Studies show that for ultra-thin layer, for example, at 60nm, we can achieve a wide range of widths that fulfilled the SM condition, ranging from 2 um to 5 um. SM condition becomes more stringent when the Si3N4 layer increases. Substrate losses are estimated at 0.001 dB/cm, 0.003 dB/cm, and 0.1 dB/cm for slab height at 100nm, 80nm, and 60nm respectively. We fabricated our waveguides using plasma enhanced chemical vapour deposition (PECVD) and characterization is currently underway to study the propagation loss.

8980-54, Session 14

Group-velocity slowdown in quantum dots and quantum-dot molecules *(Invited Paper)*

Hans Christian Schneider, Stephan Michael, Technische Univ. Kaiserslautern (Germany); Weng W. Chow, Sandia National Labs. (United States)

This talk reviews some basics on the theory of quantum coherence schemes in self-organized semiconductor quantum-dot systems. In typical quantum coherence schemes, pump and probe fields drive a quantum coherence, which is nonresonant with both fields. The influence of the quantum coherence then changes the optical properties on the probe transition. In this contribution, we concentrate on the effect of group-velocity slowdown that is achievable by quantum coherence schemes. Different schemes, such as V-type and Lamba-type schemes are introduced, numerically analyzed, and the achievable slowdown is characterized both in the frequency and the time domain. The performance of quantum coherence schemes depends crucially on the dephasing properties of the quantum coherence. We therefore adapt a microscopic theory of scattering and dephasing dynamics in quantum dots, which allows us to compare different quantum-dot setups without introducing phenomenological dephasing times. Based on this approach to electronic dynamics in the quantum dots and including pulse propagation, we compute the group velocity slowdown in the frequency and the time domain. A theoretical design for a quantum-dot molecule is introduced, which is optimized to lead to long dephasing times for the quantum coherence. It is shown that this design promises a pulse slowdown that is much better than that achievable in single quantum dots.

8980-55, Session 14

Monte Carlo markovian modeling of modal competition in dual-wavelength semiconductor lasers

Laurent Chusseau, Fabrice Philippe, Univ. Montpellier 2 (France); Alain Jean-Marie, INRIA Sophia Antipolis - Méditerranée (France) and Univ. Montpellier 2 (France)

CW dual-mode semiconductor lasers are key components for low cost microwave or terahertz beating generation. Besides multisection devices with independent gain regions, coupled-cavity microlasers sharing the same gain medium are attractive for compactness and simplified pumping scheme. We have analytically demonstrated that bulk or quantum-well are not appropriate for that purpose because of the short intraband relaxation time that renders the gain broadening nearly homogeneous and the laser bistable. Quantum dots are the solution that solves the mode competition because the difference between homogenous broadening due to temperature and inhomogenous broadening due to growth process dispersion helps decoupling the modes. We supplement here a previous analytical work by a fully numerical one using a Monte Carlo markovian model. Electrons and photons are treated as particles exchanged in the course of time between two families of QDs and a common barrier. Mode competition is thus accounted ab initio and simultaneously the model yields steady-state solutions and optical noise of both modes. An extensive parametric study has been conducted seeking for the CW stability conditions of such dual-mode microlaser as a function of external parameters (pumping, temperature) as well as intrinsic characteristics (gain dispersion, non-radiative recombinations in QDs and barrier, excited state exchange via the wetting layer or thermoionic refilling of the barrier). As a major result, coupled-cavity laser including QDs are found to operate CW dual-mode in every reasonable conditions thereby complementing our previous analytical study with a more extensive account of electron and photon coupling mechanisms.

8980-56, Session 14

Nondegenerate four-wave mixing in a dual-mode injection-locked InAs/InP(100) quantum dot laser

Frédéric Grillot, Télécom ParisTech (France); Cheng Wang, Institut National des Sciences Appliquées de Rennes (France); Ivan A. Aldaya-Garde, Christophe Gosset, Télécom ParisTech (France); Thomas Batte, Institut National des Sciences Appliquées de Rennes (France); Etienne Decerle, Yenista Optics (France); Jacky Even, Institut National des Sciences Appliquées de Rennes (France)

Nondegenerate four-wave mixing (NDFWM) in semiconductor gain media is a promising source for wavelength conversion in the wavelength division multiplexed systems and for fiber dispersion compensation in the fiber links [1]. In contrast to bulk and quantum well semiconductors, the quantum dot (QD) gain medium is quite favorable for enhancing the performance of the FWM because of the wider gain spectrum, larger nonlinear effect and the ultrafast carrier dynamics [2]. Especially, the reduced linewidth enhancement factor (LEF) can eliminate the destructive interference of different nonlinear processes for obtaining high efficiency in the wavelength up-conversion [3]. This work reports an efficient NDFWM in a dual-mode injection-locked QD Fabry-Perot laser lasing in the U band. The device has a wide gain spectrum with a full width at half maximum more than 80 nm and a maximum net modal gain of of 14.4 cm-1. The free running laser is featured with two lasing peaks induced by Rabi oscillation, which provides the possibility for efficient FWM generation [4]. The injection locking technique is widely used to reduce relative intensity noise and spectral linewidth in semiconductor lasers [5]. Employing the dual-mode injection-locking scheme, this work demonstrates an efficient NDFWM up to a detuning range of 1.7 THz with an injection ratio as low as 0.44. The normalized conversion efficiency (NCE) and the side-mode suppression ratio (SMSR) with respect to the converted signal are analyzed following the physical mechanisms. The highest NCE is -17 dB at the detuning 110 GHz with a SMSR of 20.3 dB.

8980-57, Session 14

Ultra-strongly sub-Poissonian light generation in a quantum dot-bimodal cavity system

Wen Zhang, Zhongyuan Yu, Yumin Liu, Yiwei Peng, Beijing Univ. of Posts and Telecommunications (China)

We theoretically investigate the sub-Poissonian light generation in a cavity quantum electrodynamics system of a single quantum dot coupled a bimodal nanocavity. In a recent work [Arka Majumdar et.al, Phys. Rev. Lett. 108, 183601 (2012)] it was showed that the system can generate strongly sub-Poissonian light when one mode of the cavity is driven coherently and resonantly. Here, we study the two-mode coherent driving of the coupled system by numerically solving the Lindblad mater equation. The effect of additional cavity mode driving on the statistical characteristics of photon emission is presented, and we obtain the dependence of the zero-time second-order autocorrelation function g2(0) on driving lasers strength and the strength ratio of two modes for resonant driving. We observe that g2(0) can be reduced up to four orders of magnitude (g2(0)<0.0001) compared to one-mode driving system (g2(0)>0. 1), indicating an ultra-strongly sub-Poissonian light generation. In addition, the strong dependence of g2(0) on the driving strength ratio provides a method to realize on-demand control of single photon emission using continuous-wave and pulse driving laser mixture in such system.

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8981-1, Session 1

Simulation of absorption, photogeneration, and carrier extraction in nanostructure-based and ultra-thin-film solar cell devices beyond the classical picture *(Invited Paper)*

Urs Aeberhard, Forschungszentrum Jülich GmbH (Germany)

With the introduction of novel light-trapping schemes reaching beyond the ray-optics limit, high-efficiency solar cells with an active absorber thickness of only a fraction of the typical irradiation wavelength are becoming interesting alternatives to expensive wafer-based architectures. In the case where these ultra-thin film solar cells are made of high-mobility semiconductors such as GaAs, the classical picture of local charge carrier generation and diffusive transport in thermalized distributions may no longer be appropriate, especially in the presence of strong doping-induced internal fields. The same applies to a wide range of nanostructure-based photovoltaic device components, such as quantum well and quantum dot structures or highly doped tunnel junctions, where the local electronic structure deviates strongly from the flat band bulk picture conventionally assumed in photovoltaic device simulations.

In this presentation, a microscopic theory of non-local photon absorption, photocurrent generation and carrier extraction in ultra-thin film solar cell devices is formulated for arbitrary spatial variation of electronic potentials and optical modes and transport regimes ranging from ballistic to diffusive. After verification of consistency with the classical picture in the flat band bulk limit and between the currents derived from optical absorption and electronic generation, the formalism is applied to the case of an ultra-thin GaAs solar cell, a III-V superlattice solar cell component and an InAlGaAs-InGaAs double quantum well tunnel junction.

8981-2, Session 1

The effects of electric field on InGaAs quantum well i-region placement in InAlGaAs solar cells

Christopher G. Bailey, Matthew P. Lumb, Raymond Hoheisel, Maria Gonzalez, U.S. Naval Research Lab. (United States); David V. Forbes, Rochester Institute of Technology (United States); Michael K. Yakes, Phillip P. Jenkins, Louise C. Hirst, Robert J. Walters, U.S. Naval Research Lab. (United States)

For the past decade, the inclusion of nanostructures in photovoltaic devices has been an exciting method of bandgap-engineering for the pursuit of improved solar cell performance. Multiple quantum wells (QW), in particular, are one of the most well-studied and best performing examples of these nanostructured devices. The performance of quantum well embedded photovoltaic devices has also shown a dependence on the location of the QWs in the i-region, as the collection of carriers generated in these structures can be highly dependent on the electric field as well as the magnitude of Shockley-Reed-Hall recombination.

In this investigation, the benefits of QWs in varying locations within the i-region will be considered. Specifically, four InGaAs QW structures of varying depth embedded in a 1.0 eV InAlGaAs n-i-p solar cell will be evaluated experimentally as a function of depth in the intrinsic region. Experimental device performance will be studied via standard photovoltaic device measurements. Drift-diffusion modeling will be used to relate these measurements to the expected trends with a focus on the effects of the electric field. Results will be presented discussing the potential for the use of QWs for devices attempting to mitigate various degradation effects typical in solar cell applications.

8981-3, Session 1

Enhanced light absorption in InGaN multiple quantum-wells solar cell with three-dimensional quasi-periodic air-void GaN layer

Yu-Lin Tsai, Da-Wei Lin, Chun-Kai Chang, Chien-Chung Lin, Peichen Yu, Hao-Chung Kuo, National Chiao Tung Univ. (Taiwan)

The enhanced light absorption is demonstrated in InGaN/GaN multiple quantum well (MQW) solar cells by utilizing three-dimensional quasi-periodic nano-air void u-GaN layer. In this research, the three-dimensional quasi-periodic nano-air void u-GaN layer was fabricated by combining nano-sphere lithography and re-epitaxial techniques. The SEM images indicate that the quasi-periodic nano-air-viod array have been successfully fabricated. From the results of Raman spectrum, the strain of GaN layer is reduced with the increase of the number of air-void layer. Furthermore, the nano-air-void provides refractive index mismatch causing high reflection and provides light scattering effect which benefit in absorbing light. The three-dimension air-viod u-GaN layer can reflect photons back into absorber layer and increases light absorption of InGaN solar cell further to enhance the conversion efficiency of InGaN MQW solar cell. From the absorption spectrum of the devices, The estimated Jsc of single, double and triple nano-air-void layer devices calculated from absorption spectrum achieved 6.75%, 18.1% and 24.1% enhancement, respectively. We believe that the InGaN/GaN MQW solar cells with three-dimensional quasi-periodic nano-air void u-GaN layer offers a viable solution to high efficiency InGaN/GaN MQW solar cells.

8981-4, Session 1

Absorption enhancement and dark current reduction in quantum-dot solar cells

Seth M. Hubbard, Kristina Driscoll, Stephen J. Polly, Staffan Hellström, David V. Forbes, Rochester Institute of Technology (United States); Rao Tatavarti, MicroLink Devices, Inc. (United States)

Quantum dot (QD) superlattices have been proposed as a means to harness the lower energy photons normally lost to transmission, extending the absorption range of solar cells and thus increasing the short-circuit current. Two specific applications for this effect have recently emerged, namely, bandgap engineering of multi-junction solar cells and as a miniband in the intermediate band solar cell. A key drawback to the QD approach has been both increasing the absorption cross section of the QD layers (and thus the photocurrent enhancement) as well as re-duction of the open circuit voltage loss often observed in QD solar cells. In this paper, we investigate the effects of QD solar cell design on both absorption and open circuit voltage. Simulations suggest placing the QDs off-center reduces non-radiative recombination and thereby the dark saturation current. A series of three samples with the QD placed in the center and near the doped regions of a pin-GaAs solar cell were grown and fully characterized. The experiment showed the emitter-shifted devices exhibit a marked decrease in open-circuit voltage and fill factor. This behavior was attributed to non-negligible n-type background doping in the intrinsic region. In addition, utilizing thin film QD devices allows a larger design space for nanostructure absorption enhancement and are promising candidates for efficient light trapping. Inverted devices on ELO templates were grown at RIT with a 10 layer superlattice of QDs. The EQE shows that sub-bandgap current increased due to the contribution of the QDs and thin film process. As well, the QD contribution to the spectral response shows strong resonant peaks, not seen when compared to a traditional upright QD cell. Results demonstrate that enhancement of the electric field in the infrared (due to the cavity formed by the thin film device) can be effectively used to improve the QD absorption and carrier collection.

8981-50, Session 1

High-efficiency nanopillar solar cells employing wide-bandgap minority carrier recombination barriers *(Invited Paper)*

Giacomo Mariani, Michael Haddad, Abhejit Rajagopal, Diana L. Huffaker, Univ. of California, Los Angeles (United States)

In this work, we present nanostructured solar cells based on patterned GaAs nanopillars (NPs) grown by MOCVD. The patterns are lithographically defined and center-to-center pitch, hole size and tiling pattern can be precisely determined a-priori at nanometer resolution. The inherently catalyst-free approach eliminates any metal (i.e.) diffusion into the NPs that could reduce the carrier lifetime.

The study delves into the characterization of different high-bandgap in-situ passivation shells applied to axial GaAsP NP photovoltaics. InGaP (direct bandgap) and GaP (indirect bandgap) are exploited as two different minority-carrier barriers to prevent surface recombination. Optoelectronic modeling correlated to experimental results highlights Voc values extremely dependant on the energy bandgap of the epitaxial passivation barrier. Optically, dome-shaped ITO top electrode functions as a 2-D periodic array of subwavelength lenses that focus the local density of optical states within the NP region. Figures of merit such as rectification ratios in the order of >107, and dark currents of ~ 540 pA at -1 V are indicative of high-quality p-n junctions. Under AM 1.5G conditions, VOC of 0.77 V, JSC of 16.7 mA/cm^2, fill factors of 71 % are measured, leading to PCE of 9.14 %. The data is presented in a comparative fashion with respect to state-of-the-art literature in the field.

8981-5, Session 2

Preparation and study of artificial graphene-type semiconductor superlattices *(Invited Paper)*

Daniel Vanmaekelbergh, Utrecht Univ. (Netherlands); Christophe Delerue, Efterpi Kalesaki, Univ. des Sciences et Technologies de Lille (France); Cristiane Morais Smith, Utrecht Univ. (Netherlands); Wiel Evers, Technische Univ. Delft (Netherlands)

The interest in 2-dimensional systems with a honeycomb lattice and related Dirac-type electronic bands has exceeded the prototype graphene1. Currently, 2-dimensional atomic2-6 and nanoscale7-10 systems are extensively investigated in the search for materials with novel electronic properties that can be tailored by geometry. Here, we show that atomically coherent honeycomb superlattices of rocksalt (PbSe, PbTe) and zincblende (CdSe, CdTe) semiconductors can be obtained by nanocrystal self-assembly and subsequent cation exchange. These artificial graphene systems combine Dirac-type electronic bands with the beneficial properties of a semiconductor, such as the presence of a band gap and strong spin-orbit coupling. This is attested by electronic structure calculations using the [sp]^3 d^5 s^* atomistic tight-binding method11. In the case of a zincblende atomic lattice separated conduction 1S and 1P Dirac cones of considerable bandwidth (100 meV) are found, as well as dispersionless P-bands. This rich band structure is attributed to the absence of hybridisation of the 1S- and 1P-type nanocrystal wavefunctions. Moreover, for heavy-element compounds such as CdTe, strong intrinsic spin-orbit coupling opens a non-trivial gap at the P-type Dirac point, possibly leading to a quantum Spin Hall effect12,13.

We will also present the first experimental results dealing with the band structure (obtained by cryogenic STM) and the first carrier transport measurements (TRMC and field-effect transistors) in these systems. In the last part of the lecture, we will discuss possible applications of these high-mobility systems in single-photon detection and photovoltaic cells.

8981-6, Session 2

Group IV clathrates: synthesis, optoelectonic properties, and photovoltaic applications *(Invited Paper)*

Adele C. Tamboli, Aaron D. Martinez, Lakshmi Krishna, Lauryn L. Baranowski, Mark T. Lusk, Eric S. Toberer, Colorado School of Mines (United States)

Although Si dominates the photovoltaics market, only two forms of Si have been thoroughly considered: amorphous Si, and Si in the diamond structure (d-Si). Silicon can also form in other allotropes, including clathrate structures. Silicon clathrates are inclusion compounds which consist of a Si framework surrounding templating guest atoms (e.g. Na). After formation of the type II Na24Si136 clathrate, the guest atoms can be removed (Si136), and the material transitions from degenerate to semiconducting behavior with a 1.9 eV, direct band gap. This band gap is tunable in the range of 1.9 to 0.6 eV by alloying the host framework with Ge, enabling a variety of photovoltaic applications including thin film single junction devices, Si136 top cells on d-Si for all-Si tandem cells, and multijunction cells with varying Si/Ge ratios. In this work, we present electronic structure calculations showing the evolution of the direct transition as a function of Si/Ge ratio across the alloy range. We present the synthesis and characterization of type II Si/Ge clathrates spanning the whole alloy range. We also demonstrate a technique for forming Si clathrate films on d-Si wafers and sapphire substrates and optical characterization of these films. Finally, we discuss the challenges and successes in achieving extremely high purity Si clathrates suitable for optoelectronic applications.

8981-7, Session 2

New approaches for improving the photovoltaic performances of kesterite Cu2ZnSn(S,Se)4 thin film solar cells

Giovanni Altamura, CEA Grenoble (France) and Joseph Fourier Univ. (France); Louis Grenet, Charles Roger, Frederic Roux, CEA Grenoble (France); Valérie Reita, Institut NÉEL (France); Raphael Fillon, H. Fournier, S. Perraud, CEA Grenoble (France); Henri Mariette, CEA Grenoble (France) and Institut NÉEL (France) and Joseph Fourier Univ. (France)

Quaternary Cu2ZnSn(S,Se)4 (CZTSSe) compounds have attracted a lot of attention as promising absorber materials for thin film solar cells although the efficiency is not yet comparable with other thin film solar cell technologies. In the present work, two different approaches are explored to improve CZTSSe-based solar cell performances: (i) changing the back contact (BC) and (ii) introducing [S]/([S]+[Se]) ratio gradients in the CZTSSe absorber.

To the best of our knowledge, no experimental study has been carried out so far to test whether CZTSSe solar cells built on a BC other than Mo could exhibit better photovoltaic properties. For this purpose various metals (Au, W, Pd, Pt, Ni) are deposited as BC, and it is demonstrated that it is possible to synthesize device-quality CZTSSe thin films on W, Au and Pt back contacts. It is shown that that W and Au back contacts allow enhancing the photogenerated current, but that Mo remains the best back contact in terms of power conversion efficiency.

The effects of [S]/([S]+[Se]) ratio tuning on CZTSSe based solar cell performances are studied by solar cell capacitance simulator (SCAPS) to find out the optimum absorber composition. The simulations show that if the sulfur content is linearly decreased in the CZTSSe absorber from the back contact towards the buffer layer, then the power conversion efficiency can be increased by 5% (absolute) compared to the case of a homogenous absorber.

Based on these results, we propose that bandgap engineering based on the control of [S]/([S]+[Se]) ratio in the CZTSSe absorber is a powerful tool for improving the photovoltaic performances of CZTSSe-based solar cells.

8981-8, Session 2

Micrometric characterization methods of thin-film solar cells using luminescence emissions

Amaury Delamarre, Gilbert El-Hajje, Myriam Paire, Jean-François Guillemoles, Laurent Lombez, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France)

Spatial characterization methods allow a precise understanding of the solar cells mechanisms. Firstly, they enable to monitor the carriers transport properties. Secondly, for inhomogeneous absorbers, we get insight in the spatial variations of their properties. Fluctuations of minority carrier lifetimes and collection efficiencies are reported [1], and their influence on the cell efficiencies needs to be clarified. We record spectrally resolved photoluminescence (PL) and electroluminescence (EL) images, with spatial resolution below 2 µm, in order to investigate the cells properties. New analysis methods are presented, allowing a better understanding of the physical mechanisms.

The EL emissions are analyzed with the reciprocity relations [2,3], so that the spatial carrier collection efficiencies can be determined. Its variations with the voltage applied to the cell are investigated, and a good agreement was found with the photocurrent variations. A GaAs cell is characterized with this method, and application to CIGS cells is discussed.

Maps of the quasi-Fermi level splitting (qFls) are obtained from spectrally resolved images of CIGS PL fluxes. Good agreements are found between mean values and open-circuits voltages. However, we demonstrate that the qFls spatial fluctuations cannot be related to locally varying voltages. Comparison with EL images allows distinguishing variations of carrier lifetime properties and collection efficiencies.

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8981-9, Session 3

Upconverter materials and upconverter solar-cell devices: Simulation and characterization with broad solar spectrum illumination *(Invited Paper)*

Stefan Fischer, Benjamin Fröhlich, Fraunhofer-Institut für Solare Energiesysteme (Germany); Aruna Ivaturi, Heriot-Watt Univ. (United Kingdom); Barbara Herter, Sebastian Wolf, Fraunhofer-Institut für Solare Energiesysteme (Germany); Karl W. Krämer, Univ. Bern (Switzerland); Bryce S. Richards, Heriot-Watt Univ. (United Kingdom); Jan Christoph Goldschmidt, Fraunhofer-Institut für Solare Energiesysteme (Germany)

Upconversion of sub-band-gap photons has the potential to significantly increase the efficiency of solar cells. The radiative efficiency limit of silicon solar cells is enhanced due to upconversion from close to 30% up to more than 40%. With regard to silicon solar cells, especially lanthanide-doped materials are suitable upconverter materials, like the well-known hexagonal sodium yttrium fluoride (beta-NaYF4) doped with trivalent erbium (Er3+).

We investigate Er3+-doped beta-NaYF4 to determine the upconversion quantum yield under monochromatic laser and broad-band excitation as well as under solar concentration. These results are compared to our comprehensive rate equation model to describe the upconversion dynamics. This upconversion model considers all relevant upconversion processes and is based on experimentally determined Einstein coefficients of the beta-NaYF4 with 20% Er3+ doping. The line shape functions of all absorption and emission processes have been determined and incorporated into the model. Hence, the upconversion quantum yield under broad-band excitation, like for example the solar spectrum, can be modeled. Furthermore, we will discuss the potential of photonic structures to further enhance the upconversion quantum yield.

We characterized upconverter solar cell devices under monochromatic and broad-band excitation as well as under concentration of the solar spectrum. These devices were produced by attaching upconverter materials on the rear side of bifacial silicon solar cells. The light of a solar simulator was focused with a Fresnel lens on the upconverter solar cell devices and we determined an increase in the short-circuit current density due to upconversion of sub-band-gap photons of 13.1 mA/cm2 under a concentration of 210 suns.

8981-10, Session 3

Enhanced performance of up-conversion photovoltaic (UC-PV) devices via photonic crystals and plasmonic layers

Bryce S. Richards, Jose Marques-Hueso, Sean K. W. MacDougall, Heriot-Watt Univ. (United Kingdom); Karl W. Krämer, Univ. Bern (Switzerland); Jonathan A. S. Morton, Eliyas D. Mammo, Georgios E. Arnaoutakis, Aruna Ivaturi, Heriot-Watt Univ. (United Kingdom)

Up-conversion (UC) offers one route for overcoming the sub-bandgap losses experienced by single-junction solar cells and hence possibly overcoming the Shockley-Queisser limit for photovoltaic (PV) devices. There have been many papers examining the application of various UC materials to different solar cell systems, including c-Si, GaAs, and a-Si:H. For all of these PV technologies, erbium (Er3+) doped UC materials have played a crucial role due to their ability to UC sub-bandgap light into useful above bandgap light. For c-Si solar cells, the key Er3+ absorption window is 1480-1560nm, with energy transfer up-conversion (ETU) processes resulting in >97% of the above-bandgap emitted light coming from the 4I11/2?4I15/2 transition (980nm peak). For GaAs and a-Si:H devices, it is typically the sub-bandgap light in the range 900 – 1050nm that is UC on the Er3+ ion to green/red wavelengths, with this process performing even better once the system is co-doped with ytterbium (Er3+). While respectable monochromatic and broadband photoluminescent quantum yields are being reported, along with external quantum efficiencies and, more recently, short-circuit current densities, we are yet to see a real UC-PV device. The further realization of UC-PV devices is limited by the non-linear nature of the UC process and thus the relatively low efficiencies, as well as the narrow bandwidths over which Er3+ can weakly absorb and up-convert sunlight. This paper examines ways in which photonic crystals and plasmonic layers might help UC-PV devices overcome performance short-comings. The approaches discussed are also relevant for other spectral conversion technologies.

8981-11, Session 3

Cutoff wavelength optimization for high-efficiency split spectrum photovoltaics

Chandler Downs, Thomas E. Vandervelde, Tufts Univ. (United States)

Split spectrum photovoltaics, where incident light is divided onto multiple cells on the basis of wavelength, are an exciting recent development in the solar energy field. This technology has the potential to exceed record conversion efficiencies by utilizing a large number of active p-n junctions while mitigating the constraints that plague monolithic cells: lattice matching and current matching. Each cell in a split spectrum system can be designed to have a different lattice constant (allowing for more combinations of materials) and have different operating currents (allowing for more combinations of band spacing).

In this work, we examine a split spectrum system utilizing a single spectrum splitting device to divide the solar spectrum onto two cells. Whereas many split spectrum designs use numerous filters direct light onto single junction cells, in this system each cell is composed of multiple active junctions. Each cell is then tailored to absorb a portion of the solar spectrum. The combination of the two cells allows for five active junctions while maintaining lattice and current matching conditions in each cell.

A number of different cutoff frequencies for the dichroic filter are examined. Each cutoff frequency corresponds to its own combination of ideal band placements for both the shorter and longer wavelength cells. Designs for which it is to have both cells meet the lattice matching and current matching conditions are then simulated using TCAD Sentaurus. These devices are then are then grown by MBE, fabricated, and tested.

8981-12, Session 3

Interdependence of reabsorption and internal energy losses in luminescent solar concentrators

Jennefir Digaum, Stephen M. Kuebler, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

As a complementary device to photovoltaic (PV) cells, luminescent solar concentrators (LSCs) can reduce the cost of solar energy by replacing the expensive PV material with inexpensive energy-harvesting plastic or glass matrix. However, due to its low efficiency, LSCs are still not commercially viable. The low efficiency is due to the various losses associated with light harvesting and trapping. Most of these losses come from reabsorption and escape of re-emitted energy from the LSC device. State-of-the-art LSC technology focuses on decreasing reabsorption loss by employing lumophores with a large Stokes shift. But these materials typically have low quantum yield. Increasing the Stokes shift of the lumophore reduces reabsorption but introduces substantial loss due to low quantum yield and the Stokes shift of the re-emitted photons. The interdependence of these losses is studied computationally using a ray-tracing model that accounts for reabsorption, Stokes shift, escape cone loss, and matrix loss. It is shown that using high Stokes-shift lumophores does not give the highest energy efficiency. Higher energy efficiency is obtained by optimizing the Stokes shift. Even greater performance can be achieved by employing high-quantum-yield dyes with intermediate Stokes shift. LSC devices based on this approach could be nearly twice as efficient as those based on conventional lumophores, such as Rhodamine B.

8981-57, Session 3

Impact of light management on photovoltaic characteristics of GaAs solar cells with photonic crystals and quasi-photonic crystals

Tung-Ting Yang, National Chiao Tung Univ. (Taiwan); Yi-Chun Lai, National Chiao-Tung University Institute of Electro-Optical Engineering (Taiwan); Peichen Yu, Muming Hung, National Chiao Tung Univ. (Taiwan); Martin D. B. Charlton, Univ. of Southampton (United Kingdom)

In detailed balance model, the efficiency of single-junction solar cells can be potentially as high as 33% and 41% with concentrators under AM 1.5G illumination. However the best state-of-the-art devices are still lower than those figures, even the electronic quality is nearly perfect. Therefore the efficiency gap should stem from the light management inside solar cells. Recently, external radiation efficiency (ηext) derived from detailed balance model is emphasized to evaluate light management and photon recycling, which aggregates entirely the loss of backward emission and non-radiative recombination. This factor can be highly relevant to the cell's performance, especially open-circuit voltage (Voc), and maximizing Voc is generally considered as the last mile to approach ultra-high efficiency Shockley-Queisser limit (SQ limit). In this work, we try to assess rods and cones arranged in typical two-dimensional photonic crystals (PC) and quasi-photonic crystals (QPC) as top structure on solar cells. We not only simulate anti-reflection (AR) characteristics, but light extraction ability to improve ηext. The simulation tools are RCWA simulation and photon recycling model NREL developed. The results show that cones structure arranged in 12 folds symmetry (12F) QPC possesses extraordinary omni-directional AR even in all azimuthal angles. As for PC/QPC to improve light extraction, we find out that though PC/QPC structures can improve light extraction. The Voc enhancement is ~13 meV at most by the top structures we simulated, and it's not much dependent on the quality or back reflectivity of solar cells.

8981-13, Session 4

Ab-initio studies of nanoparticle photovoltaics: multiple-exciton generation, exotic core-phase nanoparticles, and complementary transport channels *(Invited Paper)*

Gergely T. Zimányi, Márton Vörös, Univ. of California, Davis (United States); Stefan Wippermann, Max-Planck-Institut für Eisenforschung GmbH (Germany); Guilia Galli, Univ. of California, Davis (United States)

We report extensive ab-initio studies of nanoparticles for photovoltaic applications. Molecular Dynamics methods are applied to determine the structures of Si and Ge nanoparticles, followed by Time-Dependent Density Functional Theory-based calculations to determine the optical spectra and exciton generation rates. (1) First, the Multiple Exciton Generation (MEG) rate is determined for Si nanoparticles up to sizes of 220 Si atoms. Strategies are explored to enhance the MEG rate, including the surface recombination that has the potential of lowering the gap substantially. (2) Another avenue to lower the gap is to employ exotic core phase Si nanoparticles. It is shown that the Si III/BC8 phase offers promisingly low gap values and it is proposed that the presence of this exotic phase has already been observed in laser-formed black-Si crystals. (3) Finally, Si and Ge nanoparticles embedded in ZnS matrices are explored. It is found that the band alignment that is strongly Type I in the bulk, can turn into Type II. Such band-alignment naturally separates the photo-excited electron hole pairs: the electrons remain localized on the nanoparticles and can transport by particle-particle tunneling, whereas the lower mobility holes get localized into the host matrix and form a complementary transport channel. The spatial separation of the two transport channels substantially suppresses the rate of carrier-recombination, enhancing the charge extraction rate for such devices. (4) A kinetic Monte Carlo work is then reported to directly model transport through these complementary transport channels. Several limits and trends will be analyzed.

8981-14, Session 4

Optical Phonon Decay In Cubic Semiconductors: A Hot Carrier Solar Cell Picture

Hugo Levard, Sana Laribi, EDF Recherche & Développement (France); Jean-François Guillemoles, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France)

Photovoltaic energy conversion yield is limited at first by the carriers thermalization. Indeed, after being photoexcited, the carriers reach the bottom of the conduction band in a picosecond range, cooled down through electron-(LO)phonon interaction. The electrogenerated hot phonons then decay in a few picoseconds range. One of the HCSC main challenges then is to find an absorber material in which the electro-emitted hot phonons has a relaxation time longer than the carriers cooling time, so that we can expect the electron to "reabsorb" a phonon, slowing down the electronic cooling. HCSC yield is ultimately limited by LO phonon decay, though.

In the present work, we present theoretical results obtained from ab initio calculations on III-V and IV-IV compounds describing the electronic and phononic band structure together with an accurate description of the two-phonon final states in the entire reciprocal space. In the particular case of zinc-blende-SiSn, the phonon lifetime due to three-phonon decay processes is found to be very long compared to most III-V and IV-IV semiconductors. It also turns to be very dependent on the phonon momentum, which is in contradiction with the usual "zone-center approximation" for LO-phonon decay process. In conclusion, we found that Si-Sn based compounds are very promising materials for the future of HCSC.

8981-15, Session 4

Hot-carrier solar cell spectral insensitivity: Why develop the hot carrier solar cell when we have multi-junction devices?

Louise C. Hirst, U.S. Naval Research Lab. (United States); Matthew P. Lumb, Raymond Hoheisel, The George Washington Univ. (United States); Simon Philipps, Andreas W. Bett, Fraunhofer-Institut für Solare Energiesysteme (Germany); Robert J. Walters, U.S. Naval Research Lab. (United States)

The fundamental limiting efficiency of single junction devices is dominated by the transmission and thermalization of low and high energy photons respectively. These dominant loss mechanisms are targeted in multi-junction and hot carrier device designs. These two high efficiency approaches have comparable limiting efficiency however, their prospects for practical implementation are very different. Substantial research efforts in multi-junction device development have yielded efficiencies >40%. By comparison, the hot carrier solar has never been experimentally demonstrated and significant challenges remain. Given the disparity of their relative stages of development one might question "Why develop the hot carrier solar cell when we have multi-junction devices?"

In this paper we use detailed balance simulations to calculate the material parameters required to produce a hot carrier solar cell with efficiency comparable to multi-junction devices. We identify the relative spectral insensitivity of hot carrier solar cells as a key motivation for investing in this development. The solar spectrum changes with location as well as seasonally and diurnally. We show that hot carrier solar cells are much less sensitive to these changes than multi-junction devices giving annual energy yields closer to peak power output as well as more efficient power production in the mornings and evenings. We also show that a hot carrier device which is optimized for one location will operate close to optimally in a variety of locations with very different atmospheric conditions, unlike the highly location dependent performance of multi-junction devices.

8981-16, Session 4

Hot-carrier solar cell absorbers: materials, mechanisms, and nanostructures

Gavin Conibeer, The Univ. of New South Wales (Australia)

The key property for a hot carrier absorber is to slow the rate of carrier cooling from the picosecond timescale to at least 100s of ps, but preferably ns to be similar to the rate of radiative recombination. Hot carriers cool primarily by emission of LO phonons. The general properties of phonons and carriers required of a hot carrier absorber have been defined. Materials and structures that exhibit some of these properties fall into two categories:

(a) Slowed cooling has been observed in some III-V compounds in which there is a large difference in atomic mass. This has been shown in slowed carrier cooling for InN and for slower carrier cooling in InP compared to the small mass ratio GaAs.

(b) Low dimensional multiple quantum well (MQW) systems have also been shown to have lower carrier cooling rates. This has been seen in various lattice matched MQW systems and more recently in strain balanced MQWs in which barrier height and well width affect the temperature.

Hafnium nitride and zirconium nitride have been grown by sputtering and atomic layer deposition. Preliminary results on their measured phonon dispersions and rates of carrier cooling will be presented. These tentatively indicate large gaps in the phonon dispersion appropriate to block optical phonon decay and also show that material quality is of great importance in order to allow slowing of carrier cooling. Work will also be presented on multiple quantum well materials grown by collaborators. These have been measured with time resolved photoluminescence to measure carrier cooling rates and do indeed show longer carrier cooling rates than bulk materials.

8981-17, Session 4

Understanding the evolution of the biexciton quantum yield in "giant" CdSe/CdS colloidal nanocrystals as a function of the core size and shell thickness

Sid Sampat, The Univ. of Texas at Dallas (United States); Benjamin Magnum, Yagnaseni Ghosh, Han Htoon, Jennifer A. Hollingsworth, Los Alamos National Lab. (United States); Anton V. Malko, The Univ. of Texas at Dallas (United States)

Semiconductor nanocrystal quantum dots (NQDs) have long being known to possess attractive photophysical properties, such as facile chemical preparation methods, tunability of emission wavelength, and high photoluminescence (PL) quantum yields (QY) of the excitonic (X) emission. Such useful properties make NQDs attractive for the large swath of applications, ranging from biological imaging [1] to light emitting diodes (LEDs) [2] to lasers quantum cryptography [3].

With an end goal to obtain photo stable dots with reliable PL properties, much research has gone into manufacturing blinking-free dots. A new type of core/shell NQDs in which a CdSe core is overcoated with especially thick (3-5 nm) multilayer CdS shell has been realized. Such multishell NQDs, dubbed giant (gNQDs) have shown high degrees of blinking suppression, with on-time fraction (NQD population that stays “ON” for more than 99% of time) in excess of 80% for CdSe/CdS gNQDs with d=3.8 nm cores and thick, >15 monolayer (ML) shells [5]. In addition to blinking suppression, gNQDs have shown considerably reduced Auger recombination rates, far beyond of what is expected from simple volume scaling model [6]. As a result of the suppressed Auger recombination, thick shell CdSe/CdS gNQDs exhibit high biexcitonic (BX) and higher-order (up to 5th) multiexcitonic (MX) quantum yields (QY) to the level allowing spectroscopic visualization of MX PL signatures [7].

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8981-18, Session 5

Silicon tandem solar cells: The ultimate photovoltaic solution? *(Keynote Presentation)*

Martin A. Green, The Univ. of New South Wales (Australia)

The recent dramatic cost reduction in silicon cell technology has made this technology even more difficult to displace. Commercial cell efficiencies will steadily approach the 25% laboratory performance level demonstrated in the author’s group. The availability of cheap, increasingly high quality silicon wafers suggests a possible evolutionary path whereby these are used as substrates for high performance silicon-based tandem cells with efficiency levels potentially as high as 40%. Possible approaches and results to date will be outlined.

8981-19, Session 5

Optical requirements for >30% tandem solar cells built on crystalline silicon

Niraj N. Lal, Thomas P. White, Kylie R. Catchpole, The Australian National Univ. (Australia)

Industrial silicon solar cells are rapidly approaching the 25% laboratory cell efficiency record that has stood for over 15 years. Leveraging the success of c-Si solar cells, one approach to go beyond 25% is to utilise high-bandgap earth-abundant semiconductors in top tandem cells placed above an underlying silicon cell. To achieve efficient tandem solar cells based on such materials, it is important to understand the effect of optical design on device performance.

Applying a simple analytical model, we present key photonic engineering principles for light distribution in these devices. The parasitic light absorption of two transparent conducting layers is found to require top-cell efficiencies greater than 15% to achieve a break-even tandem efficiency of 25%. Low-pass intermediate reflectors are observed to be detrimental to tandem performance, and single-pass absorption is identified to be preferable to Lambertian light trapping mechanisms that introduce typical optical losses. Design principles are quantified with detailed Figure of Merit calculations, and simple light trapping mechanisms are proposed that distribute light effectively across the tandem cell. Applying these principles to a top cell characterized by strong absorption and poor electronic quality – typical characteristics of low-cost earth-abundant semiconductors – we show that tandem efficiencies greater than 30% are possible using thin film absorbers in a top cell with carrier diffusion lengths of 100nm and luminescence efficiencies of 10^-5.

8981-20, Session 5

Advances in III-V/active-silicon multijunction photovoltaics for high efficiency *(Invited Paper)*

Steven A. Ringel, Tyler J. Grassman, John A. Carlin, Christopher Ratcliff, Daniel J. Chmielewski, The Ohio State Univ. (United States); Stephen P. Bremner, Ibrahim Al-Mansouri, Martin A. Green, The Univ. of New South Wales (Australia); Elisa Garcia-Tabares, Ignacio Rey-Stolle, Carlos Algora del Valle, Univ. Politécnica de Madrid (Spain)

Recent advances in the nucleation of high-quality GaP layers, and improved subsequent GaAsP metamorphic growth, on Si by both metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) have opened a viable pathway for high performance III-V/active-Si multijunction PV devices in which optical access to the underlying Si is feasible. Realistic modeling shows that a 4-junction solar cell based on this architecture, using comparatively low-cost Si substrates, can achieve efficiencies exceeding 48% under concentration. However, this requires optimization of the III-V sub-cells in conjunction with the Si sub-cell, the practical design of which must account for ensuring an ideal surface to enable the sensitive GaP nucleation process, as well as maintaining the high PV quality of the underlying Si sub-cell/substrate. This presentation will describe the design and experimental progress toward achieving high performance III-V/active-Si multijunction photovoltaic materials and devices grown by both MOCVD and MBE from basic materials to multijunction cells. Comparative results obtained using both ex-situ (pre-processed) and in-situ (CVD reactor processed) approaches for active-Si junction formation beneath III-V solar cell growth will be discussed, as well as the impact of the III-V epitaxial processes on Si sub-cell performance. We will also discuss the subsequent growth of GaAsP-based metamorphic buffers and integrated 1.55 eV GaAsP and 2 eV GaInP sub-cells and multijunction structures and devices.

8981-21, Session 6

Modeling intermediate band solar cells: a roadmap to high efficiency *(Invited Paper)*

Jacob J. Krich, Univ. of Ottawa (Canada); Liang Feng, Nanjing Univ. (China); Alexandre W. Walker, Univ. of Ottawa (Canada)

Intermediate band (IB) photovoltaics have the potential to be highly efficient and cost effective solar cells. When the IB concept was proposed in 1997 [1], there were no known intermediate band materials. In recent years, great progress has been made in developing materials with intermediate bands, though power conversion efficiencies have remained low [2,3]. To understand the material requirements to increase IB device efficiencies, we must develop good models for their behavior under bias and illumination. To evaluate potential IB materials, we present a figure of merit, consisting of parameters that can be measured without solar cell fabrication. We present a new model for IB devices, including the behavior of their junctions with n- and p-type semiconductors. Using a depletion approximation, we present analytic approximations for the boundary conditions of the minority carrier diffusion equations. We compare the analytic results to Synopsys Sentaurus device models.

We use this model to find the optimal thickness of the IB region based on material parameters. For sufficiently poor IB materials, the optimal thickness is zero – i.e., the device is more efficient without the IB material at all. We show the minimum value of the figure of merit required for an IB to improve the efficiency of a device, providing a clear goal for the quality of future IB materials.

8981-22, Session 6

Simulation of an intermediate-band solar cell comprising superlattices of electronically-mismatched semiconductor alloys

Alexandre Freundlich, Akhil Mehrotra, Liberty Falcon, Univ. of Houston (United States)

In this work we evaluate an intermediate band solar cell design, wherein a superlattice comprising lattice-matched layers of electronically mismatched GaAsSbN and thin barriers of AlGaAs is inserted within the intrinsic region of an AlGaAs p-i-n diode. In the proposed design the upper conduction band of GaAsSbN is maintained in resonance with the barrier conduction band of host material to promote an efficient extraction of electrons whereas the 3D nature of the this band favors a strong intermediate (superlattice fundamental miniband)- to band second photon absorption. In this design carriers can be promoted either directly to the conduction band or via the intermediate band, permitting the absorption of low energy photons whilst maintaining a high cell voltage. To attain the necessary combination of high and low bandgaps and low dislocation density, we use materials that are lightly strained or lattice-matched to an GaAs (or Ge) substrate. GaAsN (Sb) quantum well layers are incorporated into direct bandgap low Al content (x<30%)) AlGaAs host material, to attain high bandgaps of 1.8- 1.9 eV, and low-energy bandgaps of 1-1.2 eV. Detailed balance evaluation of the proposed device that incorporates calculation of the absorption properties of the SL region suggests potential for AM0 efficiency in excess of 38% (and AM1.5 efficiency >52% under 1000X concentration). Device design parameters are also further optimized using a drift diffusion code toward achieving >30% AM0 End of life efficiencies for typical 1 MeV electron fluence in excess of 1015cm-2.

8981-23, Session 6

Imaging quasi fermi level splitting in intermediate-band solar cells

Jean-François Guillemoles, Laurent Lombez, Amaury Delamarre, Gilbert El-Hajje, Pierre Rale, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France); Kentaroh Watanabe, Masakazu Sugiyama, Yoshitaka Okada, Ryo Tamaki, Yasushi Shoji, The Univ. of Tokyo (Japan)

Various MQW and MQD containing pin diodes have been grown on GaAs substrates, along with a control GaAs diode, otherwise similar. Dots and wells were placed within the i region . Measurements by PL at performed under different excitation power and wavelength (to separate excitation in the wells from that in the barriers), will be compared to electroluminescence measurements made at various injection levels, all of them at room temperature. These luminescence experiments are made by an imaging spectrometer meaning that both spatial and spectral information can be obtained from the data, from which the quasi Fermi level splitting can be obtained accurately, as previously shown.

This paper will present our findings as to how much QFL splitting can be obtained in such heterostructures, and about the magnitude of the IBSC effect that can be achieved.

8981-24, Session 6

InAs/AlAsSb self-assembled quantum dots for next-generation solar cells *(Invited Paper)*

Ramesh Babu Laghumavarapu, Meng Sun, Baolai L. Liang, Paul J. Simmonds, Diana L. Huffaker, Univ. of California, Los Angeles (United States)

For the last decade, quantum dots (QD) have been explored for next generation high-efficiency solar cells. Though intermediate band solar cell (IBSC) theory predicts over 63% energy conversion efficiency, no practical QD system with high efficiency has been demonstrated, mainly due to the use of materials with inappropriate band gaps and band alignments. In this work we have investigated type II InAs QDs in AlAsSb barriers on InP substrates with close-to-ideal band gaps and alignments for IBSC applications. We have also studied the effects of different cladding schemes on the optical and structural properties of the InAs/AlAsSb QDs. We demonstrate an optimized cladding scheme for this self assembled QD (SAQD) system that has GaAs under the SAQDs and GaAsSb as the capping layer. This scheme results in improved dot morphology and significantly increased photoluminescence intensity. Solar cells devices fabricated with QDs and cladding layers are compared with control cells containing no QDs. AlAsSb solar cells with InAs QDs show extended photo response beyond the AlAsSb band gap (up to 1.8 microns), the longest response observed to date in a QD solar cell. A device containing only the cladding layers shows response up to 1.1 microns. Low temperature quantum efficiency measurements are performed in presence of secondary infrared light to study two-photon absorption in InAs/AlAsSb QD solar cells.

8981-25, Session 7

Modeling space radiation effects in multijunction solar cells *(Invited Paper)*

Scott R. Messenger, U.S. Naval Research Lab. (United States)

Ground irradiation testing primarily uses monoenergetic particles at normal incidence to the material or device of interest. In a space environment, however, the radiation environment is considered to be an omnidirectional energy spectrum and the devices are protected by some shielding. The question then arises as to the relevance of current ground testing methods. This paper will present some Monte Carlo transport analyses using omnidirectionally incident energy spectra of protons and electrons on shielded devices representative of present day practices for space solar arrays. The results will shed some light on how to design ground testing methods to provide a better match to the expected environment.

8981-26, Session 7

Increased radiation tolerance in thin IMM solar cells using back reflection

Akhil Mehrotra, Alexandre Freundlich, Univ. of Houston (United States)

In this work, within the framework of 4J-IMM solar cell material system, efficiencies as function of the combined effects of dislocation densities, radiation doses (1 MeV equivalent electrons) and device emitter and base design have been computed and, it is shown that by implementing an appropriate design the efficiencies for space solar cells can be significantly improved. The irregular radiation degradation behavior in 4-junc IMM is also explained by use of thinner 0.7ev sub-cell than 1.0ev sub-cell, due to the back photon reflection from gold contacts. Optimization of device design of IMM solar cell would also relax the need for having low defect densities as the performance of the cell would be

controlled by space radiation. Hence use of thin sub-cells and presence of high dislocation densities (with more dislocation tolerance) due to thin graded buffer would result in less material usage and faster growth times, thus significantly reducing the solar cell cost, without having any effect on efficiency of space solar cells.

8981-27, Session 7

Degradation modeling of InGaP/GaAs/Ge triple-junction solar cells irradiated by protons

Sergey I. Maximenko, U.S. Naval Research Lab. (United States); Matthew P. Lumb, The George Washington Univ. (United States); Scott R. Messenger, U.S. Naval Research Lab. (United States); Raymond Hoheisel, The George Washington Univ. (United States); Chaffra A. Affouda, David Scheiman, U.S. Naval Research Lab. (United States); Maria Gonzalez, Sotera Defense Solutions, Inc. (United States); Justin R. Lorentzen, Phillip P. Jenkins, Robert J. Walters, U.S. Naval Research Lab. (United States)

III-V-based triple-junction (3J) solar cells grown on Ge substrates are the primary leaders in space photovoltaic technology due to their high efficiency (~30%). However, a primary concern is a degradation of the end-of-life performance due to electron and proton irradiation. In this work, modeling of the degradation of 3J cells subjected to proton irradiation with high damage doses up to 2E13 MeV/g is presented. The diffusion length of minority carriers and the position of the junction regions were experimentally determined by the electron beam induced current (EBIC) mode of scanning electron microscopy (SEM) for different radiation-induced degradation levels. Based on the experimentally obtained data for the minority carrier transport properties, we used the NRL MultiBandsTM software package, consisting of both numerical and analytical drift-diffusion solvers, to explain and verify the experimental quantum efficiency and light current-voltage characteristics for different degradation levels. Also, we discuss the quantum efficiency degradation behavior of each sub-cell on the basis of majority carrier removal mechanism and type conversion.

8981-28, Session 7

Enhancement of radiation tolerance with the use of a doping superlattice solar cell

Michael A. Slocum, Seth M. Hubbard, David V. Forbes, Rochester Institute of Technology (United States)

Doping superlattice devices have the ability to minimize the impact of shorter diffusion lengths with the use of multiple parallel connected junctions. Experimental results have shown that doping superlattice devices can have a remaining factor for efficiency of 101% at a beta particle dose of 2x10^15 /cm^2 while the conventional pin design used for comparison had a remaining factor of 65% at half the dose. The doping superlattice devices have 25 homojunctions with doped layer thicknesses of 50 nm which reduces the required diffusion length to capture photo-generated carriers as compared to the pin design with a 500 nm emitter and 2μm base. Increases in current at doses higher than 4x1014 /cm2 have also been seen, which is expected to be related to the intrinsic region becoming slightly p-type due to carrier removal. Slight reductions in VOC were seen at doses higher than 4x10^14 / cm^2, which is to be expected due to the multiple junctions contributing to dark current in the device, however the reduction was much smaller than expected and requires further study. In a study of grid design higher remaining factors were seen in doping superlattice devices that had closer grid finger spacing, which is expected to be related to series resistance in the 50 nm thick lateral conducting layers. Additional testing will be completed to evaluate alternate doping superlattice designs to understand the tradeoff between beginning and end of life efficiency.

8981-29, Session 7

Conductive-space solar-cell coverglass replacement technology

David M. Wilt, Zach S. Levin, Air Force Research Lab. (United States)

No Abstract Available

8981-31, Session 8

Experimental demonstration of a self-tracking solar concentrator

Volker Zagolla, Eric J. Tremblay, Christophe Moser, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

The state-of-the-art concentrators use free-space optics to concentrate sunlight onto photovoltaic cells. To achieve high concentration factors it is necessary to track the sun's position. In current systems, mechanical actuators keep the focal spot in the solar cell. Planar concentrators have recently emerged, which use a waveguide slab to concentrate the sunlight. Here we demonstrate the development of a phase-change actuator (PCA) for self-adaptive tracking. The demonstrated mechanism is light-responsive and provides self-adaptive light concentration in a planar waveguide while maintaining efficient concentration over an angular range of +/- 20 degrees. The proposed system consists of a lens array to focus the sunlight, a waveguide slab acting as a concentrator, a dichroic prism membrane, splitting the solar spectrum into a visible (VIS) and infrared (IR) part, and the phase-change actuator. The actuator undergoes a phase change upon absorption of the IR light and vertically expands, creating a coupling feature upon contact with the waveguide. Visible light is then reflected off the prism membrane and efficiently coupled into the waveguide. As the focus spot moves, so does the coupling feature due to the light responsiveness of the actuator. We show an experimental proof-of concept prototype, highlighting the desired features of the concept. This is then further expanded by simulations of a full system achieving high effective concentrations (>100X) and first experimental results expanding the prototype to a full system.

8981-32, Session 8

Design of sub-wavelength dielectric antireflective grading for multijunction concentrator photovolatics

Wei Wang, Alexandre Freundlich, Univ. of Houston (United States)

In III-V concentrator applications, sunlight is focused with wide angular distribution. Furthermore the transmission properties generally degrades non-uniformly over the electromagnetic spectrum, which in the case of multi-junction solar cells leads to additional sub-cell current matching related losses. Here, in an attempt to identify a better alternative to the conventional 2-layer ARCs, a systematic analysis of design parameters and angular dependent anti-reflective properties of dielectric grating formed through the implementation of sub-wavelength arrays of 1D rectangle binary grating, 2D pyramidal, and hemispherical textures have been modeled through thin film model by using effective medium approximation. The study includes evaluation of these properties for several common dielectrics i.e. SiO2, TiO2, and ZnS through a careful selection of dielectric material and design. These structures can significantly surpass the performance of planar double layer ARCs (i.e.

MgF2/ZnS), and the total number of reflected photons over 380-2000 nm wavelength range can be reduced to less than 2%, i.e. on a 0.67 eV semiconductor, by use of single material textured dielectric. It is also shown that the implementation of these structures for a typical concentrated 3 or 4 junction solar cell with aperture angles ranging from 0-60 degrees, reduces reflected photon losses for each sub-cell to less than 4%, hence reduce current degradation. The study indicated limited improvement for devices operated with SiO2 like cover glass. In the absence of SiO2 like cover glass, the evaluation indicated that reflection-loss related current losses can be reduced by 2-3 fold compared to their double-layer ARC counterparts. i.e. for a 3J metamorphic device this lead to a current improvement of 0.7 mA/cm2per X concentration for a 60 degree aperture angles.

8981-33, Session 8

Cu(In,Ga)Se2 mesa microdiodes: study of edge recombination and behaviour under concentrated sunlight

Myriam Paire, Cyril Jean, Laurent Lombez, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France); Stéphane Collin, Jean-Luc Pelouard, Lab. de Photonique et de Nanostructures (France); Daniel Lincot, Jean-François Guillemoles, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France)

In order to develop photovoltaic devices with increased efficiency using less rare semiconductor materials, the concentrating approach was applied on Cu(In,Ga)Se2 thin film devices. Thanks to the miniaturization of the devices, ultrahigh fluxes can be studied (> ?1000) [1,2]. Compared to previous generation of devices with only a structuring of the window layer with intact absorber, new Cu(In,Ga)Se2 microcells with a mesa design are fabricated.

We analyse the influence of different etching techniques on the edge recombination signal. It is found that bromine etch result in well passivated surfaces, and devices as small as 50x50 μm do not experience edge recombination efficiency limitations. This is behaviour is remarkable compared to that of microcells made of crystalline materials. For devices where the edges are deteriorated by a chemical post-treatment, a quasi-shunting signal is seen, which is similar to what is known on crystalline cells [3]. We tested these microcells under concentrated illumination and important Voc and efficiency gains are seen. In order to compare the mesa design to microcell without absorber structuring, and isolate the role of the edge surfaces, cartographic characterizations such as EL, LBIC and EBIC are performed.

Cu(In,Ga)Se2 mesa diodes prove to be appropriate for a use under concentration, leading to significant gains in terms of efficiency and material usage.

[1] Paire et al, Appl. Phys. Letters, 98, 26, 264102 (2011)

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8981-34, Session 9

Small molecule organic solar cells: from molecules to devices *(Keynote Presentation)*

Karl Leo, Technische Univ. Dresden (Germany)

Organic solar cells have recently achieved enormous progress and have crossed the 10% efficiency mark. For a broad application, further significant improvements are still needed. In this presentation, I will discuss recent work on small-molecule organic solar cells. One central research area is the design of suitable molecules which form the bulk heterojunction active layer, requiring a nanoscale phase separation and optimized morphology to achieve efficient operation. A key challenge of the field is to find design rules which relate the molecular structure of absorber materials to layer morphology and cell properties. The difficulty is that small changes of the molecular structure, leaving the electronic properties of the individual molecule nearly unchanged, can lead to large changes in the crystal packing and molecular orientation, causing significant differences in the electronic properties in the active layer. Furthermore, I will discuss highly efficient tandem structures with optimized electrical and optical properties. Very efficient recombination contacts can be realized by n- and p-type doped transport layers. Structures based on these approaches have reached efficiencies of 12% and have the potential to reach approximately 20%. Furthermore, these high-efficiency cells also show already reasonable lifetimes.

8981-35, Session 9

Ag nanoparticle-blended plasmonic organic solar cells: performance enhancement or detraction?

Tze Chien Sum, Bo Wu, Nripan Mathews, Nanyang Technological Univ. (Singapore)

Incorporation of organic ligand encapsulated plasmonic nanoparticles in the active layer of bulk heterojunction organic solar cells is a relatively quick and easy light trapping approach. However, there has been much controversy over the reports of enhancement and detraction in performance of the devices. Herein, through comprehensive transient optical spectroscopy and electrical measurements, we uncover evidence of traps responsible for performance degradation in plasmonic organic solar cells fabricated with oleylamine-capped silver nanoparticles blended in the poly (3-hexylthiophene): [6,6]-phenyl-C 61-butyric acid methyl ester active layer. [1] Despite an initial increase in exciton generation promoted by the presence of silver nanoparticles, transient absorption spectroscopy revealed no increase in the later free polaron population – attributed to fast trapping of polarons by nearby nanoparticles. The increased trap-assisted recombination is also reconfirmed by light intensity dependent electrical measurements. These new insights into the photophysics and charge dynamics of plasmonic organic solar cells would resolve the existing controversy and provide clear guidelines for device design and fabrication.

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8981-36, Session 9

Directed energy transfer through size-gradient nanocrystal layers into Si substrates

Michael Nimmo, Louis Caillard, William deBenedetti, Hue M. Nguyen, Yves J. Chabal, Yuri Gartstein, Anton V. Malko, The Univ. of Texas at Dallas (United States)

Nanostructured materials attract great interest as candidates for next generation of photoelectronic devices. Presently, the majority of hybrid devices are based on charge transfer in which exciton break-up occurs at the interface between dissimilar materials. Poor interface quality and carrier transport are issues that result in a conversion efficiencies lower than in the inorganic crystalline devices. An alternative approach is based on hybrid structures, which combine strongly absorbing components such as nanocrystal quantum dots (NQDs) and adjacent high-mobility semiconductor layers coupled via proximal energy transfer. Building on our previous work1, we examine non-radiative energy transfer (NRET) between NQDs grafted on a hydrogenated Si surface via amine modified carboxy-alkyl chain linkers. A macroscopically thick, size–gradient NQD film is prepared on top of crystalline Si layer to explore directed energy tranfer into the substrate. Steady-state and time-resolved

photoluminescence studies show effective energy transfer between adjacent layers and into the Si substrate with the transfer efficiency exceeding 90% among layers. This demonstrates the viability of NQD-Si hybrid structures for photovoltaic devices.

1 H. M. Nguyen et al., APL 98, 161904 (2011)

8981-37, Session 9

Hybrid bulk heterojunction solar cells based on low-band-gap polymers and CdSe nanocrystals

Sergey V. Dayneko, National Research Nuclear Univ. MEPhI (Russian Federation); Alexey R. Tameev, Marine G. Tedoradze, A.N. Frumkin Institute of Physical Chemistry and Electrochemistry (Russian Federation); Igor L. Martynov, Pavel Linkov, Pavel S. Samokhvalov, National Research Nuclear Univ. MEPhI (Russian Federation); Igor R. Nabiev, Univ. de Reims Champagne-Ardenne (France) and National Research Nuclear Univ. MEPhI (Russian Federation); Alexander A. Chistyakov, National Research Nuclear Univ. MEPhI (Russian Federation)

Solar energy converters based on organic semiconductors are inexpensive, can be layered onto flexible surfaces and show great promise for photovoltaics. In bulk heterojunction polymer solar cells, charges are separated at the interface of two materials, the electron donor and acceptor. Typically, only the donor effectively absorbs light. Therefore, the use of acceptors with wide absorption spectra and high extinction coefficients and charge mobilities should increase the efficiency of bulk heterojunction polymer solar cells. Semiconductor nanocrystals (quantum dots and rods) are good candidate acceptors for these solar cells. Recently, most progress in the development of bulk heterojunction polymer solar cells was achieved using PCBM, a traditional fullerene acceptor, and two low band gap polymers, poly[N-9'-heptadecanyl-2,7-carbazole-alt-5,5-(4',7'-di-2-thienyl-2',1',3'-benzothiadiazole)] (PCDTBT) and poly[[4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-b:4,5-b']dithiophene-2,6-diyl][3-fluoro-2-[(2-ethylhexyl)carbonyl]thieno[3,4-b]thiophenediyl]] (PTB7). Therefore, the possibility of combining these polymers with semiconductor nanocrystals deserves consideration.

Here, we present the first comparison of the solar cells based on PCDTBT and PTB7, where CdSe quantum dots serve as acceptors. We have found that PTB7-based cells are more efficient than that made with PCDTBT. The efficiency strongly depends on the nanocrystal size. An increase in QD-diameter from 5 to 10 nm causes a more than fourfold increase in the cell efficiency. This is determined by the relationship between the nanoparticle size and energy spectrum and clearly demonstrates how the mutual positions of the donor and acceptor levels affect the solar cell efficiency. These results will help to develop novel, improved nanohybrid components of solar cells based on organic semiconductors and semiconductor nanocrystals.

8981-38, Session 10

Analytical modeling of III-V solar cells close to the fundamental limit *(Invited Paper)*

Matthew P. Lumb, U.S. Naval Research Lab. (United States); Myles A. Steiner, John F. Geisz, National Renewable Energy Lab. (United States); Robert J. Walters, National Renewable Energy Lab. (United States) and U.S. Naval Research Lab. (United States)

A highly effective strategy of photon management is to use a back surface reflector (BSR). Reflecting the incident photons from the rear surface of the absorber enhances the absorption, allowing thinner absorber layers. This enables lower dark current and improved carrier collection, and also allows higher doping concentrations to be employed, promoting the dominance of radiative recombination. Another important contribution from the BSR is to recycle the photons emitted by the absorber layers under operation. Photon recycling leads to an increase in the external luminescent efficiency, the fraction of internally radiated photons that are able to escape through the front surface, which, in a device limited by radiative recombination, results in a larger open circuit voltage.

Modeling the effect of a BSR has been attempted by numerous authors using numerical approaches. However, III-V solar cells can also be accurately and efficiently simulated using an analytical approach. In this work, we present a full analytical model incorporating effects from both the modified generation function and photon recycling in GaAs solar cells. We discuss the impact of doping concentration, non-radiative recombination, the solar cell dimensions and the BSR reflectivity on the conversion efficiency, and compare the prediction of the device models to experimental data measured on GaAs devices. This analytical tool is of practical importance for simulating a wide variety of materials for high-efficiency solar energy conversion and we use the model to predict the performance of alternative III-V materials, such as InP, comparing the predicted performance to state-of-the-art GaAs solar cells.

8981-39, Session 10

Electrical and optical modeling of an amorphous silicon solar cell with a graded intrinsic layer and a periodically corrugated metallic back reflector

Tom H. Anderson, The Univ. of Edinburgh (United Kingdom); Muhammad Faryad, The Pennsylvania State Univ. (United States); Tom G. Mackay, The Univ. of Edinburgh (United Kingdom); Akhlesh Lakhtakia, The Pennsylvania State Univ. (United States)

Electrical and optical properties of a thin film solar cell made of alloys of amorphous silicon were studied theoretically. The solar cell was backed by a periodically corrugated metallic back reflector. The intrinsic layer of the solar cell was taken to be nonhomogeneous normal to the metal/semiconductor interface. The nonhomogeneous intrinsic layer may trap the incident light better than a homogeneous layer and increase the generation rate of charge carriers. The periodically corrugated metallic back reflector can excite surface plasmon-polariton waves as well as bulk waveguide modes. The nonhomogeneity in the semiconductor was supposed to result from the nonhomogeneity in the composition of the amorphous silicon. The generation rate of electron-hole pairs was computed using the rigorous coupled-wave approach and the drift-diffusion model was used for the computation of the current-voltage characteristics of the cell. Only the Auger recombination in the amorphous silicon was considered. The photovoltaic efficiency of the solar cell was computed as a function of the incidence angle by assuming an AM1.5 solar irradiance spectrum.

8981-58, Session 10

Factors limiting the efficiency of laser power converters under low- and high-intensity illumination

Jayanta Mukherjee, Scott Jarvis, Tom Wilson, Univ. of Surrey (United Kingdom); Matthew Perren, EADS Astrium (France); Stephen J. Sweeney, Univ. of Surrey (United Kingdom)

We have developed III-V based high-efficiency photovoltaic converters (PVs) for conversion of monochromatic laser radiation at 1.55 μm

into electrical energy. These dedicated PVs or laser power converters (LPCs) find applications in fibre-optic or free-space terrestrial- and space-based laser power transfer, remote powering of subcutaneous equipment etc. The LPC design is based on a bulk InGaAsP/InP structure with elements for photon-recycling and efficient carrier extraction. The LPC achieves a maximum conversion efficiency of 45±1 % at 1kW/m2 (1.55μm illumination). At illumination intensities beyond 1 kW/m2, a conversion efficiency droop is observed. In order to further understand the underlying physics and scale the efficiency at higher illumination intensities in our next generation LPC design, we have performed intensity-, temperature- and incident wavelength- (absorber wavelength tracked) dependent characterization of the LPCs. In addition, we have measured the temperature dependent electroluminescence from the LPC. Comparing the experimental results with a detailed theoretical model, we separate the intensity regime where Auger-recombination takes over the defect (Shockley-Read-Hall) recombination as the dominant non-radiative recombination mechanism limiting the conversion efficiency of the LPC. Together with a series resistance induced thermal load, we show that non-radiative recombination plays a significant role in limiting the efficiency of the LPC at higher illumination intensities. As the LPC forms an excellent prototypical system for probing fundamental efficiency limits of PVs, our comprehensive study gives useful insights into the design and material improvements required for conversion efficiency scaling in future solar cells, for applications under normal as well as concentrated illumination.

8981-40, Session 11

Modeling, design, and experimental results for high-efficiency multi-junction solar cells lattice matched to InP *(Invited Paper)*

Maria Gonzalez, Sotera Defense Solutions, Inc. (United States) and U.S. Naval Research Lab. (United States); Matthew P. Lumb, The George Washington Univ. (United States); Michael K. Yakes, U.S. Naval Research Lab. (United States); Christopher G. Bailey, U.S. Naval Research Lab. (United States) and National Research Council (United States); Joseph G. Tischler, Igor Vurgaftman, U.S. Naval Research Lab. (United States); Louise C. Hirst, U.S. Naval Research Lab. (United States) and National Research Council (United States); Joshua Abell, Jerry R. Meyer, U.S. Naval Research Lab. (United States); Jessica G. J. Adams, Glen Hillier, MicroLink Devices, Inc. (United States); David V. Forbes, Seth M. Hubbard, Rochester Institute of Technology (United States); Nicholas J. Ekins-Daukes, Imperial College London (United Kingdom); Robert J. Walters, U.S. Naval Research Lab. (United States)

The high conversion efficiencies demonstrated by multi-junction solar cells over the past three decades have made them indispensable for use in space and are very attractive for terrestrial concentrator applications. The multi-junction technology consistently displays efficiency values in excess of 30%, with record highs of 37.8% under 1 sun conditions and 44% under concentration. However, as the material quality in current III-V multi-junction technology reaches practical limits, more sophisticated structures will be required to further improve on these efficiency values. In a collaborative effort amongst the US Naval Research Laboratory, Imperial College London, Microlink Devices, and Rochester Institute of Technology, we have developed a novel MJ solar cell design that has the potential to approach 50% conversion efficiency. This invited talk will describe the modeling effort, the MJ cell design and our most recent experimental results in each of the individual subcells.

Our design consists of a three junction cell grown on InP in which the optimal bandgaps for solar energy conversion can be attained while the multi-junction structure is maintained under lattice matched conditions. For the top cell, InAlAsSb quaternary material is currently being developed. For the middle, InGaAlAs and InGaAsP materials and devices are compared. For the bottom, an InGaAs cell is demonstrated and the possibility of adding multiple quantum wells for fine bandgap tunability is presented. In addition, we discuss the design and characterization of the tunnel diodes required for the electrical connection of the sub-cells within the multijunction device.

8981-41, Session 11

Ga-rich Ga(x)In(1-x)P solar cells on Si with 1.95 eV bandgap for ideal III-V/Si photovoltaics

Christopher Ratcliff, Tyler J. Grassman, The Ohio State Univ. (United States); John A. Carlin, The Ohio State Unv. (United States); Daniel J. Chmielewski, Steven A. Ringel, The Ohio State Univ. (United States)

Theoretical models for III-V compound multijunction solar cells show that solar cells with bandgaps of 1.95-2.3 eV are needed to create ideal optical partitioning of the solar spectrum for device architectures containing three, four and more junctions. For III-V solar cells integrated with an active Si sub-cell, GaInP alloys in the Ga-rich regime are ideal since direct bandgaps of up to ~ 2.25 eV are achieved at lattice constants that can be integrated with appropriate GaAsP, SiGe and Si materials, with efficiencies of almost 50% being predicted using practical solar cell models under concentrated sunlight.

Here we report a comparative study of single junction Ga-rich (~1.95 eV) GaInP solar cells grown on GaAs, GaP, and Si substrates. Excellent carrier collection efficiency was measured via internal quantum efficiency measurements and with their design being targeted for multijunction implementation (i.e. they are too thin for single junction cells), initial cell results are encouraging with efficiencies for these large bandgap, thin single junction cells ranging from 7% on Si to 11% on GaAs without antireflection coatings, systematically tracking the change in defect density as a function of growth substrate. The performance metrics are close to what is modeled for the state of the technology and details will be discussed. Currently, GaInP materials with bandgaps of 2.0 - 2.1 eV, grown on Si, are also being investigated, and we anticipate discussing a systematic study of carrier lifetime and transport properties of GaInP as a function of bandgap, composition and dislocation density.

8981-42, Session 11

Detailed physics based modeling of triple-junction InGaP/GaAs/Ge solar cell

Alexandre I. Fedoseyev, Timothy Bald, Ashok Raman, CFD Research Corp. (United States); David V. Forbes, Seth M. Hubbard, Rochester Institute of Technology (United States); Alexandre Freundlich, Univ. of Houston (United States)

We have developed a detailed 3D TCAD model of a triple-junction photovoltaic (TJ PV) cell, and calibrated the various physical parameters to match experimental data, such as dark and light JV.

A detailed model of triple-junction InGaP/GaAs/Ge solar cell has been developed and implemented in CFDRC's NanoTCAD simulator. The model schematic, materials, layer thicknesses, doping levels and meshing are discussed. This triple-junction model is based on the experimental measurements of a Spectrolab triple-junction cell by [1] with material layer thicknesses provided by Rochester Institute of Technology [2].

This model of the triple-junction solar cell is primarily intended to simulate the external quantum efficiency (EQE) of a physical cell. Simulation results of light JV characteristics and EQE are shown. The calculated performance parameters compare well against measured experimental data [1].

Photovoltaic performance parameters (Jsc, Voc, Jm, Vm, FF, and Efficiency) can also be simulated using the presented model. This TCAD model is used to design an enhanced TJ PV with increased efficiency and radiation tolerance.

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8981-43, Session 11

Variable-temperature carrier dynamics in bulk (In)GaAsNSb materials grown by MOVPE for multi-junction solar cells

Yongkun Sin, Stephen LaLumondiere, Nathan P. Wells, William T. Lotshaw, Steven C. Moss, The Aerospace Corp. (United States); Tae Wan Kim, Luke J. Mawst, Thomas F. Kuech, Univ. of Wisconsin-Madison (United States)

III-V multi-junction solar cells are typically based on a triple-junction design that consists of an InGaP top junction, a GaAs middle junction, and a bottom junction that employs a 1 – 1.25eV material grown on GaAs substrates. The most promising 1 – 1.25eV material that is currently under extensive investigation is bulk dilute-nitride such as (In)GaAsNSb lattice matched to GaAs substrates. The approach utilizing dilute-nitrides has a great potential to achieve high performance triple-junction solar cells as recently demonstrated by one group, who achieved a record efficiency of 43.5% from multi-junction solar cells including MBE-grown dilute-nitride materials. Although MOVPE is a preferred technique over MBE for III-V multi-junction solar cell manufacturing, MOVPE-grown dilute-nitride research is at its infancy compared to MBE-grown dilute-nitride. In particular, carrier dynamics studies are indispensible in the optimization of MOVPE materials growth parameters to obtain improved solar cell performance.

We employed time-resolved photoluminescence techniques to study carrier dynamics in MOVPE-grown bulk dilute-nitride (In)GaAsNSb materials (Eg= 1 – 1.25eV at RT) lattice matched to GaAs substrates. In contrast to our earlier samples that showed high background C doping densities, our current samples grown using different metalorganic precursors at higher growth temperatures showed a significantly reduced background doping density. We studied carrier dynamics in (In)GaAsNSb double hetero-structures (DH) with different N compositions at room temperature. Post-growth annealing yielded significant improvements in carrier lifetimes of (In)GaAsNSb DH samples. Carrier dynamics at various temperatures between 16K and RT were also studied from (In)GaAsNSb DH samples at different stages of post-growth thermal annealing steps.

8981-53, Session PWed

Design strategy for low emissivity windows with effective insulation

Mike P. Watts, Impattern Solutions (United States)

Low emissivity windows are a critical element of designing energy efficient structures. Windows are a surprisingly interesting and complex engineering challenge. There are 4 energy bands that contribute to energy transfer in windows; visible radiation, solar near IR radiation, re-radiated mid IR and thermal convection. Effective window design must manage each of these energy bands, and their interactions.

Analytical models were developed for thermal transfer, and re-radiation transfer. Commercial optical multilayer filter design tools were used for visible and near IR. Based on these models, a set of design rules were developed and used to select commercially available glasses in the IGDB data base, for either hot or cold climates. The performance of completed windows were compared using a program (Window) developed by LBL and DOE. The Window program is used to Energy Star rate windows for domestic consumers. The best windows were triple pane with low conductivity gas fill, multiple silver coatings to reject the re-radiated mid IR, and different multilayer stacks to transmit the visible while either blocking or transmitting the near solar IR.

The paper will describe the models, the “bottoms up” optimization process, the results and a “tops down” analysis of the materials and window engineering that produces windows with greater than 3x insulation properties compared to double pane windows.

This work has no commercial connections.

8981-54, Session PWed

An innovative microlens array design base on light pipe

Jong-Woei Whang, Xiao-Rong Wu, Shih-Min Chao, National Taiwan Univ. of Science and Technology (Taiwan)

With the countries in the world, are to advocate the natural and sustainable green life. Many researchers has focused on the Natural Light Illumination System (NLIS), it’s a novel and eco-friendly illumination system directing sunlight into buildings for illumination without the opto-to-electricity conversion. NLIS can be divided into three subsystems: (1) collecting subsystem; (2) transmitting subsystem; and(3) emitting subsystem.

The transmitting subsystem utilize the light pipe to transmit sunlight. However, there is one problem about the light pipe which can’t collect large angle due to the limitation of the numerical aperture of convex lens.

In this study , we present a innovative light pipe with a microlens array to couple light pipe and bi-convex lens in transmitting system. Microlens array can change the light direction and increase angle of received light by applying in the light pipe. The new structure of design will increase 15% angle of received light and advance 30% uniformity.

8981-55, Session PWed

A high-efficiency optical light pipe based on modular microlens design

Jong-Woei Whang, Ya-Chieh Ho, Shih-Min Chao, National Taiwan Univ. of Science and Technology (Taiwan)

Many recent studies focused on use of sunlight to provide indoor lighting and save energy. And sunlight is primarily transmitted through optical fiber and light pipe. Due to the high cost of optical fiber, many researches utilize the lens to repeatedly focus the sunlight through the light pipe. However, traditional lens are bulky and heavy. An important feature of this paper is using the advantage of the microlens array. By replacing every lens with microlens, the weight of light pipe could be decreased. Therefore, we use a plurality of microlens to focus the sunlight on the same point so that the overall uniformity and brightness could be improved.

8981-59, Session PWed

The optimization of textured a-Si:H solar cells with a fully three-dimensional simulation

Chun-Yao Lee, Hui-Hsin Hsiao, Tsung-Jui Yang, Yuh-Renn Wu, National Taiwan Univ. (Taiwan); Chun-Ming Yeh, Chien-Fu Huang, Yung-Tsung Liu, Chia-Ming Fan, Industrial Technology Research Institute (Taiwan)

Amorphous Silicon solar cells are important for large area and low cost applications. However, due to their short diffusion length, the film thickness is limited where the light absorption could be an issue. To solve this dilemma, textured surface technologies such as Lambertian limit of randomly textured surface, nano light trapping structures, and periodic structures have gotten more and more attention. In this research, we studied textured a-Si:H solar cells by using three dimensional(3D) simulation programs including 3D finite-difference time-domain method and 3D Poisson and drift-diffusion solver. With these fully 3D models without much approximation, we can calculate the real device performance with higher accuracy. For the random-rough surface, we found that structures with the average roughness equal to 30.60 nm and the root mean square (rms) roughness equal to 38.50 nm have the maximal energy conversion efficiency due to the stronger light absorption. Besides, the optimized thickness of absorber we proposed is 150.0 nm under a trade-off between the light absorption and the carrier lifetime. We also implemented a hole blocking layer into the n-type a-Si:H layer to reduce the back surface recombination of longer wavelength by 53.69%. On the other hand, we found that if each pyramid textured surface in the solar cell has a similar height near that optimized rms (38.50 nm), it has a stronger light absorption and it reveals the potential of using periodic-rough surface structures. Therefore, the a-Si:H solar cell based on periodic roughness structure will be studied in this research. The periodic structure is expected to have a higher optical performance. By analyzing and comparing the optical and electrical properties for both random and periodic roughness structures, we expected to find a guideline for achieving high conversion efficiency solar cells.

8981-60, Session PWed

Extraordinary resonance in highly-lossy media and its application to ultrathin solar cells

Sungyong Seo, Kyu-Tae Lee, Jae Yong Lee, L. Jay Guo, Univ. of Michigan (United States)

Solar cells have been implemented in various fields from industrial power generation to home appliances. Furthermore, they can be considered for building smart windows and for flexible clothes. In this regard, solar cells made of ultra-thin semiconductor films are advantageous to meet future requirements of different demands, such as flexibility, transmittance and fabrication cost. The challenge is to ensure high optical absorption in the ultrathin layer. In ultra-thin region, optical interference in highly lossy materials (i.e. semiconductors) cannot be discarded and should be considered in device design. In this work, an optimal thickness for power generation in an ultra-thin (6-30nm) solar cell based on extraordinary resonance in undoped hydrogenated amorphous silicon (a-Si:H) is demonstrated. The optimal device generates larger photocurrent (Jsc) than that of thicker device, which is not found in conventional devices. In addition, rather than the dull, black color of the traditional Si solar panel, these cells show distinct, tunable colors, which can be used for decorative purpose. The simulation results show good agreement with the measured external quantum efficiency of the ultrathin solar cells.

8981-61, Session PWed

On the light-trapping mechanism in silicon solar cells with backside diffraction gratings

Markus Wellenzohn, Rainer Hainberger, AIT Austrian Institute of Technology GmbH (Austria)

In the field of silicon solar cell technology the use of light trapping mechanisms exploiting diffraction of incident sunlight on embedded nanostructures has attracted much interest. In particular, for thin silicon solar cells with an absorber thickness in the micrometer regime a significant fraction of long wavelength photons is lost due to their weak absorption in silicon. Light trapping can be used to increase the interaction length of long wavelength photons resulting in an enhancement of the cell efficiency.

In this numerical study, we investigate the light trapping mechanism in silicon solar cells with backside diffraction gratings. In order to obtain a clearer view on the physical mechanism underlying the light trapping we employ a simulation scheme that combines ray tracing with rigorous coupled wave analysis (RCWA). This combined simulation approach treats the light propagation inside the silicon absorber layer incoherently and averages out Fabry-Perot resonances, which otherwise would obscure characteristic humps in the absorption spectra that are directly related to light trapping effect of the diffraction gratings. We provide an in-depth explanation for the origin of these characteristic humps and their interrelationship with the silicon absorber thickness.

A major benefit of this combined RCWA/ray tracing approach compared to the fully electromagnetic simulation methods RCWA and finite difference time domain (FDTD) is the more efficient use of computational power accompanied by a gain in simulation precision, in particular for cells with an absorber thicker than 10 µm.

8981-62, Session PWed

Stable efficiency analysis of ZnS/CIGS solar cells possessing by thermal treatment

Jyh-Jier J. Ho, National Taiwan Ocean Univ. (Taiwan)

In this paper, we use chemical bath deposition (CBD) to explore the electrical performance of ZnS / Cu(In,Ga)Se2 (CIGS) solar cells which are processed in different coating time. In addition, the electrical characteristic of the ZnS / CIGS cells are measured after the step of light Soaking and the heat treatment process. To explore effect of both light soaking and heat treatment. The results show that the steps combine light soaking and heat treatment can provide stable cells in efficiency. In the darkroom, the efficiency loss of ZnS / CIGS cell with efficiency of 10.64%, after 24 hours, is only 0.21%.

8981-63, Session PWed

Be implant activation and damage recovery study in N-type GaSb

Nassim Rahimi, Andrew A. Aragon, Orlando S. Romero, Thomas J. Rotter, Tito L. Busani, Olga Lavrova, Ganesh Balakrishnan, The Univ. of New Mexico (United States); Luke F. Lester, Virginia Polytechnic Institute and State Univ. (United States)

GaSb (Eg = 0.72 eV) is a suitable replacement for Germanium as the near IR absorber in multijunction solar cells. However for the realization of solar cells based on GaSb, selective area doping is required to obtain high performance ohmic contacts as well as PN junctions. This could possibly be achieved using epitaxial and non-epitaxial techniques such as diffusion and ion-implantation. Epitaxial growth of GaSb PN junctions has issues with defects which prevents realization of large area diodes. Among non-epitaxial processes, reliable diffusion technique has not been established to dope GaSb because Sb evaporates from the GaSb surface at 370 °C. This leaves ion implantation as the only possible selective area doping technique for GaSb.

The study involved implanting n-type GaSb with Be followed by the rapid thermal annealing (RTA) to activate the implanted doping and to "heal" the damage caused to the crystalline structure. Precautions were taken to protect the GaSb during the heating process. Among the several methods used for RTA, we describe face to face annealing and Si3N4 protective capping layer. The thick Si3N4 capped RTA process showed lesser outdiffusion of Sb than the face to face sample. The optimal temperature range to activate the ion implanted doping and heal the crystalline damage has been found to be 600 0C for 10 sec. Complete recovery of the semi-conductor was observed using X-Ray Diffraction and Transmission Electron Microscopy. Doping profiles were analyzed using Capacitance-Voltage measurement. After the samples were annealed, the implant activation was measured by processing a basic diode structure on the ion implanted GaSb samples and an excellent diode behavior was achieved.

8981-65, Session PWed

Cheap and efficient plasmonic solar cell

Mohamed A. Swillam, Ahmed E. Khalifa, The American Univ. in Cairo (Egypt)

Plasmonic solar cell is a very promising structure for high efficient solar cell application. It has some unique characteristics that allow high energy localization and higher solar energy absorption. Most of the proposed designs are based on using noble metals such as gold and silver to achieve the plasmonic effect. These metals are, however, expensive and increase the cost of the solar cell. Thus, the need to propose novel and cheap material with plasmonic like effect is of prime importance. In this work we demonstrate the applications of TiN that has good plasmonic like effect over wide bandwidth. A detailed comparative study of TiN and conventional plasmonic material is presented and optimized solar designs are proposed.These designs have comparable field localization and light scattering effects to those of the conventional plasmonic material. In addition TiN is more compatible with the CMOS fabrication technology than the conventional plasmonic metals, which can even ease the integration with other optoelectric devices . Should the electrical performance be further studied and optimized, the overall efficiency of the solar cell can be maintained and/or enhanced and total cost/watt dramatically reduced.

8981-66, Session PWed

Broadband antireflective GaOOH nanostructures for solar-cell applications

Jae Su Yu, Jung Woo Leem, Kyung Hee Univ. (Korea, Republic of)

Over the past decade, III-V compound semiconductor solar cells have been widely studied to improve power conversion efficiency (PCE). Among various strategies for enhancing the PCE, one of simple approaches is to reduce the surface Fresnel reflection losses, which enhances the light trapping in the active layer of devices. Thus, efficient broadband antireflection coatings (ARCs) are essential to cover the wide wavelength region. Recently, the various nanostructures such as nanowires, nanorods, and nanoporous films have been demonstrated as an ARC for solar cell applications. Meanwhile, gallium oxide hydroxide (GaOOH) with a wide bandgap of about 4.75 eV has a high transparency in the wide wavelength region, a high thermal stability, and a relatively low refractive index. In this presentation, we report the fabrication of GaOOH nanorods (NRs) by an electrochemical deposition method and investigate their optical reflection properties as well as the effect of the ARC on the efficiency of III-V solar cells. Additionally, the GaOOH NRs exhibit a hydrophobic surface and a relatively low solar weighted reflectance in the wavelength region of 300-1800 nm. By employing the GaOOH NRs as an ARC on the III-V solar cell, the significant improvement in the PCE is achieved compared to the conventional cell without ARCs.

8981-68, Session PWed

Tunable light trapping by ultra thin metal-nanoporous spacer-metal structures

Ali Özhan Altun, Hyung Gyu Park, ETH Zürich (Switzerland)

We have realized hexagonal arrays of sub 30 nanometer-sized semi-spherical pores on polysterene film using block copolymer (BCP) lithography, achieving uniform coverage over an entire wafer of 10 cm in diameter. We show that the conditions for such uniformity control of the nanopore array critically depends on the initial roughness of the metal layer. As long as a sufficiently low roughness of the metal thin film is provided, the process can be applicaple on various different metals such as gold, silver, aluminum and nickel. On this structure, we coated a thin (5-nm-thick) gold layer, that forms gold islands of ~10 to 15 nm in diameter. We suprisingly observed that this thin metal coating turned the color of the polymer coated metal onto different tones of blue, depending on the type of the reflector metal. We conducted a set of controlled experiments, verifying the effect of the porosity of the spacer. When an identical thickness of the spacer is not patterned, the absorption was much weaker. When the porousity exist, the absorption is much stronger (<95%) at the absorption peak and absorption band is quite wide in the 600-1100 nm spectral range, which is particularly meaningful in thin-film photovoltaics.

8981-44, Session 12

Silicon solar cell enhancement by plasmonic silver nanocubes

Ryan J. Veenkamp, Shuyu Y. Ding, Ian J. Smith, Winnie N. Ye, Carleton Univ. (Canada)

Our paper presents a detailed numerical simulation and experimental study of the efficiency enhancement gained by optimizing metal nanocubes incorporated on the surface of silicon solar cells. We investigate the effects of nanoparticle size, surface coverage and spacer layer thickness on solar absorption and cell efficiency. The fabrication of nanocubes on solar cells is also presented, with the trends observed in simulation verified through experimental data. Testing reveals that nanocubes show worse performance than nanospheres when sitting directly on the silicon substrate; however, enhancement exceeds that of nanospheres when particles are placed on an optimized spacer layer of SiO2, for reasonable surface coverages of up to 25%. Our analysis shows that for a large range of particle sizes, 60-100nm, enhancement in light absorption remains at a high level, near the optimum. This suggests a high level of fabrication tolerance which is important due to the chemical growth mechanism used for nanocube synthesis, as it consistently produces nanocubes in that range. Further, we note that efficiency enhancement by nanocubes is influenced by particle size, surface coverage, and spacer layer thickness much differently than that for a spherical geometry, thus our study focuses on the optimization of the nanocube parameters. We show that 80nm nanocubes on a 25nm SiO2 spacer layer realize ~24% enhancement in light absorption compared to an identical particle-free cell. Finally, we present both the numerical and experimental results for silicon solar cells coated with nanocube arrays.

8981-45, Session 12

Device performance of ultra-thin GaAs single-junction solar cells with a reflective backscattering layer

Shi Liu, Jacob Becker, Ying-Shen Kuo, Weiquan Yang, Yong-Hang Zhang, Arizona State Univ. (United States)

Surface roughing is an effective approach for light management in solar cells, which increases the optical thickness of the absorber. Such surface roughness is particularly beneficial for solar cells made of non-ideal material with substantial non-radiative recombination loss as the total absorber thickness can be greatly reduced when sun light is scattered and strongly trapped inside the solar cell. We recently demonstrated ultra-thin GaAs single-junction solar cells integrated with an AlInP layer

coated with an Au mirror for reflective back scattering. Efficiencies of 19% and 20% are achieved for cells using 300-nm and 1000-nm absorbers, respectively. Detailed device characterizations are carried out, including dark and light current-voltage measurements, front surface reflectance measurements, and external quantum efficiency (EQE) measurements, from which series resistance, energy conversion efficiency, open-circuit voltage, short-circuit current, fill factor, EQE, front surface reflection loss and internal quantum efficiency are obtained. The experimental results are carefully compared with theoretical analysis using various models. A factor that describes the ideality of Lambertian scattering of the rough back surface has been extracted by comparing the simulated and experimental EQE spectra. Moreover, by using an optimized contact grid design and more precise control of anti-reflection coating deposition, the devices are expected to reach an efficiency greater than 23%.

8981-47, Session 12

Optimum feature size of randomly textured glass substrates for maximum scattering inside thin-film silicon solar cells

Nasim Sahraei, Selvaraj Venkataraj, Armin G. Aberle, Marius Peters, National Univ. of Singapore (Singapore)

Optimisation of light scattering by designing proper randomly textured surfaces is one of the important issues while designing thin-film silicon solar cell structures. The critical wavelength region that needs to be scattered depends on the absorber material of the solar cell. The optimum morphology of the textured substrate can be defined regarding the critical wavelength region. Good scattering is experimentally achieved by optimising the fabrication process of the randomly textured substrate. However, optimum morphological parameters have not been analytically formulated for maximum scattering inside the desired material.

In this work we will show the optimum morphological criteria for optimum light scattering in a-Si:H solar cells for Aluminium Induced Textured (AIT) glass. Haze (the ratio of the scattered over total light) is widely used as an evaluating factor for scattering properties. Haze can be easily measured for the substrate/air interface. However, the relevant scattering properties are those in the absorber material, which cannot be measured directly but can be calculated with a suitable method. The simple model for haze calculation based on scalar scattering theory cannot correctly estimate the haze value because it only considers the root mean square (RMS) roughness value of the textured surface, which does not contain the information about lateral feature size. In addition, the opening angel of the haze measurement is not considered in the equation. In this work, we demonstrate that the power spectral density (PSD) function of the randomly textured surface can provide the missing information in the haze equation. We have used this calculated haze value as a measure to find the optimum lateral feature size for scattering a specific wavelength into the desired material. The optimum lateral feature size for scattering of the weakly absorbed light λ= 650 nm inside a-Si:H absorber layer is 320nm. The general formulation for calculating the lateral feature size based on the PSD function is presented in the paper.

8981-48, Session 12

Simulation of the scattering effect of randomly textured surfaces on the efficiency of thin film tandem solar cell

Zhabiz Rahimi, Christoph Pflaum, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Thin film silicon solar cells have been optimized in recent years in order to increase efficiency. One of the techniques used for higher efficiency was to increase the path length of incoming light inside the solar cell. This was done by using textured surfaces which enhanced light trapping through scattering of incoming light. Surface textures are applied to transparent conductive oxide (TCO) layers by sputtering and etching techniques. The impact of these layers on the quantum efficiency (QE) of solar cells can be studied using experimental methods. This requires depositing different layers and building the thin film solar cell, which is time consuming and prone to error. Numerical modeling of a solar cell can be useful for minimizing the necessity of real experimental measurements. The applications of simulation methods are important in predicting the light scattering effect in large areas of solar cells with textured layers. Furthermore, the absorption of light in the full range of light spectrum can be calculated through simulation. We have developed a conformal Finite Integration Technique (FIT) that can efficiently simulate both complex geometries and surface roughness. The advantage of using the FIT method is that it is highly parallelizable. This facilitates the simulation of large 3 dimensional domains using parallel computers.

We present the simulated QE for thin film solar cell with a muc-Si layer and a TCO layer with surface roughness in this paper. The textured structure was obtained by AFM scanning of the surface. A comparison was made with corresponding experimental measurement.

8981-49, Session 12

Optical scattering by anodized aluminum oxide for light management in thin film photovoltaics

Brian Roberts, Qi Chen, Pei-Cheng Ku, Univ. of Michigan (United States)

Thin film photovoltaics (PVs) have the potential to significantly reduce solar energy costs as compared to bulk semiconductors, though optically thin layers suffer from incomplete absorption. Light management is thus critical to enable high efficiency. We investigate the optical scattering properties of self-assembled nanoporous anodized aluminum oxide (AAO) films, and propose integrating AAO as a backscattering layer in thin film PVs. Experimental measurements and finite element optical models of AAO indicate angle-dependant scattering physics that can be exploited for light management.

When paired with a low index material, backscattering by AAO films is highly angle dependant - normally incident light is transmitted across the membrane while angled light probes the sub-wavelength structure and scatters multiple times. Placed behind a thin absorbing layer, an angle selective semitransparent PV structure can be realized, for which normally incident light is transmitted and angled light is scattered and absorbed. We propose that this functionality can be applied to improving absorption in PV window coatings without sacrificing transparency in the horizontal direction.

Particularly, we note that light can be backscattered from an AAO film to greater angles than the incident - this extreme angle scattering results in an improved path length and coupling to long propagating modes in accompanying thin absorber layers. When AAO is paired with a high index material, extreme angle scattering results in light backscattered beyond the critical angle for total internal reflection, allowing an additional mechanism for light trapping in materials like thin epitaxial semiconductors, without texturing.

8981-51, Session 13

InP-based nano solar cells *(Invited Paper)*

Florian Proise, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France); Fabrice Pardo, Lab. de Photonique et de Nanostructures (France); Anne-Laure Joudrier, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France); Christian Njel, Univ. de Versailles Saint-Quentin-en Yvelines (France); José Alvarez, Lab. de Génie Électrique de Paris (France); Amaury Delamarre, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France); Anne-Marie Gonçalves, Univ. de Versailles Saint-Quentin-en Yvelines (France); Aristide Lemaître, Lab. de Photonique et de Nanostructures (France); Nathalie Bardou, Christophe Dupuis, Laboratory for Photonics et Nanostructures (LPN-CNRS) (France); Arnaud Etcheberry, Univ. de Versailles Saint-Quentin-en Yvelines (France); Jean-François Guillemoles, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France); Jean-Luc Pelouard, Lab. de Photonique et de Nanostructures (France)

Light concentration increases solar cell conversion efficiency if resistive loss is kept low [1]. In this paper, we study the extreme case of photovoltaic nano-cells smaller than photons wavelength. This study is based on two complementary approaches: designing optical nano-antenna to couple the incoming light with nano-cells and making nano-diodes. It leads to two challenges, the nanofabrication and the electrical behaviour to minimize dark current.

Our work is close to the border between nanophotonic and nanoelectronic fields. The nano-scale dimension rises nanofabrication issues.

We first deal with nano-photonic. Theoretical results are obtained using a Rigorous Maxwell Constitutive Approximation (RMCA) code [2] to address the optical response of the Metal-Insulator-Metal (MIM) nano-antenna. Calculations show that more than 60% of the broad-band incoming solar spectrum can be absorbed with only 300 nm absorber thickness and a 1/3 coverage fraction.

We will show that simulated structures can be effectively made with clean room nanofabrication process.

The absorber is made in InP, which has low surface recombination velocity. This choice is motivated by the low diodes dimensions which amplify surface influence.

The electrical behavior is also studied with nano-diodes current-voltage characterizations.

Finally, we will show that InP passivation is needed and has been succesfully done with a polyphosphazen film [3]. An increase of photoluminescence (PL) spectra intensity of two orders of magnitude has been reported with polyphosphazen. Advanced optical characterization such as time-resolved PL and hyperspectral imager results will also be shown.

[1]M. Paire et al. Appl. Phys.Lett. 98(22), (2011) 264102

[2]P. Bouchon et al. J. Opt. Soc. Am. A 27(4) 696 (2010)

[3]A-M. Gonalves et al.. Chem. Mater. 22 (2010) 3114-3120

8981-52, Session 13

Dedicated nanoantenna element for vertical nanorods in plasmonic photovoltaics

Hossein Alisafaee, Michael A. Fiddy, The Univ. of North Carolina at Charlotte (United States)

Plasmonic solar cells posses a high potential of rapid advancement for future photovoltaic devices. Here, we investigate a novel light conversion scheme in nanostructures for such a highly demanding field. In our study, we incorporate vertical nanorods made of semiconductor materials, which are coupled optically to plasmonic nanoantennas. Apart from an improvement in carrier recombination, employing nanorod structures leads to a large drop in the cost of materials used. This reduction can be approximated to be 4000 times less than material used in conventional crystalline silicon cells. Along with nanorod elements, to obtain an optimal absorption for sunlight, we create nanoantenna elements such that emission pattern is effectively directed toward the absorber material. Since plasmonics can provide a suitable tool for manipulation of light at nanoscale, we investigate the design of such dedicated nanoantenna elements utilizing the unique properties of localized surface plasmon resonances. The result provides a highly efficient light-matter interaction that can be exploited in the realm of photovoltaics and also in other similar applications like detectors.

As it is well-known, the properties of localized surface plasmons are dependent on the material, shape and size of nanostructure as well as its surrounding medium. In our approach, we use a computational finite element method to investigate the effects of size and shape of metallic nanoparticles for creation of an asymmetric radiation pattern that matches the geometry of our design. By comparing the effectiveness of a dedicated nanoantenna and a conventional element, we demonstrate the benefits of works presented here.

8981-64, Session 13

Extending the operational wavelength of thermophotovoltaics through superlattice and barrier engineering

Abigail S. Licht, Dante F. DeMeo, Tufts Univ. (United States); Jean-Baptiste Rodriguez, Institut d'Electronique du Sud (France); Thomas E. Vandervelde, Tufts Univ. (United States)

Thermophotovoltaics (TPV) convert infrared radiation from a hot temperature source into electricity through photovoltaic mechanisms. TPV bulk photodiode bandgaps typically range from 0.5 – 0.74 eV, which correspond to temperature sources greater than 1000°C. Our research serves to extend the operational wavelength of TPV to convert longer wavelength radiation from lower temperatures sources, allowing for more widespread applications for TPV.

Operation of narrow (< 0.5 eV) bandgap devices has not yet been realized due to increased non-radiative recombination with decreasing bandgap. Recent infrared photodetector research demonstrates that recombination can be reduced by employing a type-II superlattice (T2SL). In these structures, the conduction bands of one material overlap with the valence bands of the other, creating highly tunable quasi-bandgaps. Inherent to these structures is a larger separation between heave-hole and light-hole bands; this separation leads to decreased Auger recombination and enhanced carrier lifetimes. Further research shows that inserting a wide band gap, monovalent barrier within the p-n junction leads to reduced Shockley-Reed-Hall recombination, increasing the overall current.

In our research we investigate the T2SL structure for TPV diodes. We examine 5 micron TPV diodes, which corresponds to Eg = 0.248 eV. Through simulations with the program Silvaco we compare the p-i-n and pBn structures. The feasibility of this device at room temperature is also investigated. The simulations are compared with diodes fabricated by MBE and processed with conventional photolithography methods. These diodes are characterized using calibrated blackbody sources and tested under standard conditions.

8982-1, Session 1

High-power resonantly-pumped holmium-doped fibre sources *(Invited Paper)*

Alexander V. Hemming, Nikita Simakov, John Haub, Defence Science and Technology Organisation (Australia); Adrian L. Carter, Nufern (United States)

Laser sources operating in the spectral region beyond 2 µm are of interest for a range of applications in the areas of remote sensing, medicine, industrial materials processing and defence. These applications require a diverse range of sources of various temporal, spectral and output power levels to meet their requirements.

The operation of silica fiber lasers at 2 µm has advantages in terms of the suppression of non-linear effects such as stimulated Brillouin and Raman scattering which can limit high power operation of fibre based devices. The majority of silica fibre based sources developed for the 2 µm spectral region have used thulium fibres. Various pulsed sources have been realised, including Q-switched, gain switched and mode-locked lasers. CW thulium sources have been demonstrated at more than 1 kW of output power with excellent beam quality, as well as narrow line-width operation producing 608 W of output power. Further power scaling of thulium lasers is currently limited by diode brightness and the thermal performance of coating materials.

Resonantly pumped holmium fibre lasers have several advantages over thulium based devices. Of particular interest is the ability to operate in the atmospheric transmission window beyond 2.1 µm. For high power operation the resonantly pumped holmium fibre architecture has advantages for power scaling due to the availability of mature thulium fibre lasers operating at 1.95 µm. These lasers can be utilised as high brightness pump sources providing thermal advantages and flexibility in fibre design. We have demonstrated a kW power level array of monolithic thulium fibre lasers, and used it to resonantly pump a holmium fibre laser to achieve 400 W in CW operation at 2.12 µm. Further power scaling of holmium fibre lasers and amplifiers applicable to both pulsed and CW operation is currently being performed.

We will review the benefits of resonantly pumped holmium fibre lasers, and present recent results of the high power operation of both CW and pulsed sources. These results demonstrate the utility of this fibre laser architecture and its suitability for high power laser operation and for providing pump sources for non-linear frequency conversion.

8982-2, Session 1

Titanium enhanced Raman microcavity laser

Nishita Deka, Ashley J. Maker, Andrea M. Armani, The Univ. of Southern California (United States)

Due to their long photon lifetimes, ultra high quality factor (Q) silica microcavities form an ideal platform for microlaser development. Previous work verified that these devices exhibit Raman lasing, because the high Q compensates for the low Raman gain of silica. However, only devices with Q>1E8 are able to achieve microwatt thresholds, limiting the application space. One approach for overcoming this barrier is to increase the inherent Raman gain of the material without degrading the optical performance of the device.

To address this challenge, we synthesize a series of Titanium (Ti) doped silica sol-gels with different concentrations of Ti, including a null. The refractive indices of the coatings are characterized using spectroscopic ellipsometry and increase linearly with the concentration of Ti from 1.44 to 1.53. We apply the sol-gel as a conformal coating on silica toroidal microcavities and characterize the basic cavity properties (Q) and the lasing behavior, including the lasing threshold and the slope efficiency. All measurements are performed in ambient conditions. Although the cavity Q's are modest (5E6), comparable lasing thresholds (microwatt) to higher Q silica devices are achieved because of the reduction in mode volume and the increase in Raman gain due to the presence of the Ti. Additionally, the efficiency of the laser increases with increasing Ti concentration.

8982-3, Session 1

Fibercore AstroGain(TM) fiber: multichannel Erbium doped fibers for optical space communications

Mark D. Hill, Rebecca L. Gray, Fibercore Ltd. (United Kingdom); Judith Hankey, Andy Gillooly, Fibercore (United Kingdom)

There is a growing need in the communications sector for erbium doped fiber amplifiers (EDFAs) suitable for space environments. In Earth orbit, various radiation environments are encountered, with different particle types and intensities. Generally, radiation damage to a fiber causes the creation of point defects, as well as further damaging of pre-existing defects inherent in the fiber structure. The modification and creation of point defects results in changes to the energy level structure of the fiber, such that photons travelling through the fiber are absorbed by defects, causing increased attenuation – so called Radiation Induced Attenuation (RIA).

To solve this problem, Fibercore have developed a fiber optimized for use in multichannel amplifiers in optical inter-satellite communications. The fiber has been designed to take full advantage of the photoannealing effect that results from standard pumping in the 980nm region. The unique trivalent structure of the core matrix allows optimum recovery following radiation damage to the fiber, whilst also providing a market leading EDFA efficiency.

Direct measurements have been taken of amplifier efficiency in a multichannel assembly, which show an effective photoannealing recovery of up to 100% of the RIA through excitation of the defects. It has also been demonstrated through analysis of the optical spectral output that this effect reverses the gain tilt, or spectral narrowing, induced by radiation damage through the C and L band. These combined fiber characteristics allow performance stability of the amplifier over the lifetime of the space mission.

8982-4, Session 1

Novel low-phase-noise low-amplitude-noise semiconductor laser

Steven Coleman, Alex Rosiewicz, EM4, Inc. (United States)

A simple, highly manufacturable method of creating a narrow linewidth semiconductor diode laser has been created and demonstrated. The measured linewidth is <5kHz. The technique operates over a broad wavelength range with a tuning range >120GHz with no effect on the linewidth. The RIN remains low at <-150dB/Hz from 10kHz to over 26GHz. Output power from the fiber coupled laser is >40mW. Overall size ~120x70x20mm.

8982-5, Session 1

Spatially resolved in-core temperature measurement in rare-earth doped fibers during pumping

Julia Fiebrandt, Martin Leich, Sonja Unger, Matthias Jäger, Manfred Rothhardt, Hartmut Bartelt, Institut für Photonische Technologien e.V. (Germany)

In order to improve the stability and performance of fiber lasers, it is necessary to understand the temperature evolution inside the laser active fiber during lasing. Therefore, we have studied the temperature behavior of differently doped fibers during pumping using fiber Bragg gratings (FBG) and additionally investigate a technique for a spatially resolved temperature measurement using an array of FBGs.

The FBGs in the differently doped fibers are inscribed directly inside the active fiber core using UV fs pulses and a phase mask interferometer technique.

During pumping of the actively doped fibers containing the FBG sensors, we find two main effects contributing to the temperature evolution. An initial thermal heating is attributed to an energy deposition mainly due to the quantum defect. Subsequently, the temperature raises further due to the pump light absorption by photodarkening (PD) defects. To avoid disturbing PD during our distributed measurement we inscribe the FBG array in a PD-reduced, cerium co-doped fiber. We demonstrate a spatially resolved temperature measurement using the FBG array during 976nm-pumping, enabling the detection of a temperature profile along a fiber during laser operation.

8982-6, Session 1

Low-threshold integrated microlaser emitting in the blue formed from thulium-doped silica

Simin Mehrabani, Andrea M. Armani, The Univ. of Southern California (United States)

Developing an integrated blue microlaser on a silicon wafer can advance optical biodetection platforms and enable the fundamental biophysical studies. However, there are very few methods which are able to achieve emission in this wavelength range. The primary approach which is being pursued relies on second harmonic generation. However, this approach can be inefficient and has very high lasing thresholds, and therefore, requires a high power, increasing the overall system cost and size.

In the present work, we explore a different approach of designing a blue laser which is based on upconversion of near-IR by thulium. While this effect has been demonstrated in previous systems, namely fiber lasers, in the present work, we integrate the thulium into an optical resonant cavity. Optical resonant cavities store light in circular orbits, enabling high optical field intensities to build-up. Unlike in an optical fiber where photons only interact with the thulium a single time, in a resonant cavity, photons interact with the dopant numerous times, increasing the probability of excitation and decreasing the required threshold for lasing. The interaction length is directly proportional to the photon lifetime in the cavity or quality factor (Q). Therefore, a higher Q is desirable.

In the present work, we fabricate silica toroidal cavities on silicon from thulium doped sol-gels. Thulium is excited at 1060nm, and it emits at 780nm and 450nm with sub-mW thresholds. The quality factor and lasing characteristics of the doped silica microtoroids are characterized at various thulium concentrations of the dopant.

8982-7, Session 1

High-gain 1.3-?m GaInNAs SOA with fast-gain dynamics and enhanced temperature stability

Dimitris Fitsios, Ctr. for Research and Technology Hellas (Greece) and Aristotle Univ. of Thessaloniki (Greece); Giannis Giannoulis, Nikos Iliadis, National Technical Univ. of Athens (Greece); Ville-Markus Korpijärvi, Jukka Viheriälä, Anti Laakso, Tampere Univ. of Technology (Finland); Stefanos Dris, Maria Spyropoulou, Hercules Avramopoulos, National Technical Univ. of Athens (Greece); George T. Kanellos, Ctr. for Research and Technology Hellas (Greece); Nikos Pleros, Ctr. for Research and Technology Hellas (Greece) and Aristotle Univ. of Thessaloniki (Greece); Mircea D. Guina, Tampere Univ. of Technology (Finland)

Semiconductor optical amplifiers (SOAs) are a well-established solution of optical access networks. They could prove an enabling technology for DataCom by offering extended range of active optical functionalities. However, in such cost- and energy-critical applications, high-integration densities increase the operational temperatures and require power-hungry external cooling. Taking a step further towards improving the cost and energy effectiveness of active optical components, we report on the development of a GaInNAs/GaAs (dilute nitride) SOA operating at 1.3?m that exhibits a gain value of 28 dB and combined with excellent temperature stability owing to the large conduction band offset between GaInNAs quantum well and GaAs barrier. Moreover, the characterization results reveal almost no gain variation around the 1320 nm region for a temperature range from 20o to 50o C. The gain recovery time attained values as short as 100 ps, allowing implementation of various signal processing functionalities at 10 Gb/s. The combined parameters are very attractive for application in photonic integrated circuits requiring uncooled operation and thus minimizing power consumption. Moreover, as a result of the insensitivity to heating issues, a higher number of active elements can be integrated on chip-scale circuitry, allowing for higher integration densities and more complex optical on-chip functions. Such component could prove essential for next generation DataCom networks.

8982-8, Session 2

Cavity-enhanced perfect mid-Infrared absorption in perforated graphene

Alexander Y. Zhu, Fei Yi, Jason C. Reed, Ertugrul Cubukcu, Univ. of Pennsylvania (United States)

Graphene has recently emerged as a highly promising nanoscale opto-electronic material due to its ability to support highly confined surface plasmons with exceptionally long lifetimes, as well as the intrinsic tunability of its chemical potential by electrostatic gating. Nevertheless the vast majority of efforts related to graphene optics thus far have been directed towards the far infrared/terahertz regime, where graphene behaves like a truly metallic substance, with noble-metal like permittivity values. The mid infrared regime presents a more significant challenge due to graphene being much less metallic, by virtue of its frequency-dependent optical sheet conductivity; important performance parameters/observables such as absorption and modulation are therefore, in general, much weaker in this regime. Here we report a theoretical study showing that the coupling of a continuous monolayer of periodically perforated graphene to simple optical cavities results in greatly enhanced absorption in the mid-infrared regime, with tunability of the resonance peak by more than its full-width at half maximum (FWHM). In particular, we find that coupling with quarter wavelength (thickness ≈ ?/4n) Fabry-Perot cavities results in near-unity absorption, while integration with deeply subwavelength (thickness ≤0.1?/4n) cavities enhances absorption approximately four-fold. The performance characteristics and parameter dependence of these designs are explored using both analytical theory and numerical simulation techniques. The

structural simplicity and large spectral tunability of the proposed designs render them applicable to infrared modulators, sensors and bolometers.

8982-9, Session 2

Investigation of liquid crystal materials doped with quantum dots: properties and potential applications

Katarzyna Komorowska, Krystian Zygadlo, Bartlomiej Cichy, Michal P. Nikodem, Wroclaw Research Centre EIT+ (Poland)

Liquid crystal (LC) based devices is a large group of instruments ranging from simple LC cells to complex, high resolution spatial light modulators. In last decades they all became key components in various optical applications such as displays, optical tweezers, spatial phase modulators, LC lasers and many others. Yet, their performance is still limited by the properties of liquid crystal itself. Therefore in this paper we will focus on the optical and electro-optical properties of liquid crystals. We will present our studies on LC materials doped with non-toxic quantum dots (QDs). The effects of doping and its impact on Fredericks threshold voltage and response time will be investigated. We will also analyze the dispersion, aggregation and pattern formation of quantum dots in different chiral and non-chiral liquid crystalline phases. Presentation of the material studies will be followed by example applications of LC cells doped with QDs. Those include optical control of LC cells for optically addressed LC systems, and polarization rotation/regulation over broad range of frequencies from visible to mid-IR. Application of LC-based polarization controllers in compact mode-locked fiber lasers will be presented. We will also propose systems with surface modulation change based on azo-dye self-assembling layers leading to local change of refractive index with the resolution of the size of addressing beam.

8982-10, Session 2

Growth model of transparent conductive graphene

Shih-Hao Chan, Chien-Cheng Kuo, Sheng-Hui Chen, National Central Univ. (Taiwan)

Indium tin oxide (ITO) is the dominant material used in transparent electrodes which were 3-billion-dollar worth in 2010 with a 20% growth rate through 2013. Several types of new transparent electrode materials can potentially replace ITO, including metallic nanowires, carbon nanotubes and graphene films. Graphene, an sp2-hybridized carbon film with unique properties, has attracted substantial interest in recent years, and it is a candidate for several applications. The carriers in graphene are transported in the π-orbitals that are perpendicular to the surface so the optical transparency of a single layer of graphene can be as high as ~97% and it can exhibit excellent electronic properties with reported mobilities of between 3000 and 27000 cm2/Vs. Recently, synthesis of uniform and large-scale graphene films by CVD on transition metals has been demonstrated. However, CVD graphene films are found to be polycrystalline, consisting of numerous grain boundaries, which can degrade its electrical properties. Stacking multilayers or doping carriers can reduce the sheet resistance of graphene films. In this study, we elucidate the growth model of graphene and analysis the graphene grain boundaries by ambient chemical vapor deposition system under different hydrogen flow rates from 10 to 50 sccm. The grain density decreased with increasing hydrogen flow rate. We obtained an optimal of electrical value with 30 sccm of hydrogen flow rate. The intensity ratios of 2D and D peaks to G peak were 2.29 and 0.07, respectively. The single layer graphene shows the lowest sheet resistance value of 310 Ω/□ and the value reduced to 180Ω/□ by HNO3 doping method.

8982-11, Session 3

Materials growth and processing in the capillaries of photonic crystal fibres: towards the lab-in-a-fibre protocol *(Invited Paper)*

Ioannis Konidakis, Maria Konstantaki, Stavros Pissadakis, Foundation for Research and Technology-Hellas (Greece)

Photonics crystal fibres (PCFs) have evolved into versatile optical device platforms, hosting micro-fluidic, biological or optomechanical functionalities that are probed or induced by the light guided inside them; these functionalities constitute steps towards the Lab-in-a-Fibre protocol. A parameter of fundamental significance accelerating the development of multi-functional photonic devices in PCFs is the growth of optical materials and scaling-down of processing techniques to fit inside their micrometer sized capillaries. Herein, we review recent results on the infiltration and/or growth of glass and crystalline materials inside the capillaries of PCFs for demonstrating all-solid photonic band-gap (PBG) and/or antiresonant reflecting optical waveguide (ARROW) guidance, seeking specific sensing and light confining properties of those multi-component PCFs. First results will report the infiltration of silver metaphosphate glass composites inside PCFs, the observation of PBG, and the subsequent thermal poling of those hybrid fibres for attaining plasmon resonance characteristics. Additionally, the wet chemistry growth of crystalline ZnO layers inside PCFs will be presented; as well as the structural characterisation of these crystalline thin films and nanostructures. Furthermore, work will be presented on the use of laser radiation for refractive index engineering and relief periodic structuring of PCFs. Finally ongoing work refers to the exploitation of plasmon resonance guiding in the phosphate glass-PCFs for sensing applications, and the tailoring of the wetting properties of the in-fibre ZnO films for developing optofluidic actuators; emerging results will be presented on-site.

8982-12, Session 3

GeO2 glass ceramic planar waveguides fabricated by RF-sputtering

Alessandro Chiasera, Univ. degli Studi di Trento (Italy); Carlos E. Macchi, Univ. Nacional del Centro de la Provincia de Buenos Aires (Argentina); Sebastiano Mariazzi, Univ. degli Studi di Trento (Italy); Sreeramulu Valligatla, Istituto di Fotonica e Nanotecnologie (Italy) and Univ. of Hyderabad (India) and Univ. degli Studi di Trento (Italy); Stefano Varas, Maurizio Mazzola, Istituto di Fotonica e Nanotecnologie (Italy); Nicola Bazzanella, Univ. degli Studi di Trento (Italy); Lorenzo Lunelli, Cecilia Pederzolli, Fondazione Bruno Kessler (Italy); Narayana R. Rao, Univ. of Hyderabad (India); Giancarlo C. Righini, Istituto di Fisica Applicata Nello Carrara (Italy) and Museo Storica della Fisica e Ctr Studi e Ricerche Enrico Fermi (Italy); Alberto Somoza, Univ. Nacional del Centro de la Provincia de Buenos Aires (Argentina); Roberto S. Brusa, Univ. degli Studi di Trento (Italy); Maurizio Ferrari, Istituto di Fotonica e Nanotecnologie (Italy)

GeO2 transparent glass ceramic planar waveguides were fabricated by a RF-sputtering technique and then irradiated by a pulsed CO2 laser. Different techniques like m-line, micro-Raman spectroscopy, atomic force microscopy, and positron annihilation spectroscopy were employed to evaluate the effects of CO2 laser processing on the optical and structural properties of the waveguides. The GeO2 planar waveguide after 2h of CO2 laser irradiation exhibits an increase of 0.04 in the refractive index, measured at 1542 nm. Moreover, the technique of laser annealing is demonstrated to significantly reduce propagation loss in GeO2 planar waveguides due to the reduction of the scattering. Upon irradiation of the surface the roughness decreases from 1.1 to 0.7 nm, as measured

by AFM. Attenuation coefficients of 0.7 and 0.5 dB/cm at 1319 and 1542 nm, respectively, were measured after irradiation. Micro-Raman measurements evidence that the system embeds GeO_2 nanocrystals and their phase varies with the irradiation time. Moreover, positron annihilation spectroscopy was used to study the depth profiling of the as prepared and laser annealed samples. The obtained results yielded information on the structural changes produced after the irradiation process inside the waveguiding films of approximately 1 µm thickness.

8982-13, Session 3

Low-loss titanium-dioxide strip waveguides by atomic layer deposition

Markus Häyrinen, Matthieu Roussey, Vishal Gandhi, Markku Kuittinen, Seppo Honkanen, Univ. of Eastern Finland (Finland)

We present an innovative approach to fabricate low-loss titanium dioxide (TiO_2) strip waveguides. During the etching process, a roughness appears on the sidewalls of the waveguides. The overlap of the modes with this sidewall roughness generates propagation losses. We propose to show how these losses can be reduced by re-coating the waveguide by Atomic Layer Deposition (ALD) with the same material. The structure is a 1 µm-wide TiO_2 strip waveguide fabricated by patterning with e-beam lithography a 450 nm-thick ALD TiO_2 film. Using the advantages of the ALD technique to provide conformal coating, we show the vanishing of the sidewall roughness of the waveguides by successive re-coatings. The deposition of a very thin TiO_2 film on a waveguide made of the same material allows us to virtually remove the rough TiO_2/air interface and replace it by a smoother one. We have experimentally measured the propagation losses on large panel of waveguides using the cut-back method and we have shown a decrease of the losses from 5 dB/cm to 2.4 dB/cm with an additional coating of 30 nm-thick. We propose here the design and the theoretical study of the waveguides and the effect of the recoating, the description of the fabrication process and the measurements of the propagation losses in the structures at the telecom working wavelength 1550 nm. TiO_2 becomes then an alternative to silicon. Indeed, the material has a high refractive index and presents nonlinear properties without the inconvenient two-photon absorption in the visible and near infrared wavelength range.

8982-14, Session 3

Efficient "disc-to-fiber" multimaterial stacked coextrusion for optical fibers

Guangming Tao, Ayman F. Abouraddy, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Multimaterial extrusion technology could produce robust infrared glass fiber that was hampered for several decades because of glass material's unfavorable mechanical characteristics. High purity, large scale chalcogenide glass synthesize technology also obstacles the transfer this novel technology from academia to industry. In this report, we bring out a new multimaterial extrusion technology, high efficiency "discs-to-fibers" multimaterial extrusion technology, which could produce 10-micron core fiber by one-step extrusion from two glass discs with 10-mm diameter and 3-mm thickness to preform and one-step fiber drawing from preform to optical fiber. Several grams glass material could produce several hundreds of meter optical fiber. This technology swept away all possible obstacles for glass material group to produce optical fiber, also reduce the production cost for industry. New design of extrusion billet could result higher purity extruded preform, therefore lower loss optical fiber after drawing since optical glass billet has less contact with metal sleeve during the hot extrusion process.

8982-15, Session 3

Flexible glass flat-fibre chips and femtosecond laser inscription as enabling technologies for photonic devices

Christos Riziotis, National Hellenic Research Foundation (Greece); Kyriacos Kalli, Cyprus Univ. of Technology (Cyprus); Christos Markos, National Hellenic Research Foundation (Greece); Andreas Posporis, Charalambos Koutsides, Cyprus Univ. of Technology (Cyprus); Andrew S. Webb, Christopher H. Holmes, James C. Gates, Jayanta K. Sahu, Peter G. R. Smith, Univ. of Southampton (United Kingdom)

There is immense interest in developing enabling technologies for potential use in smart structures, integrated photonic circuits and devices for use in optofluidics, and where the availability of a flexible, optically-flat, glass fibre would offer a means to incorporate all the advantages of densely packed planar chips, with the many advantages afforded by optical fibres. A waveguiding glass substrate or flat optical fibre chip is inherently compatible with optical fibres, sharing all the advantages of the cylindrical glass optical fibres, such as the ability to withstand high ambient temperatures, a chemically inert host material, but having a large flat surface area allowing for material processing. Coupled with low manufacturing costs, these flexible chips can prove to be a key technology applied to disposable high-end sensing devices or fully distributed point sensors. Here we present experimental investigations into creating novel structures (such as microfluidic channels, ring resonators, etc.) using a direct write approach and a femtosecond laser on a new flat-fibre platform. We have successfully demonstrated the use of femtosecond laser micro-machining and inscription of different micro-optical structures, such as ring and disk resonators, Mach-Zender interferometers, in addition to a complex microfluidic device, in a novel flat optical fibre chip. The inscribed structures are subsequently filled with active polymer and other materials for various sensing applications. Furthermore, direct write femtosecond-laser inscribed Bragg gratings have been written in the Ge-doped core of the flat-fibre. The morphology of the fabricated structures has been characterized using optical microscopy and 3D optical profilometry.

8982-16, Session 3

Fabrication of AsS single-mode microstructured optical fibers for supercontinuum generation in the mid-IR

Laurent Brilland, PERFOS (France); Perrine Toupin, Sciences Chimiques de Rennes (France); Celine Caillaud, Johann Troles, Univ. de Rennes 1 (France); Laurent Provino, David Mechin, PERFOS (France)

Chalcogenide glasses are known for their large transparency window in the mid-infrared and their high nonlinear optical properties. The nonlinear refractive index, n2 can be more than two order of magnitude greater than in silica. The AsS microstructured optical fibers (MOF) are attractive for a supercontinuum generation up to 6µm. Indeed, they can exhibit an endlessly single mode operation, and the zero dispersion wavelength (ZDW) can be shifted below 2µm. Moreover, the sulphide based glasses have a high laser damage threshold (>12GW/cm2 in ps regime).

The chalcogenide preforms are fabricated by using the casting methodwhich works well with selenide based glasses but is more complicated to implement for Sulphide based glasses. A new 10µm core 3-rings AsS MOF with optical losses lower than 0.5 dB/m near 3.5µm has been successfully fabricated. The ZDW is estimated to be at 3.7µm and the anormal dispersion regime can be reached by pumping the fiber with an OPO laser or via the generation of 4 or 5 Raman stokes with a 2.4 µm fiber laser. Also, with this single mode design, we observed that the

OH absorption at 3µm is significantly reduced which is favorable for their integration in future lasers sources.

8982-17, Session 4

Ultrathin metals and nano-structuring for photonic applications *(Invited Paper)*

Valerio Pruneri, ICFO - Institut de Ciències Fotòniques (Spain)

Ultrathin materials and nano-structuring are becoming essential for the functionalization of optical surfaces. In the talk we will show how ultrathin metals can be exploited to create competitive transparent electrodes. At the same time they can be used to create nanostructured surfaces through mass scalable dewetting and etching techniques. After presenting the techniques we will focus on the applications made possible by these materials and technologies, including self-cleaning or easy-to-clean display screens, efficient indium-free light emitting diodes and photovoltaics, antireflective structures for the laser industry and super-wetting surfaces for biology.

8982-18, Session 4

Metamaterial selective emitters for photodiodes

Dante F. DeMeo, Nicole Pfeister Latham, Tufts Univ. (United States); Corey Shemelya, The Univ. of Texas at El Paso (United States); Thomas E. Vandervelde, Tufts Univ. (United States)

This work demonstrates a metamaterial (MM) emitter for potential use with energy harvesting photodiodes, such as thermophotovoltaic cells. It serves, to radiate light in a narrow band towards a photovoltaic diode. By tailoring the emission of the MM to just above the bandgap of the photovoltaic device, the efficiency can be improved compared to a broadband radiator, natural selective emitters, or recent photonic crystal emitters. Emission can be designed to match virtually any photodiode; it can be tailored to any device property of choice, such as the bandgap, the absorption, or the quantum efficiency.

Preliminary structures have been designed, simulated, and fabricated using CST Microwave Studio, electron beam evaporation, atomic layer deposition, and electron beam lithography. These structures were made using a stack of sapphire substrate, platinum grounding plane, alumina dielectric layer, and patterned Pt rods.

Measurements show the wavelength peak to match simulation. Thermal cycling of the sample shows no degradation of performance, with slightly better selectivity seen after heating. Thermal emission tests show a peak shifted roughly 50nm from the expected 1µm, but at the expected magnitude. Results have shown MM emitters to have a much higher degree of tunability than photonic crystal emitters, which allows for better matching of emitter to photodiode. This improvement in matching is especially seen in the shorter wavelengths.

Samples are characterized at 1000+°C and paired with MBE grown GaSb TPV cells. Optimization of the design process and fabrication of both the emitter and photodiode are discussed.

8982-19, Session 4

Multilevel light-bending in nanoplasmonics

Mohamed H. El Sherif, Osman S. Ahmed, Mohamed H. Bakr, McMaster Univ. (Canada); Mohamed A. Swillam, The American Univ. in Cairo (Egypt)

Nanoplasmonic optical interconnects are proposed to mitigate challenges facing electronics integration. It provides fast and miniaturized data channel that overcome the diffraction limit. We present a three dimensional plasmonic coupler that vertically bend the light to multilevel circuit configurations. It exploits light guiding in nanoscale plasmonic slot waveguides (PSWs). A triangularly-shaped plasmonic slot waveguide rotator is introduced to attain such coupling with good efficiency over wide bandwidth. Using this approach, light propagating in a horizontal direction is easily converted and coupled to propagate in the vertical direction and vice versa. The proposed configuration is further extended to the design of a multilayer power divider/combiner with ultra-compact footprint that guides the light to multiple channels. A detailed study of the triangular rotator is demonstrated with the analysis of multiple configurations. This structure is suitable for efficient coupling in multilevel nano circuit environment.

8982-20, Session 4

Huygens Lens for angle compensation

Quentin Levesque, Patrick Bouchon, ONERA (France); Fabrice Pardo, Lab. de Photonique et de Nanostructures (France); Riad Haïdar, ONERA (France); Jean-Luc Pelouard, Lab. de Photonique et de Nanostructures (France)

Plasmonic lenses are based on the possibility to tailor the effective optical index of a subwavelength metallic slit by simply tuning its width. Thus, an array of subwavelength slits of different widths in a metallic layer can induce a lens effect for a TM-polarized incident plane wave. However the realization of such devices requires etching an array of slits of various aspect ratios while keeping nanometric precision: indeed, a small deviation in their aspect ratio can significantly change the induced phase pattern. These technological constraints are hardly achievable, thus underlining the need for a simpler design.

For this purpose, we propose a two-step simplification of the design of plasmonic lenses, thanks to basic physical and technological assumptions. This template introduces the new concept of Huygens lens that consists in the combination of a wide central slit surrounded by external single mode slits (technologically viable and convenient aspect ratios). Huygens lenses are no longer based on the guided mode index modulation but on wave interferences.

Indeed, the width of the central slits localizes the focalization spot at the desired focal length given by the Rayleigh-Sommerfeld diffraction formula. Then, single mode slits are added on each side of the central aperture at positions that lead to constructive interferences at the desired focal point. We design a Huygens lens and show that the focalization is sharper for larger number of secondary slits, in agreement with the lens aperture theory.

8982-21, Session 4

Toward dynamic metamaterials for monothically-integrated multilayer polarization filters

Nicole Pfiester, Tufts Univ. (United States); Corey Shemelya, The Univ. of Texas at El Paso (United States); Thomas J. Rotter, Ganesh Balakrishnan, The Univ. of New Mexico (United States); Thomas E. Vandervelde, Tufts Univ. (United States)

Metamaterials are engineered nanostructures that can interact with light in novel ways, with wide ranging applications including wavelength specific polarizing filters. Dynamic metamaterials, whose interaction with light is dependent on the application of a bias voltage, allow the individual layers of a monothically integrated stack to be engaged at will while appearing transparent in the absence of bias.

Our research seeks to generate polarization-dependent interactions with light. Specifically, the application of a bias changes the metamaterial response and blocks polarized waves parallel to the x-axis. Further manipulation of the base pattern resulted in a static filter that admits

polarized light parallel to the x-axis of the unit cell while blocking perpendicular polarizations. Transmission measurements through representative layers of material show how light will interact with a multilayer metamaterial stack. The success of this work lends the possibility of incorporating this data into an x and y polarization filter stack in future designs.

The samples were fabricated on a sapphire substrate with a Si-doped GaAs layer that was grown epitaxially via MOCVD. The gold metamaterials were deposited along with ohmic and schottky contacts using physical vapor deposition. The pattern dimensions were tuned for wavelengths in the mid-infrared transmission window, from 4 to 6?m, and have applications as sensors for man-made objects.

8982-22, Session 5

Unusual 3D lithography approaches for fabrication of polymeric photonic microstructures *(Invited Paper)*

Pietro Ferraro, Istituto Nazionale di Ottica (Italy)

Novel and intriguing lithographic approaches based on instabilities of liquid polymers and electro-hydro-dynamic at nanoscale have been developed. The unusual fabrication methods were aimed at fabricating 3D polymeric microstructures. A variety of microstructures were fabricated and tested for applications in different fields.

8982-23, Session 5

Nanolaminate structures fabricated by ALD for reducing propagation losses and enhancing the third-order optical nonlinearities

Lasse Karvonen, Aalto Univ. (Finland); Tapani Alasaarela, Henri Jussila, Aalto Univ. School of Science and Technology (Finland); Seyed Soroush Mehravar, College of Optical Sciences, The Univ. of Arizona (United States); Ya Chen, Antti Säynätjoki, Aalto Univ. (Finland); Robert A. Norwood, Nasser N. Peyghambarian, Khanh Q. Kieu, College of Optical Sciences, The Univ. of Arizona (United States); Seppo Honkanen, Univ. of Eastern Finland (Finland); Harri Lipsanen, Aalto Univ. School of Science and Technology (Finland)

We demonstrate a novel atomic layer deposition (ALD) process to control the crystallinity of titanium dioxide (TiO2) and zinc oxide (ZnO) using amorphous intermediate Al2O3 layers. The waveguide losses of TiO2/Al2O3 nanolaminates measured using prism coupling method for both 633 nm and 1551 nm wavelengths are as low as 0.2 ± 0.1 dB/mm with the smallest crystal size. In comparison, plain TiO2 deposited at 250°C without the intermediate Al2O3 layers shows high scattering losses and is not viable as a waveguide material. The third-order optical nonlinearity in TiO2/Al2O3 nanolaminate is studied, and it is shown that the crystallinity controlled ALD-TiO2 is an excellent candidate for various optical applications, where good thermal stability and high third-order optical nonlinearity are needed. [1] We also investigate the third-order optical nonlinearity in ZnO/Al2O3 nanolaminates fabricated by atomic layer deposition and show that the third-order optical nonlinearity can be enhanced by nanoscale engineering of the thin film structure. The grain size of the polycrystalline ZnO film is controlled by varying the thickness of the ZnO layers in the nanolaminate. Nanoscale engineering enables us to achieve a third harmonic generated signal enhancement of ~13 times from the optimized nanolaminate structure compared to a ZnO reference film of comparable thickness. [2]

[1] T. Alasaarela et al., "High quality crystallinity controlled ALD TiO2 for waveguiding applications", Accepted to Optics Letters, 2013.

[2] L. Karvonen et al., "Enhancement of the third-order optical nonlinearity in ZnO/Al2O3 nanolaminates fabricated by atomic layer deposition," Applied Physics Letters, Vol. 103, Issue 3, pp. 031903 (2013).

8982-24, Session 5

Split-gate and asymmetric contact carbon nanotube optical devices

Mark A. Hughes, Kevin P. Homewood, Richard J. Curry, Univ. of Surrey (United Kingdom); Yutaka Ohno, Takashi Mizutani, Nagoya Univ. (Japan)

We report rectification, electroluminescence (EL) and photocurrent from carbon nanotube (CNT) field effect transistors with asymmetric contacts and split gate geometries. The appropriate split gate bias can be used to select the rectification direction, modify the reverse bias saturation current (I0), ideality factor (η), rectification ratio, EL full width at half maximum (FWHM), short circuit current (ISC) and open circuit voltage (VOC). EL was measured from a symmetric contact device at various bias configurations, the minimum FWHM was 38 meV. This EL FWHM was considerably lower than other bias configurations, and was due to the preference of tunnelling over thermionic emission of carriers. This control of EL FWHM could have applications in telecommunications. We estimate the quantum efficiency of the EL to be 1x10-5. With a fixed Vd, increasing the opposite split gate bias caused the EL to increase monotonically from zero, indicating an ambipolar emission mechanism. A single CNT asymmetric contact device had an on/off ratio of 1x107 and a mobility of 39 cm2/Vs. The transfer characteristic from both or individual gates, and the Id-Vds characteristics can be explained if the Schottky barrier for electrons is lower at the Pd contact than it is at the Ti contact. When operated as a photodiode, we estimate a power conversion efficiency of 1x10-6. Increasing opposite split gate bias causes ISC and VOC to increase, then plateau at 41 pA and 0.34 V, respectively. This control of VOC could allow the bandwidth/efficiency trade-off of this photodiode to be overcome.

8982-25, Session 5

Optical magnetic scattering from sub-wavelength rectangular apertures

Dukhyung Lee, Sanghoon Han, Young-Mi Bahk, Ji Yeah Rhie, Dai-Sik Kim, Seoul National Univ. (Korea, Republic of)

We measured scattering from sub-wavelength rectangular apertures in metallic film and found out that magnetic field dominates the scattering process. To discriminate the effect of magnetic field and electric field on scattering process, we used oblique TM and TE incidences with large incidence angle. We did polar plot measurement of scattering polarization for the two incidences. Polar plots show that scattering polarization was rotated to the short axis direction as expected from the shape effect. Interesting feature is that scattering intensity from TM incidence is much higher than that from TE incidence indicating rectangular apertures interact with magnetic field more easily than electric field. To investigate further, we measured scattering intensity from TM and TE incidence, aligning the long axis to magnetic field and the short axis to electric field respectively, and calculated ratio between the two intensities. All scattering intensity ratios are over 1 (typically order of ten for 79° incidence angle) and increase with incidence angle and wavelength. To explain the ratios, we made a model assuming that scattering is proportional to the surface electric field. Larger-than-1 ratios indicate that the incident magnetic field induced electric field is much larger than its electric counterpart. At metal surface, incident magnetic field interferes constructively with reflected field and incident electric field interferes destructively, which gives the difference in induced surface electric field. This is the same thing that Fresnel formulas state. This interference feature is enhanced for large relative permittivity, or longer wavelength.

8982-27, Session 6

Optical properties of Yb-doped fibers prepared by gas phase doping

Florian Lindner, Claudia Aichele, Anka Schwuchwo, Martin Leich, Andy Scheffel, Sonja Unger, Institut für Photonische Technologien e.V. (Germany)

The performance of rare-earth doped high power silica fiber lasers has been dramatically increased with output powers in multi-kW range. The Modified Chemical Vapor Deposition (MCVD) technology in combination with solution doping is the leading technology to manufacture single or low-mode fibers with high efficiency, reliability and beam quality. Since this technology only permits the deposition of cores that possess an excellent optical quality up to a diameter of 1.5 mm, the implementation of large core/cladding ratios is limited.

Beside the powder sinter technology there is another possibility to overcome these geometrical limitations. The active core diameter in the preform can significant increased by deposition of rare earths and aluminium from the gas phase by high temperature evaporation of rare-earth chelates and aluminium chloride in the MCVD process. For this reason a state-of-the-art facility has been established to realize large core fiber preforms with excellent longitudinal and radial uniformity.

Here, we report on systematical investigations of the incorporation of ytterbi-um and aluminium in silica by gas phase doping technique. Preforms and fibers were prepared in dependence on the process parameters (such as evaporator temperatures, gas flows, deposition temperatures, collapsing conditions) in a wide range of ytterbium and aluminium concentration. The samples were characterized concerning the radial distribution of refractive index and dopant concentrations and the absorption and emission properties in the UV/VIS/NIR region. First laser experiments have demonstrated slope efficiency of 80%, comparable with fibers made by MCVD/ solution doping.

8982-28, Session 6

Gamma-radiation-induced degradation of single-mode passive and ytterbium-doped optical fibers

Briana Singleton, James Petrosky, Michael Pochet, Air Force Institute of Technology (United States); Nicholas G. Usechak, Air Force Research Lab. (United States); Susan M. White, The Ohio State Univ. (United States)

The integration of optical components into the digital processing units of satellite subsystems has the potential to remove interconnect bottlenecks inherent to the volume, mass, complexity, reliability and crosstalk issues of copper based interconnects. Given that on-board high-bandwidth communications will inherently utilize passive optical fibers as the communication channel, this work investigates the impact of gamma irradiation from a Co-60 source on passive optical fibers and ytterbium-doped single mode fibers operated in situ as amplifiers for a 1060 nm light source. Standard optical patch cables were evaluated along with passive double clad fibers designed for use with double clad rare-earth doped fibers. Varied dose rates, exposure times and signal transmission wavelengths were used to investigate the degradation of the passive fibers exposed to total doses above 100 krad (Si). The Yb-doped fibers were evaluated in the same environments and the effect on the signal gain was measured. This paper will discuss the increased attenuation in the fibers across a broad wavelength range, while also showing strong wavelength dependence along with the effect that the increased attenuation has on the actively pumped Yb-doped fiber amplifier performance.

8982-29, Session 6

Impact of photodarkening on Yb lifetime in Al-silicate fibres

Riccardo Piccoli, Swansea Univ. (United Kingdom); David Mechin, PERFOS (France); Thierry Robin, iXFiber SAS (France); Stefano Taccheo, Swansea Univ. (United Kingdom)

In this paper, the lifetime temporal reduction in ytterbium doped aluminosilicate fibers due to the pump induced photodarkening (PD) has been reported. A linear correlation between equilibrium lifetime reduction and equilibrium losses due to the PD effect was demonstrated. A squared-law dependence between equilibrium lifetime reduction and dopant concentration (wt%) suggests a possible correction term for the rate-equations which allows to improve the accuracy on fiber lasers development. Finally a quenching effect was also observed for different pump power levels in order to find the corresponding lifetime value for different inversion levels. The quantitative analysis allows to determine the photodarkening quenching term in the laser rate equation systems

8982-30, Session 6

Novel observations on photodarkening in ytterbium-doped aluminosilicate fibers

Joan J. Montiel i Ponsoda, Aalto Univ. School of Electrical Engineering (Finland); Magnus Engholm, Mid Sweden Univ. (Sweden); Lars Norin, Acreo AB (Sweden); Seppo Honkanen, Univ. of Eastern Finland (Finland); Harri Lipsanen, Aalto Univ. School of Science and Technology (Finland)

Ytterbium (Yb) doped fibers are the preferred gain media in high peak and average power laser sources. However, the photodarkening effect, which manifests as a time dependent increase of loss in the doped core, is one of the main threats to the efficiency of the Yb-doped gain media leading to degradation of the laser performance. Different methods have been used to reduce the effect of photodarkening in Yb-doped laser fibers. The use of different co-dopants such as cerium or phosphorous can improve the photodarkening resistance of the laser fibers. On the other hand, however, these co-dopants are responsible also for increasing the fiber background loss attenuation, complicating the control of the refractive index or reducing the Yb absorption and emission cross section. We present new observations on photodarkening in Yb-doped aluminosilicate fibers. An Yb-doped fiber sample that is previously processed by a given method, is photodarkened by pumping at 976 nm at room temperature. The photodarkened sample shows spontaneous recovery at room temperature and a complete bleaching is observed in roughly 50 hours. This process also takes place with the probe turned off, which excludes the possibility of photobleaching. These results are of particular importance to improve the understanding of the photodarkening process and to develop a fabrication process to mitigate photodarkening in Yb-doped aluminosilicate fibers without the use of heavy co-doping.

8982-31, Session 6

Up-conversion emission tuning in triply-doped Yb3+/Tm3+/Er3+ novel fluoro-phosphate glass and glass-ceramics

Yannick Ledemi Sr., Andrée-Anne Trudel, Ctr. d'Optique, Photonique et Laser (Canada); Victor A. Garcia Rivera, Univ. de São Paulo (Brazil); Younès Messaddeq, Ctr. d'Optique, Photonique et Laser (Canada)

New Yb3+, Er3+ and Tm3+ triply doped fluoro-phosphate glasses belonging to the system NaPO3- YF3-BaF2-CaF2 have been prepared by the classical melt-casting technique. Glasses containing up to 10 wt.% of rare-earth ions fluorides have been obtained and characterized by using differential scanning calorimetry (DSC), UV-visible-near-infrared spectroscopy and up-conversion emission spectroscopy under excitation with a 975 nm laser diode. Transparent and optically homogeneous glass-ceramics have been reproducibly obtained by appropriate heat treatment in view to manage the red, green and blue emissions upon 975 nm laser excitation. According to the applied thermal heat-treatment, a large enhancement of intensity of the up-conversion emission – from 10 to 160 times higher – has been achieved in the glass-ceramics compared to that of glasses, suggesting incorporation of the rare-earth ions into the crystalline phase. Furthermore, a large range of color rendering has been observed in these materials by controlling the laser excitation power and material crystallization rate. Time-resolved luminescence experiments as well as X-ray diffractometry and scanning electron microscopy techniques have been employed in order to understand and correlate the multicolor emission changes to the crystallization behavior of this material. A progressive phase transformation of the fluorite-type CaF2-based nano-crystals initially generated was observed along with increasing heat-treatment time, thus modifying the rare earth ions spectroscopic features.

8982-32, Session 7

Reliability considerations of high-speed germanium waveguide photodetectors *(Invited Paper)*

Zhijuan Tu, Zhiping Zhou, Xingjun Wang, Peking Univ. (China)

Considering their practical applications in the optical communication systems, Germanium (Ge) waveguide photodetectors should have not only superior technical performances, but also long term reliability. In this paper, a 30 Gb/s Ge waveguide photodetector was demonstrated and its reliability under elevated temperatures and high stress biases were investigated. The dark current was chosen as a representative target to be monitored. For different reverse biases, the slopes of the dark current versus stress bias time curves were initiatively found to be similar and made the lifetime extrapolation feasible. The lifetime of the Ge waveguide photodetector under different stress bias was predicted by using a simple extrapolation method. So the reliability data can be obtained within a reasonably short period. The moderate bias voltage was estimated to be -3V to maintain the ten-year lifetime. As the first time, the degradation mechanism under stress biases was analyzed in detail by the reaction-diffusion model. Since disilane (Si2H6) and germane (GeH4) were employed for the epitaxial growth of SiGe buffer layer and Ge layers, Si-H bonds will be generated in the buffer layer due to the lattice constant mismatch. When the high stress biases were applied, the Si-H bonds would be broken by a thermal chemical reaction and the released hydrogen would diffuse away. Thus the dangling bonds would be generated and result in the interface traps between the SiGe buffer layer and the Ge layer, which would become the recombination centers of carries, thus increase the dark current and cause the performance degradation. The experimental results conformed well to the theoretical derivation based on reaction-diffusion model.

8982-33, Session 7

Fabrication and characterization of 120 degree optical hybrids as all-fiber monolithic 3x3 couplers

Elyes Khettal, Nicolas Godbout, Wendy-Julie Madore, Mikael Leduc, Ecole Polytechnique de Montréal (Canada)

We present the fabrication of an all-fiber 120° optical hybrid for phase measurement purposes. This is a device with two input and three output ports. As inputs, we use a modulated signal (S) in the first port and a reference signal (R) in the second. The reference R acts as the local oscillator in a coherent demodulation system which allows the reconstruction of the four quadratures of the signal S from the amplitudes of the output signals.

The optical hybrid requirements are fulfilled by a 3x3 fiber coupler in triangular cross-section geometry fabricated using a standard fusion-tapering technique. A new procedure allows the fabrication of such couplers of high quality. Fabrication parameters, such as the degree of fusion, length and taper ratio are adjusted in order to obtain the properties of a 120° hybrid. Such a device, working over the entire C-band, has the advantage of being lossless and polarization-independent. The device is also more stable mechanically and in temperature than conventional equivalent interferometers. As it enables the unambiguous measurement of the optical amplitude and phase of a signal with respect to a reference, such a component is firstly designed for coherent demodulation. We propose a post-processing of the output signals for phase measurement.

Applications for such a device are also found in imaging, such as frequency domain optical coherence tomography where a measurement of the phase solves the depth aliasing problem. It can also be used to perform accurate surface measurements for inspection of mechanical parts.

8982-34, Session 7

Fast and precise continuous focusing with focus tunable lenses

Selina Casutt, Michael Bueeler, Mark Blum, Manuel Aschwanden, Optotune AG (Switzerland)

With electrically tunable lenses it is possible to focus in milliseconds without translational mechanics involved. We demonstrate fast imaging systems which can focus at distances from infinity to a few centimeters with a high optical quality. Furthermore, fast laser processing in three dimensions is enabled without mechanical translation of the focusing lens or the sample. With tunable lenses the entire optics can be made compact, robust and abrasion-free.

We will discuss different configurations how to integrate the tunable lens in the optical path. For machine vision applications, the achievable optical quality depends on the chosen combination of the tunable lens with a fixed focal length lens and a camera. It is recommended to use a fixed focus lens with a short distance between the stop position and the front of the lens. Furthermore, we will present important points how to achieve optimal performance in laser processing applications such as orientation and position of the tunable lens, beam diameter and the used focal length range.

Additionally, we will compare various approaches for monitoring the focal length of the tunable lens. The focal length of the tunable lens is sensitive to temperature changes, as the lens material is a fluid. However, in contrast to conventional lenses, the focal length of the tunable lens can be corrected electrically. For that purpose, the tunable lens exhibits an integrated temperature sensor for temperature compensation. Also optical feedback solutions will be presented for applications requiring highest precision and tracking of the absolute focal length value.

8982-35, Session 7

Anti-reflective surface structuring of optical components: a review

Catalin M. Florea, Sotera Defense Solutions, Inc. (United States); Jasbinder S. Sanghera, U.S. Naval Research Lab. (United States); Rajendra Joshi, The Univ. of North Carolina at Charlotte (United States); Lynda E. Busse, U.S. Naval Research Lab.

(United States); Kevin J. Major, The Univ. of North Carolina at Charlotte (United States); Menelaos K. Poutous, Univ. of North Carolina at Charlotte (United States); Leslie B. Shaw, Ishwar D. Aggarwal, U.S. Naval Research Lab. (United States)

While the thin-film anti-reflective (AR) coating technology has been widely used on a variety of substrates, it does have its drawbacks due to reduced laser damage threshold and increased environmental sensitivity. In contrast, nanostructuring of the optical surface offers enhanced laser damage thresholds since no extraneous materials are used, and provides similar optical performance while making possible broader spectral windows of operation. We will present a review of the results we obtained when employing surface nanostructuring on a variety of substrates: fused silica glass windows and lenses, silica and IR fibers, spinel ceramic, rare-earth doped crystals, as well as ZnS, sapphire and germanium windows.

Reflection losses per surface for fused silica windows around 0.02% and laser damage thresholds as high as 100 J/cm2 have been demonstrated at 1.06 microns. Additionally, optical fibers with random AR surface structuring show laser damage threshold as high as 750 J/cm2. Spinel ceramic substrates have also been successfully patterned through reactive ion etching and reflection losses as low as 0.3% have been demonstrated at 1.06 microns with laser damage thresholds as high as 10 J/cm2. In general, the nanostructured substrates are indeed showing improved thresholds when compared with uncoated or traditional AR coated substrates and fibers.

Besides demonstrating results over broad spectral ranges from the visible domain to the short and medium-wave and to the long-wave regions of the spectrum, we will also address the issue of processing large-diameter optical substrates. Additionally, scattering issues and surface cleanliness procedures will be discussed as well.

8982-36, Session 7

High spectral contrast filtering produced by multiple reflections from paired Bragg gratings in PTR glass

Daniel Ott, Marc SeGall, Ivan B. Divliansky, George B. Venus, Leonid B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

The properties of multiple reflections from narrow bandwidth reflection Bragg gratings are presented as a new type of filter. The use of multiple reflections serves to increase the suppression ratio of the out of band spectral content such that contributions of grating sidelobes can be mitigated. The suppression ratio can exceed the suppression achieved by apodization techniques commonly used in manufacturing Bragg gratings. The result is a device which retains spectral and angular selectivity in a single, high efficiency diffraction order but reshapes spectral/angular response to achieve higher signal to noise ratios. The material for recording these high suppression devices is photo-thermo-refractive (PTR) glass. PTR is a highly homogeneous photosensitive glass with features such as low losses, and high laser damage threshold. It has recently been used with good success to record permanent volume Bragg gratings with high efficiency narrow band selectivity for use in laser cavities. Increasing the number of reflections from such a device, new filtering performance can be obtained. Multiple reflections from the grating surface are achieved using several different arrangements. The multiple pass grating reflections are demonstrated and compared to the performance of a single reflection from a volume Bragg grating. Applications of filters with high spectral noise suppression include spectral sensors and low spectral noise external cavity laser diodes.

8982-37, Session 7

Design and characterization of avalanche photodiodes in submicron CMOS technologies

Lucio Pancheri, Univ. degli Studi di Trento (Italy); Toufik Bendib, Univ. degli Studi di Trento (Italy) and Univ. of Batna (Algeria); Gian-Franco Dalla Betta, Univ. degli Studi di Trento (Italy); David Stoppa, Fondazione Bruno Kessler (Italy)

There is an increasing number of academic and industrial institutions who have started working on Avalanche Photodiodes (APDs) arrays fabricated in CMOS technologies. In this field, the current research is mainly focused on Geiger-mode operation, but several applications would also benefit from the monolithic integration of high-performance linear-mode APDs in CMOS processes. Although the most natural application targets for these devices are telecommunication receivers, APDs can also find applications in time-resolved optical detection and scintillation detection. CMOS integration can open the way to the fabrication of systems which are competitive in terms of cost and allow a high degree of parallelization, up to levels found in image sensors.

Most of the works recently published on CMOS linear-mode APDs, mainly targeting telecommunication applications, show experimental results from device characterization, but lack a careful analysis of the excess noise factor. In this work, we will consider the performance of Avalanche Photodiodes working in the linear mode, with particular emphasis on noise simulation and characterization. Other figures of merit of the devices will be considered, namely Quantum Efficiency, dark current, capacitance and uniformity of gain and breakdown voltage, which are particularly important in array integration. Device simulations will be used to discuss the current status and the perspectives for the integration of high-performance low-noise devices in standard CMOS processes.

8982-26, Session 8

Rare-earth emission and nanoparticles in glasses *(Invited Paper)*

Anne-Marie Jurdyc, Alice Berthelot, Univ. Claude Bernard Lyon 1 (France)

No Abstract Available

8982-38, Session 8

Electrical properties of amorphous chalcogenide/silicon heterojunctions modified by ion implantation

Yanina Fedorenko, Mark A. Hughes, Russell M. Gwilliam, Kevin P. Homewood, Daniel W. Hewak, Univ. of Surrey (United Kingdom); Tae-Hoon Lee, Stephen R. Elliott, Univ. of Cambridge (United Kingdom); Richard J. Curry, Univ. of Surrey (United Kingdom)

The question of the suitability of a number of chalcogenide materials for use in electronic devices is related to the ability to control the conductivity of these self-compensated semiconductors and to attain the formation of thermodynamically stable interfaces with technologically dominant semiconductors such as silicon. To realize this, we employ ion implantation as a non-equilibrium doping technique, capable of preventing an introduced atom from reaching its lowest energy bonding configuration and, consequently, unpinning the Fermi level. This work reports on the electrical properties of amorphous chalcogenide/silicon heterojunctions (HJs). The chalcogenides under study include Ga-La-S,

Ge-Sb-Te, and Ge-Se films prepared on Si(100) of both n- and p-type conductivity. Bismuth or aluminium ions of energy 190 keV or 35 keV, respectively, were implanted at different doses. Diode characteristics are observed on HJs formed on p- and n-type silicon, implying that rectification is band bending controlled. There are several supporting observations: (i) saturation characteristics with a slight barrier which accounts for an offset voltage are seen for the p-p devices; (ii) the photovoltaic effect is observed for the p-n and the p-p devices. It is shown that the dispersion free Mott-Schottky curves for heterojunctions can be used to assess the impact of ion implantation; the built-in potential indicates substantial interface charge is present in the implanted samples. Analysis of the forward current reveals that the charge transport mechanism is space charge limited. These results ensure that ion implantation is an useful method for the modification of chalcogenide glasses and their interfaces with silicon.

8982-39, Session 8

Multi-band reflectance spectroscopy of carbonaceous lithium iron phosphate battery electrodes versus state of charge

Krishna Iyer, Liliana Zdravkova, Ryan C. Norris, Victor L. Chabot, Patricia Nieva, Aiping Yu, Univ. of Waterloo (Canada); Xiaohui Wang, General Motors of Canada (Canada); Shih-Ken Chen, General Motors Corp. (United States)

This paper presents the results of spectroscopic studies performed on carbonaceous lithium iron phosphate (LiFePO4/C)-cathode materials obtained from deconstructed commercial cylindrical LiFePO4 batteries as a function of state-of-charge (SOC) for optical sensing applications. Previous to obtaining the cathode material samples from the deconstructed batteries, they were charged to between 30% and 80% of their nominal capacity at increments of 5%, using a constant-current, constant-voltage (CCCV) cycling method. Visible (Vis), Near Infrared (NIR) and FTIR (Fourier Transform Infrared) spectroscopy were then used to provide a methodology that can aid on a fundamental understanding of the optical properties of battery cathode materials and their relation to battery mechanisms. Knowledge of these properties could potentially offer new optical-based sensing mechanisms for measuring SOC in lithium ion batteries.

Visual inspection of the deconstructed batteries show that the LiFePO4/C-cathodes display subtle changes in color (shades of grey) with respect to SOC with green tonality observed at certain SOCs. Vis/NIR results support this visual observation by displaying uniform shifts in reflectance versus SOC within the 500 nm to 800 nm wavelength range. FTIR spectroscopy however displays a strong dependence on the lithiation state of the electrode, which in turn is a function of the SOC, in the fingerprint region between 1500 cm-1 and 500 cm-1. Although some studies have been conducted on the optical properties of LiFePO4, to the best of our knowledge, this is the first time that a broad spectrum spectroscopic analysis has been performed on electrodes extracted from commercially available LiFePO4 batteries.

8982-40, Session 8

Persistent luminescence of ZnGa2O4: Cr, an outstanding biomarker for in vivo imaging

Suchinder Sharma, Aurelie Bessiere, Didier Gourier, Laurent Binet, Bruno Viana, Ecole Nationale Supérieure de Chimie de Paris (France); Neelima Basavaraju, Kaustubh Priolkar, Goa Univ. (India); Daniel Scherman, Thomas Maldiney, Cyrille Richard, Univ. Paris Descartes (France)

Optical imaging constantly demands more sensitive tools for biomedical research and medical applications. Persistent luminescence nanoparticles emitting in the near-infrared (NIR) have been recently introduced to enable highly sensitive in vivo imaging of small animals with complete avoidance of tissue autofluorescence [1]. The imaging technique has been improved by enhancing the persistent luminescence efficiency of various red-emitting phosphors, such as Mn2+-doped silicates (CaxZnyMgzSi2O6:Mn) [2] and phosphates [3]. We now introduce a new generation of LLP biomarkers based on chromium-doped zinc gallate (ZnGa2O4:Cr) whose persistent luminescence is intense and most of all, can be re-activated in vivo through living tissues by using simple red LEDs light.

ZnGa2O4 (ZGO) is a normal spinel. When doped with Cr3+ ions, ZGO:Cr becomes a high brightness persistent luminescence material with an emission spectrum perfectly matching the transparency window of living tissues [4]. It allows in vivo mouse imaging with a better signal to background ratio than classical quantum dots. The most interesting characteristic of ZGO:Cr lies in the fact that its LLP can be excited with red light, well below its band gap energy and in the transparency window of living tissues [5]. A mechanism based on the trapping of carriers localized around a special type of Cr3+ ions namely CrN2 can explain this singularity. The antisite defects of the structure are the main responsible traps in the persistent luminescence mechanism. When located around Cr3+ ions, they allow, via Cr3+ absorption, the storage of not only UV light but also all visible light from the excitation source.

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8982-41, Session 8

Optical and electronic properties of bismuth-implanted glasses

Mark A. Hughes, Yanina Federenko, Russell M. Gwilliam, Kevin P. Homewood, Univ. of Surrey (United Kingdom); Daniel W. Hewak, Univ. of Southampton (United Kingdom); Tae-Hoon Lee, Stephen R. Elliott, Univ. of Cambridge (United Kingdom); Richard J. Curry, Univ. of Surrey (United Kingdom)

Bi-doped glasses have been used as the gain media in broadband lasers and optical amplifiers; however, their current performance is believed to be limited by bismuth optical centers not involved in the gain process. Bi is also one of the few elements known to enable carrier-type reversal in chalcogenide glasses. Bi-doped glasses are almost invariably melt-doped, allowing chemical equalisation of the Bi with its host, whereas ion implantation is a non-equilibrium doping technique. We implanted Bi into a series of glasses: thin films of Ge-Se, Ge-Sb-Te, Ga-La-S; and bulk B-P-O and SiO2. When excited at 514 nm, photoluminescence (PL) peaking at ~700 nm, characteristic of Bi melt-doped oxide glasses, was observed. Excited at 782 nm, unusual, narrow PL, peaking at ~830 nm, was observed. The binding energy of the implanted Bi, determined by X-ray photoelectron spectroscopy measurements, was characteristic of metallic Bi, rather than the significantly higher binding energy, characteristic of higher oxidation states, observed in Bi melt-doped oxide glasses. Absorption measurements indicated a blue-shift in the band edge of Ga-La-S and Ge-Se, and a red-shift in Ge-Sb-Te and SiO2. Thermopower measurements of Ge-Sb-Te indicated a significant decrease in the Seebeck coefficient with Bi implantation, and a reversal of its temperature dependence. Arrhenius plots of conductivity showed that doses over 3?1015 ions/cm2 reduced the activation energy of Ga-La-S. Ion implantation can create Bi optical centers not observed by melt doping, which may lead to higher performance optical devices; it can also modify the electronic properties of chalcogenide glasses, which may lead to novel electronic devices.

8982-42, Session 8

Quantitative characterization of photodoping phenomena in amorphous chalcogenide GeS2 film

Yoshihisa Murakami, Moriaki Wakaki, Tokai Univ. (Japan)

When metal layers like Ag and Cu deposited on the amorphous chalcogenide films such as As2S3, As2Se3, GeS2, and GeSe2, are illuminated by light, the metal diffuses abnormally into the amorphous chalcogenide layer. This abnormal diffusion of metal is called photodoping. The large modulation of refractive index is realized by the doping of large amount of Ag atoms into the amorphous network of chalcogenide film which gives the possibility for various photonic device applications. In this study, the quantitative characterization of photodoping phenomena was carried out for amorphous GeS2 films using Ag as a doping metal to obtain the basic information to the photonic device fabrication.

Quantum efficiency to reach the saturation of the doping was derived using the laser diodes of several wavelengths which cause a photodoping phenomenon.

As for the wavelength dependence of the photodoping, it was suggested that the quantum efficiency was proportional to photon energy and showed the tendency similar to the absorption spectrum of the amorphous GeS2 film.

As for the irradiation intensity dependence, the quantum efficiency was proportional to the number of incident photons at low intensity. For the intensity over 10mW, the enhancement of doping efficiency was observed due to some extra effect like thermal effect.

Makless patternings with refractive index modified films are possible by using a manipulated laser beam scanning. As an example, micro gratings were fabricated using a laser microscope and waveguides were also fabricated by scanning the doping laser.

8982-43, Session 8

Dielectric functions of AZO films grown on c-plane sapphire substrate by pulsed laser deposition

Mohammad T. Yaseen, Academia Sinica (Taiwan)

Transparent conducting polycrystalline AZO films were grown on sapphire substrates at substrate temperatures (200 to 300) °C by pulsed laser deposition (PLD). The x-ray diffraction measurement shows that the crystalline quality of AZO films was enhanced at higher substrate temperature. Then the electrical and optical properties of the AZO films have been systematically investigated by several experimental equipment. The room-temperature micro photoluminescence (μ-PL) spectra show a strong ultraviolet (UV) excitonic emission and weak deep-level emission, which indicate low structural defects in the films. A Raman shift of about 11 cm?1 is observed for the first-order longitudinal-optical (LO) phonon peak for AZO films when compared to the LO phonon peak of bulk ZnO. The Raman spectra obtained with UV resonant excitation at room temperature show multi-phonon LO modes up to third order. Optical response due to free electrons of the AZO films was characterized in the photon energy range from 0.6 to 6.5 eV by spectroscopic ellipsometry (SE). The free electron response is expressed by using a simple Drude model combined with the Cauchy model.

8982-44, Session 9

Longitudinal strain sensing with photonic crystal fibers and fiber Bragg gratings

Tadeusz Tenderenda, Michal Murawski, Michal Szymanski, Military Univ. of Technology (Poland) and InPhoTech Ltd. (Poland); Lukasz Szostkiewicz, InPhoTech Ltd. (Poland); Martin Becker, Manfred? Rothhardt, Hartmut? Bartelt, Institut für Photonische Technologien e.V. (Germany); Pawel Mergo, Krzysztof Poturaj, Mariusz Makara, Krzysztof Skorupski, Univ. of Maria Curie-Sklodowska (Poland); Pawel Marc, Leszek R. Jaroszewicz, Military Univ. of Technology (Poland); Tomasz Nasilowski, Military Univ. of Technology (Poland) and InPhoTech Ltd. (Poland)

Photonic crystal fibers (PCF), sometimes also referred to as microstructured fibers, have been a subject of extensive research for over a decade. This is mainly due to the fact, that by changing the geometry and distribution of the air holes the fiber properties can be significantly modified and tailored to specific applications, e.g. in fiber optic sensing. While pressure, bend or transversal load transducers based on novel microstructured fiber designs have been already reported, a fiber geometry with significantly enhanced longitudinal strain sensitivity has not yet been proposed. In this paper we present the results of a numerical analysis of the influence of the air hole distribution and size as well as germanium core doping level on the sensitivity of the propagated modes' effective refractive index to externally applied longitudinal strain. We propose an optimal strain sensitive fiber design, with a number of the numerically characterized fibers drawn and experimentally evaluated to confirm the theoretical results. Furthermore as the direct measurement of the effective refractive index change may be complex and challenging in field environment, we propose to use fiber Bragg gratings (FBG) and Mach-Zehnder interferometry in our sensing set ups. As the Bragg wavelength is a function of the effective refractive index, the external strain changes can be monitored through the Bragg wavelength shift with a simple optical spectrometer. Moreover, since the PCF is also optimized for low loss splicing with standard single mode fiber, our novel sensor head can be used with standard off-the-shelf components in complex multiplexed sensing arrays, with the measured signal transmitted to and from the sensor head by standard telecom fibers, which significantly reduces costs.

8982-46, Session 9

Super low power consumption middle infrared LED-PD optopairs for chemical sensing

Nikolay D. Stoyanov, Khafiz M. Salikhov, Karina V. Kalinina, LED Microsensor NT, LLC (Russian Federation); Sergey S. Kizhaev, Anton V. Chernyaev, LED Microsensor NT LLC (Russian Federation)

The new photodiodes with cut-off 3640 nm, 4600 nm and 5150 nm were developed recently in high-tech company LED Microsensor NT (St. Petersburg, Russia) in cooperation with Ioffe Institute in (St. Petersburg) and Aalto University (Espoo, Finland). Photodiode heterostructures InAsSb/InAsSbP were grown by MOCVD on InAs substrates. For PDs with cut-off 3640 nm at room temperature and wavelength 3300 nm responsivity reached 1.44 A/W, detectivity was 1.56*10^10 cm.Hz^(1/2)/W. For PDs with cut-off 4600 nm the same parameters were 2.09 A/W and 9.2*10^9 cm.Hz^(1/2)/W respectively (lambda=4600 nm). For the third type PDs with cut-off 5150 nm responsivity was 0.25 A/W, detectivity was 3.3*10^8 cm.Hz^(1/2)/W (lambda=5000 nm).

Creation of photodiodes for the spectral range 2500-5200 nm with acceptable efficiency allows designing optical cells with very low power

consumption (less than 1 mW) due to using of short pulses for driving the spectral matched LEDs.

Small size of the LED and PD dies (0.4-0.8 mm) and low heating dissipation makes possible to design very thin optical cells (less than 2 mm) for measuring CH_4, CO_2, CO, H_2O and other substances. Mounting of a few LED dies that emit at different wavelengths in such small cell allows measuring different chemical substances simultaneously. Direct coating of optical filters on the LED or PD surface during post-growth process allows improving selectivity and sensitivity of the sensor.

Super low power consumption and thin size of the optical cell opens possibility to embed optical sensors in mobile devices.

8982-47, Session 9

Influence of the mode field diameter on the strain sensitivity of different fibres

Michal Murawski, Tadeusz Tenderenda, Marek Napierala, Military Univ. of Technology (Poland) and InPhoTech Ltd. (Poland); Lukasz Szostkiewicz, InPhoTech Ltd. (Poland); Ariel Lukowski, Zbigniew Holdynski, Michal Szymanski, Military Univ. of Technology (Poland) and InPhoTech Ltd. (Poland); Mateusz Slowikowski, InPhoTech Ltd. (Poland); Lukasz Ostrowski, Military Univ. of Technology (Poland) and InPhoTech Ltd. (Poland); Pawel Marc, Leszek R. Jaroszewicz, Military Univ. of Technology (Poland); Tomasz Nasilowski, Military Univ. of Technology (Poland) and InPhoTech Ltd. (Poland)

Phase sensitivities of temperature, longitudinal strain or pressure, are very important fiber features in sensing and telecommunication applications. The most common ways to modify such sensitivities are to change the material properties (by adjusting the core doping level) or employ microstructured fibers (which properties strongly depend on the cross-section geometry). We decided to investigate strain sensitivity influenced by effective mode field area and mode field diameter as clear consequence of fiber cross-section geometry.

In this paper we present the results of a three dimensional numerical analysis of the correlation between the fiber mode field diameter and its strain sensitivity. Both conventional and microstructured (commercially available and custom designed) fibers are investigated. Furthermore we compare these theoretical results with experimental data. To measure fiber sensitivity we developed a dedicated all-fiber Mach-Zehnder interferometer which enables the measurement of strain induced phase changes in various fiber types (including conventional and microstructured fibers).

As a conclusion of our work we present relationship between strain sensitivity and MFD – the larger is the MFD, the more sensitive is the fiber to the longitudinal strain.

8982-48, Session PWed

Evanescent field scanning optical microscopy

Vitaly Sukharenko, Roger Dorsinville, The City College of New York (United States)

The authors propose an alternative method for high resolution optical microscopy - Evanescent Field Scanning Optical Microscopy (EFSOM) which eliminates implementation of the scanning tip compare to classical NSOM technique. The approach involves scanning a sample in the evanescent-field of a prism generated using total internal reflection (TIR) and recording the reflected power as a function of position. The reflection pattern of the wave is collected and processed, using comparative differentiation. The extracted information is processed further to eliminate any distortions. The system is not limited by diffraction and resolution primarily depends on the characteristics of the photo-detector and scanning velocity. Implementation of thin silver layer and coupling of incident radiation into Surface Plasmons Polaritons (SPP), improves system sensitivity and reduces photo detector dynamic range requirements.

8982-49, Session PWed

Diode-pumped white-light emission from dysprosium- and samarium-doped glasses

Rami R. Bommareddi, Alabama A&M Univ. (United States)

Energy efficient solid state white light emitters are in great demand to replace the conventional light bulbs. Only those devices are useful which are compact and can be turned by the household voltages. There are compact and efficient diodes in the market which are operated with 110 V or 220 V. If these diodes are covered with a white light emitting phosphor materials then we have an all solid state white light emitters. Sodium borosilicate glasses embedded with Dysprosium and samarium were made by the melt quenching techniques. These glasses were cut and polished for optical work. The resulting glasses are transparent. Absorption and emission measurements confirmed the presence of the dopant ions. The lifetimes of the excited levels were measured by exciting the glasses with pulsed laser beams. Under 405 nm, diode laser excitation Dy^{3+} -doped glass revealed white emission. Fluorescence spectrum revealed emission lines at 489, 582, 671 and 764 nm. A combination of blue, yellow and red emissions caused the emission to appear as white light. Under 405 nm laser excitation fluorescence of Sm^{3+} -doped borosilicate glass also appeared white in color. The fluorescence revealed transitions at 570, 606, 654 and 717 nm. A borosilicate glass was made with Sm^{3+} and Dy^{3+} ions. The glass is analyzed under 405 nm diode laser excitation. The resulting white light emission is characterized. The CIE color coordinates were also derived.

8982-50, Session PWed

Continuously-tunable dual-wavelength fiber laser using two polymer Bragg gratings

Byeong Kwon Choi, Yong Seok Kwon, Ik Gon Park, Chungnam National Univ. (Korea, Republic of); Jun Gyu Seo, Hak Kyu Lee, ChemOptics Inc. (Korea, Republic of); Min Yong Jeon, Chungnam National Univ. (Korea, Republic of)

We present a continuously tunable dual-wavelength fiber laser incorporating two polymer Bragg gratings (PBGs), which are used as wavelength selective components in the laser cavity. The continuously tunable dual- wavelength fiber laser consists of a 1500 nm semiconductor optical amplifier (SOA) as a gain medium, a 3 dB fiber coupler, an optical circulator, two polarization controllers, an erbium-doped fiber amplifier (EDFA), two reflection type PBGs as wavelength selective filter, and a 30 % output coupler. The wavelength tuning of the PBG filters could be achieved by applying electrical power to the heating electrode fabricated on the polymer material. The reflectivity of the PBG filter is measured about 7%. The 3 dB linewidth of the PBG filter has about 0.27 nm. Reflected wavelength from the PBG filter could be tuned from 1546.6 nm to 1527.6 nm by changing the applied electrical power. When the applied electrical power to the PBG is increased from 0 mW to 120 mW, then the reflected center wavelength from the PBG is moved from 1546.6 nm to 1527.6 nm. The peak wavelength of lasing spectrum shifted toward shorter wavelengths as the temperature increase. The interval of dual wavelength is tunable by 19 nm for the maximum applied electrical power of 120 mW. The corresponding frequency range is 2.375 THz. The side mode suppression ratio of the dual wavelength laser has more than 30 dB. The 3 dB linewidth of the each lasing wavelength has about 0.07 nm. Tunable dual-wavelength fiber laser can be used to generate an optical beat source for CW THz radiation.

8982-51, Session PWed

Optical glass with tightest refractive index and dispersion tolerances for high-end optical designs

Ralf Jedamzik, Steffen Reichel, Peter Hartmann, SCHOTT AG (Germany)

In high end optical designs the quality of the optical system not only depends on the chosen optical glasses but also on the available refractive index and Abbe number tolerances. The primary optical design is based on datasheet values of the refractive index and Abbe number. In general the optical position of the delivered glass will deviate from the catalog values by given tolerances due to production tolerances. Therefore in many cases the final optical design needs to be modified based on real glass data. Tighter refractive index and Abbe number tolerances can greatly reduce this additional amount of work.

The refractive index and Abbe number of an optical glass is a function of the chemical composition and the annealing process. Tight refractive index tolerances require not only a close control and high reliability of the melting and fine annealing process but also best possible material data. These data rely on high accuracy measurement and accurate control during mass production. Modern melting and annealing procedure do not only enable tight index tolerances but also a high homogeneity of the optical properties.

Recently SCHOTT was able to introduce the tightest available refractive index and Abbe number tolerance available in the market: step 0.5 meaning a refractive index tolerance of +/- 0.0001 and a Abbe number tolerance of +/- 0.1%. This presentation describes how the refractive index depends on the glass composition and annealing process and describes the requirements to get to this thightest refractive index and Abbe number tolerance.

8982-52, Session PWed

Characterization of diced ridge waveguides in pure and Er-doped lithium-niobate-on-insulator (LNOI) substrates

Detlef Kip, Sergiy Suntsov, Christian E. Rueter, Helmut-Schmidt Univ. (Germany); Greg Stone, Volkmar Dierolf, Lehigh Univ. (United States); Hui Hu, Wolfgang Sohler, Univ. Paderborn (Germany)

Lithium-niobate-on-insulator (LNOI) is a new material platform for integrated optics allowing for small bending radii, high intensities and superior electro-optical and nonlinear properties. Ridges waveguide of different width were fabricated on pure and Er-doped LNOI substrates using diamond-blade dicing, resulting in smooth side walls with lower roughness when compared with dry etching techniques.

Propagation loss for TE- and TM-polarized modes is measured by the Fabry-Perot method using a fiber coupling setup and a tunable laser at 1.5?m. Loss values as low as~1dB/cm were obtained for TE modes, while losses for TM modes are higher. Characterization of Er-LNOI ridges is performed using Raman and fluorescence spectroscopy. Spectral scans were obtained using a scanning confocal microscope and a 488nm laser. Besides line broadening that may be attributed to internal strain in the bonded layer, analysis of Raman spectra shows no significant difference between waveguide and bulk material. However, Er emission of 4H15/2 and 4S3/2 to 4I15/2 contains several differences in intensity ratios indicating that relative transition probabilities are different for smart cut waveguides. While Raman intensity has a linear relationship with pump power, the intensity of the Er emission starts saturating at pump levels of a few mW. To investigate fluorescence of the 4I13/2–4I15/2 transition inside the diced ridges, a fiber-coupled laser with wavelength 980nm is used for pumping. The emission is broadened and maxima are shifted to longer wavelengths, which may be attributed to defects induced by implantation, re-absorption of fluorescence light, and contributions by amplified spontaneous emission due to the waveguiding effect.

8982-53, Session PWed

Acousto-optical tunable transmissive grating beam splitter

Anthony Dieulangard, Jean-Claude Kastelik, Samuel Dupont, Joseph Gazalet, Univ. de Valenciennes et du Hainaut-Cambrésis (France)

We present a tunable transmissive grating beam splitter for multiple laser line separation based on acousto-optic interaction in tellurium dioxide. Acousto-optic devices are well known for light modulation, frequency shifting, filtration or deflection. For a deflector, the incident light beam is monochromatic and the angular deviation is proportional to the ultrasonic frequency excursion. For a tunable filter, the selected wavelength is determined by the ultrasonic frequency. Several wavelengths may be simultaneously diffracted using several associated ultrasonic frequencies and all the diffracted beams have the same angular deviation. Unlike the classical operating modes of acousto-optic devices, we consider the simultaneous diffraction of several optical wavelengths by a single ultrasonic frequency. The device is based on Bragg anisotropic interaction in the specific “Tangent Phase Matching” configuration. The acousto-optic interaction takes place with a single ultrasonic frequency and the diffraction efficiency remains high over a wide optical spectral range. The different diffracted beams are then angularly well separated, due to the slow velocity of the ultrasonic wave propagating in tellurium dioxide. The optical bandwidth is directly related to the operating ultrasonic frequency. Numerical calculations were carried out to determine the main parameters of the device: operating ultrasonic frequency, optical bandwidth, tunability range, crystalline cuts and transducer length. A practical device has been designed for visible spectrum. Experimental results will be presented as for example a spectral bandwidth from 450 nm to 550 nm with a RF carrier frequency f = 120 MHz.

8982-54, Session PWed

Temperature insensitive Sagnac interferometer based on the subwavelength diameter H-shaped microfiber

Min-Seok Yoon, Young-Geun Han, Hoeil Chung, Hanyang Univ. (Korea, Republic of)

A fiber-optic Sagnac interferometer with a polarization maintaining fiber (PMF) have been attracting considerable attention in a variety of applications, such as optical communication devices and sensors because of their many advantages, such as low-loss, polarization-independence to input light, and ease of fabrication and installation. Recently, highly birefringent (Hi-Bi) microfibers with high birefringence have been proposed for the realization of the highly sensitive refractometor. The high birefringence of the microfiber must reduce the physical length of the Sagnac interferometer and improve the sensitivity to external perturbation change. A Sagnac interferometer, however, exhibits the high temperature sensitivity because of the temperature dependence of the birefringence of the PMF. Therefore, it is necessary to suppress the temperature sensitivity of the Sagnac interferometer. In this paper, a temperature insensitive Sagnac interferometer based on the H-shaped Hi-Bi microfiber is proposed and experimentally demonstrated. The subwavelength-diameter H-shaped microfiber induces the extremely high group birefringence resulting from the high ellipticity of the fiber cross-section. The birefringence of the fabricated subwavelength-diameter H-shaped microfibers was measured to be 9.0x10-3. The

temperature sensitivity of the Sagnac interferometer based on the subwavelength-diameter H-shaped microfiber was measured to be 0.002 nm/oC, which is 700 times lower than that of the conventional Sagnac interferometer (1.5 nm/oC). Since the proposed H-shaped microfiber is considered as a single material composition like silica, we can succefully suppress the temperature sensitivity of the Sagnac interferometer based on the proposed H-shaped microfiber. The Sagnac interferometer based on subwavelength-diameter H-shaped microfiber exhibits the high refractive index sensitivity of 1197.6 nm/RIU.

8982-55, Session PWed

Superluminal propagation in a highly nonlinear fiber embedded in a Brillouin laser ring cavity

Dinghuan Deng, Weiqing Gao, Meisong Liao, Zhongchao Duan, Tonglei Cheng, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

Superluminal propagation at negative group velocity was demonstrated in a highly nonlinear fiber (HNLF) embedded in a stimulated Brillouin scattering (SBS) laser ring cavity. The effective mode area of the HNLF at the wavelength of 1550 nm is 11.5 µm^2, which is several times smaller than standard single-mode fiber. The backward Stokes became lasing when the forward pump signal power exceeded the SBS threshold. The pump signal was transferred to the backward Stokes lasing signal and suffered an attenuation process by the SBS induced resonance loss in the ring cavity. According to the Kramers-Kronig relation, the fast light would appear in this transfer process. The output pulse from the HNLF got closer and closer to the input pulse as the SBS lasing power was increasing, and then exceeded it and became superluminal propagation with a negative group velocity. The maximum advancement of 369 ns was observed when the fiber ring cavity was pumped with 1-W and 1 MHz sinusoidal wave modulated signal. With strong Stokes lasing power of 482.8 mW from the laser ring cavity, a very high signal to Stokes convert efficient of 48% was achieved in the experiment. The frequency dependence of fast light in this fiber ring cavity was examined with modulation frequencies of 10 kHz to 15 MHz at the output Stokes power of 200 mW. Compare to the pulse duration, a maximum fractional advancement of 0.54 was achieved.

8982-56, Session PWed

Experimental and theoretical study of supercontinuum generation in an As2S3 chalcogenide microstructured optical fiber

Weiqing Gao, Toyota Technological Institute (Japan); Mohammed El Amraoui, Univ. Laval (Canada); Meisong Liao, Hiroyasu Kawashima, Zhongchao Duan, Dinghuan Deng, Tonglei Cheng, Takenobu Suzuki, Toyota Technological Institute (Japan); Younès Messaddeq, Ctr. d'optique, photonique et laser (Canada); Yasutake Ohishi, Toyota Technological Institute (Japan)

Alternative materials to silica glass are necessary for supercontinuum (SC) generation at longer wavelengths in the mid-infrared (MIR) region. The alternative materials should possess the properties of wide transmission window and high nonlinearity, simultaneously. Chalcogenide glass is the suitable candidate due to its excellent properties of transmission and nonlinearity in MIR region. In this paper, we demonstrate the SC generation in a suspended-core As2S3 chalcogenide microstructured optical fiber (MOF). The variation of SC is investigated by changing the fiber length, pump peak power and pump wavelength. In the case of long fibers (20 and 40 cm), the SC ranges are discontinuous and stop at the wavelengths shorter than 3500 nm, due to fiber absorption. In the case of short fiber as 2.4 cm, the SC range is continuous and can extend to the wavelength longer than 4 µm. The process of SC broadening is observed when the pump peak power increases from 0.24 to 1.32 kW at 2500 nm in the 2.4 cm long fiber. The variation of SC range with the pump wavelength changing from 2200 to 2600 nm is studied. The selected wavelengths correspond to the dispersion of As2S3 MOF from the normal to anomalous region. The SC generation is simulated by the generalized nonlinear Schrödinger equation. The simulation includes the SC difference between 1.3 and 2.4 cm long fiber at 2500 nm pumping and the variation of SC with pump peak power in 2.4 cm long fiber. The simulation agrees well with the experiment.

8982-57, Session PWed

Broadband optical parametric gain by novel highly nonlinear tellurite hybrid microstructured optical fiber with four zero-dispersion wavelengths

Tuan H. Tong, Tonglei Cheng, Koji Asano, Zhongchao Duan, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

Fiber-optical parametric amplification (FOPA) has been intensively studied and exploited for various interesting applications such as wavelength conversion, wavelength division multiplexing, optical signal processing and so on. However, its efficiency is governed by the fiber nonlinearity and chromatic dispersion. By employing tellurite glass we propose novel highly nonlinear tellurite hybrid microstructured optical fibers (HMOFs) which have very high nonlinearity of 6642 W-1km-1 and near-zero flattened dispersion profiles from 1.3 to 2.3 µm with four zero dispersion wavelengths for FOPA applications. The linear phase-mismatch, optical signal gain and gain bandwidth are precisely calculated by using a full propagation constant which includes the contribution of all high-order dispersion parameters. In contrast with silica fibers, the signal gain is shown to be generated in the wavelength regions where $\Delta\beta<-4\gamma P$ and the parametric gain coefficient g is imaginary. It is shown that the proposed tellurite HMOFs with short fiber length L<90 cm have the gain bandwidth as broad as 760 nm when it is pumped at 1550 nm. The increase in pump power from 1 to 4 W not only increases the signal gain but also broadens the FOPA gain bandwidth. At 1700-nm pump wavelength, the signal gain larger than 14 dB is obtained over a very broad gain bandwidth of 1200 nm (from 1290 to 2490 nm). To our best knowledge, it is the first time that highly nonlinear tellurite HMOFs are demonstrated as attractive candidates for high performance of FOPA.

8982-58, Session PWed

In-band pumping of Tm-doped single-mode tellurite composite fiber

Kefeng Li, Xiaokang Fan, Lei Zhang, Wentao Li, Peiwen Kuan, Danping Chen, Lili Hu, Shanghai Institute of Optics and Fine Mechanics (China)

Mechanical strength is one of the biggest limitations of practical application for tellurite fiber. In this study, we design and fabricate a new tellurite composite fiber to overcome the flaw. The fiber has a double cladding structure with tellurite core and inner cladding. The outer cladding, which is made of non-tellurite glass, possesses of appropriate softening temperature and coefficient of thermal expansion, matched the novelty tellurite glass very well, the propagation loss is less than 0.02 dB/cm @1310 nm. We also investigate the laser property of this fiber by using a homemade watt-class 1590 nm fiber laser. 2 micron fiber laser is demonstrated with a 2 cm length of the fiber.

8982-59, Session PWed

The nature of induced color centers in Yb-Al- and Yb-Ce-Al-doped high-power silica fiber lasers

Magnus Engholm, Mid Sweden Univ. (Sweden); Lars Norin, Acreo AB (Sweden)

Induced optical losses, also known as photodarkening (PD) in Yb-doped silica fiber lasers has been under extensive research during the last decade. The nature and formation process of the color centers responsible for the induced losses are however still not fully understood. The ever increasing demand for higher output powers calls for the development of improved laser gain materials, which motivate further research on this subject.

In this work we address the nature of the color centers and how their formation is influenced by commonly used co-dopants in Yb-doped silica fibers. It has recently been concluded that aluminum oxygen hole centers (Al-OHCs) is responsible for the increased absorption at the pump and lasing wavelengths near 1um. We present experimental evidence that the Al-OHC is accompanied by formation of Yb2+, whose absorption bands constitute a major part of the PD spectrum in the UV range. Furthermore, the absorption cross section of the Yb2+ ion in the UV range and Al-OHC in the VIS range are of comparable magnitude. Comparison between different glass compositions such as Yb-Al and more PD resistant Yb-Al-Ce fibers, show the formation of same components but with different ratios due to the hole-capturing property of the Cerium ions. The obtained results provide an increased understanding on the color center formation in Yb-doped silica fibers. Based on these results, new routes to improve the PD resistivity in Yb-doped silica fibers will also be presented.

8982-61, Session PWed

Study of Bi-alkali Photocathode Growth on Glass by X-ray Techniques for Fast Timing Response Photomultipliers

Junqi Xie, Argonne National Lab. (United States)

Photomultiplier tubes (PMTs), kinds of versatile and sensitive detectors with excellent time resolution and good spatial resolution, have been extensively used in medical diagnostics, industrial measurement and scientific research projects. As an essential component of PMTs, photocathodes with high quantum efficiency, fast response and low noise level become critical to the performance of PMTs. Alkali antimonide compounds, due to their fast timing responses and low noise level, are the major materials used for photocathodes. However, the growth process of these materials is poorly understood, this prevents the development of high efficiency photocathodes.

In this talk, we will report the development of bi-alkali (K-Cs-Sb) photocathode at Argonne National Laboratory in collaboration with other institutes. Various X-ray techniques were applied for in-situ study and understanding of the photocathode material growth process. These studies from the basic physics lead to the development of reliable high performance photocathodes with enhanced quantum efficiency and time responses. Small PMT photocathodes with high QE were also produced through the optimized process.

8982-62, Session PWed

A highly-nonlinear three-core chalcogenide-tellurite fiber

Tonglei Cheng, Nur Asyikin, Weiqing Gao, Meisong Liao, Dinghuan Deng, Toyota Technological Institute (Japan); Morio Matsumoto, Takashi Misumi, Furukawa Denshi Co., Ltd. (Japan); Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

Multicore fibers (MCFs) have been widely applied to the fiber lasers and amplifiers, the spatial division multiplexing, the passive optical network (PON), microwave photonics (MWP) and sensing elements, etc. A novel highly nonlinear chalcogenide-tellurite fiber with three cores arranged in a trigonal array is proposed and fabricated. Each core with high-index is made of chalcogenide glass (GeGaSbS). The average diameter D0=3.12 ?m and the refractive index n0=2.24 at ?=1.55 ?m. The background with low-index is made of tellurite glass (TeO2–ZnO–Li2O–Bi2O3) and the refractive index n0=2.00 at ?=1.55 ?m. The three core glass and the background glass are thermally stable, and their thermal expansion and softening temperature are similar. Each core of this fiber can be considered as a single core and can support the single mode transmission in the near-IR and mid-IR. And it can be used for the high power transmission. The effective modal refractive index and the chromatic dispersion are calculated with the light beam coupled in one and three cores of the fiber, respectively. The optical modes are measured at ?=1.55 ?m,. Supercontinuum generations in one core and three cores are also measured at different wavelengths. The three-core chalcogenide-tellurite fiber can also be widely applied to other nonlinear applications, such as four wave mixing, dispersive wave and solitons generation.

8982-63, Session PWed

Dispersive wave generation in a tellurite hybrid microstructured optical fiber with two zero dispersion wavelengths

Zhongchao Duan, Dinghuan Deng, Tuan H. Tong, Xiaojie Xue, Tonglei Cheng, Weiqing Gao, Meisong Liao, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

Microstructured optical fibers (MOFs) have attracted much attention in the last decade, partly due to their special guiding properties, e.g. high nonlinearity and tailorable dispersion. To date, supercontinuum (SC) can be efficiently generated in MOFs due to the interplay between several nonlinear effects. However, such SC spectra are power fluctuant and modulational instable. Recent researches point out that dispersive wave originating from anomalous dispersion regime between two zero dispersion wavelengths (ZDWs) is much smooth and stable. In this work, we designed and prepared a tellurite hybrid microstructured optical fiber (HMOF) with a small core of ~1.3 μm, high nonlinearity of ~5.93 m-1W-1 and two ZDWs located at 1.28 μm and 2.30 μm, respectively. Dispersive wave generation was also demonstrated. The core is made of TLWMN tellurite glass with high linear and nonlinear refractive indices of 2.08 and 3.78x10-11 esu. The cladding is made of TZNP tellurite-phosphate glass with a low refractive index of 1.56 at 1544 nm. Six air holes with diameter of ~4.0 μm are embedded in the cladding to enhance the confinement of fiber. Dispersive wave generation was demonstrated with pump of 1.55 μm laser with pulse of 100 fs. Double-peaked SC spectra were observed with redshifted dispersive wave and blueshifted dispersive wave, which broadened to 0.87 μm and over 2.4 μm, respectively. Due to the high nonlinearity of tellurite HMOF, both redshited and blueshifted dispersive waves are much flattened than that generated in silica MOFs.

8982-64, Session PWed

Optical RAM row access using WDM-enabled all-passive row/column decoders

Sotirios Papaioannou, Theonitsa Alexoudi, Ctr. for Research and Technology Hellas (Greece) and Aristotle Univ. of Thessaloniki (Greece); George T. Kanellos, Ctr. for Research and Technology Hellas (Greece); Amalia Miliou, Nikos Pleros, Ctr. for Research and Technology Hellas (Greece) and Aristotle Univ. of Thessaloniki (Greece)

Towards achieving a functional RAM organization that reaps the advantages offered by optical technology, a complete set of optical peripheral modules, namely the Row (RD) and Column Decoder (CD) units, is required. In this perspective, we demonstrate an all-passive 2?4 optical RAM RD with row access operation and subsequent all-passive column decoding to control the access of WDM-formatted words in optical RAM rows. The 2?4 RD exploits a WDM-formatted 2-bit-long memory WordLine address along with its complementary value, all of them encoded on four different wavelengths and broadcasted to all RAM rows. The RD relies on an all-passive wavelength-selective filtering matrix (?-matrix) that ensures a logical '0' output only at the selected RAM row. Subsequently, the RD output of each row drives the respective SOA-MZI-based Row Access Gate (AG) to grant/block the entry of the incoming data words to the whole memory row. In case of a selected row, the data word exits the row AG and enters the respective CD that relies on an all-passive wavelength-selective Arrayed Waveguide Grating (AWG) for decoding the word bits into their individual columns. Both RD and CD procedures are carried out without requiring any active devices, assuming that the memory address and data word bits as well as their inverted values will be available in their optical form by the CPU interface. Proof-of-concept experimental verification exploiting cascaded pairs of AWGs as the ?-matrix is demonstrated at 10Gb/s, providing error-free operation with a peak power penalty lower than 0.2dB for all optical word channels.

8982-66, Session PWed

Infrared absorption and fluorescence properties of Ho-doped KPb2Br5

EiEi Brown, Uwe H. Hömmerich, Simone Hyater-Adams, Hampton Univ. (United States); Olusola Oyebola, Univ. of Lagos (Nigeria); Althea Bluiett, Elizabeth City State Univ. (United States); Sudhir B. Trivedi, Brimrose Corp. of America (United States)

The development of novel infrared fluorescent materials continues to be of interest for applications in solid-state gain media, IR sensing, optical taggants, and optical cooling [1-3]. Fluorescent materials based on Ho3+ doped crystals and glasses with narrow phonon spectra cover a wide wavelength range from ~1.2 to 3.9 µm. In this work the material purification, synthesis, crystal growth, and IR spectroscopy was investigated for Ho3+-doped into KPb2Br5 (KPB). KPB is a non-hygroscopic crystal with a narrow phonon spectrum not exceeding ~140 cm-1 leading to efficient IR fluorescence at longer wavelengths The investigated Ho-doped KPB material was synthesized through careful purification of starting materials including multi-pass zone-refinement and bromination. The bromination process was critical for removing oxidic impurities and enhancing the quality of the crystal. Under near IR laser pumping (~890nm), IR emissions centered at 1.2, 1.7, 2.0, 2.9, and 3.9 ?m were observed from Ho: KPB corresponding to the 5I6->5I8, 5I5->5I7, 5I7->5I8, 5I6->5I7, and 5I5->5I6 transitions of Ho3+ ions. Spectroscopic results and data modeling including Judd-Ofelt analysis, transition cross-sections, and fluorescence dynamics will be presented at the conference.

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8982-67, Session PWed

A novel acousto-optic modulation-deflection mechanism using refractive index grating as graded index beam router

Alireza Jangjoo, Payam Noor Univ. of Shiraz (Iran, Islamic Republic of)

A novel acousto-optic modulation mechanism will be addressed in this paper. Focused Gaussian beam passing through acousto-optic media experiences different refractive index regions arising from acoustic waves generated by ultrasonic source. In this way according to the snell's law of refraction the beam propagation path will be altered when these periodic traveling waves reach the incoming radiation where a typical p-n junction photodiode located inside the rising or falling lobe of the undiffracted Gaussian beam senses these small lateral deflections. Due to small variations of the refractive index the magnitude of deflection will be on the order of tens of micron outside the modulator. Hence, sharp intensity gradient is required for detecting such small beam movements by appropriate lens configuration to focus the Gaussian profile on the detector junction area. In the other words intensity profile of zero order beam oscillates proportional to the time dependent amplitude of the acoustic waves versus previous methods that intensity of diffracted beam changes with applied ultrasonic intensity. The extracted signal properties depend on the beam collimation, quality of beam profile and depth of focus inside the modulator. The first experimental approach was proceeded using a collimated 532 nm diode laser source (TEM00), distilled water as interaction media and 10 MHz transducer as ultrasonic generator where a cylindrical glass column with input-output flat windows was used for liquid support. The present method has advantages over common acousto-optical techniques as low cost, simplicity of operation, direct modulation of the signal and minimum alignment requirement.

8982-68, Session PWed

Development of chalcogenide glass with thermal stability for molded infrared lens

Ju H. Choi, Woo Young Lee, Hye-Jeong Kim, Jeong-Ho Kim, Du Hwan Cha, Hee Young Kang, Korea Photonics Technology Institute (Korea, Republic of)

Chalcogenide glasses have been attracted because of their use in moldable lenses for the application in range of 3-12 ?m. In this study, amorphous Ge-Sb-Se chalcogenide was prepared by a standard melt-quenching technique for moldable lenses. Moldable lens should have unique thermal mechanic properties in order to be applied to molding process. Thus, the optical and thermal properties to find out right composition were characterized by IR transmission spectroscopy and DSC, respectively. Specifically, the Ge:Sb ratio were controlled in order to find out the most stable glass forming area. The relations between thermal properties and the moldability were studied by using a optical microscopy in term of thermal properties such as Tg and Tx. Transcription properties of the surface of lens or molds were explained in terms of thermal properties in their composition The preferential Ge:Sb ratio in Ge-Sb-Se based chalcogenide glasses was selected for producing moldable lenses.

8982-69, Session PWed

Broadband photosensor with a tunable frequency range built on the basis of nanoscale carbon structure with field localization

Alexander N. Yakunin, Garif G. Akchurin, Institute of Precision Mechanics and Control (Russian Federation); Nikolay P. Abanshin, Boris I. Gorfinkel, Volga-Svet Co. Ltd. (Russian Federation)

The work is devoted to the development of a new direction in creating of broadband photo sensors which distinctive feature is the possibility of dynamic adjustment of operating frequency range. The author's results of study of red threshold control of classic photoelectric effect were the basis for the work implementation. This effect was predicted theoretically and observed experimentally during irradiation of nanoscale carbon structure of planar-edge type by stream of low-energy photons. The variation of the accelerating voltage within a small range allows you to change photoelectric threshold for carbon in a wide range - from UV to IR. This is the consequence of the localization of electrostatic field at tip of the blade planar structure and of changes in the conditions of non-equilibrium electrons tunneling from the boundary surface of the cathode into the vacuum. The generation of nonequilibrium electrons in the carbon film thickness of 20 nm has a high speed which provides high performance of photodetector. The features of the use of nanoscale carbon structure photocurrent registration as in the prethreshold regime, and in the mode of field emission existence are discussed. The results of simulation and experimental examination of photosensor samples are given. It is shown that the observed effect is a single-photon tunneling. This in combination with the possibility of high-speed dynamic tuning determines the good perspectives for creation of new devices working in the mode of select multiple operating spectral bands for the signal recording. The architecture of such devices is expected to be significantly simpler than the conventional ones, based on the use of tunable filters.

8982-70, Session PWed

Light-induced self-written waveguides based on NaYF4/polymer composites for the C-band amplification

Xiaojie Xue, Weiqing Gao, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

We successfully synthesized Er3+/Yb3+/Ce3+-codoped cubic phase NaYF4 nanocrystals with the size of around 14 nm by a solvothermal method. Under the excitation of a 976 nm laser diode, the as-prepared nanocrystals strong 1530 nm emissions and weak visible emissions. With the addition of Yb3+ ions, both visible and near-infrared emissions of Er3+ were enhanced. The addition of Ce3+ ions can effectively quench the visible emissions and increase the population of electrons on the 4I13/2 of Er3+ ions, further enhance the 1530 nm near-infrared emissions. The doping concentrations of lanthanide ions were carefully adjusted. It was found that the NaYF4 nanocrystals doped with 1% Er3+, 10%Yb3+, and 5%Ce3+ showed the most intense 1530 nm emissions and a long emission lifetime. By dispersing the as-prepared nanocrystals in bisphenol A ethoxylate diacrylates (BPAEDA), the transparent nanocrystals doped polymer composite materials were prepared. By using the technique of light-induced self-written waveguide fabrication, NaYF4 nanocrystals doped waveguides with the length of 20 mm were prepared. Under the excitation of a 976 nm laser, the green visible light was observed from the waveguide devices. The optical gains of the waveguide devices on the 1530 nm signal light were measured.

8982-71, Session PWed

Theoretical investigation of pulse-dependent optical parametric amplification for microstructured optical fiber

Edmund P. Samuel, Tuan H. Tong, Koji Asano, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

Recently, demand of optical fibers with high nonlinearity coefficient has increased to fulfil the need of modern communication system. The advantage of these highly nonlinear fibers over silica which has well matured technology is to obtain optical interaction at shorter fiber length and lower absorbance at longer wavelengths. The optical communication devices need optical amplifiers and one can use the optical parametric amplifiers (OPA) which involves four wave mixing for amplification. The parametric amplifier is the combination of signal and strong pump source of the fiber which has immense potential applications such as wavelength conversion, phase-sensitive optical amplification and signal conjugator. The OPA provides wider parametric gain bandwidth and can be tailored to operate at desired wavelength.

We present here, the extensive study of broadband and high parametric gain in highly nonlinear tellurite optical fiber. The low chromatic dispersion fiber has been designed to achieve broadband and phase-matching over broad spectral range. The optical parametric gain under pulse dependence and pulse-independent has been calculated. When shorter pulse has been included the peak gain obtained to be 40 dB. While, when shorter pulse was excluded the peak parametric gain found to be 52 dB. Similarly, when the pulse was included for parametric gain calculation, the gain bandwidth found to be shrinking abruptly due to small change (decrease) in pump power. The repetition rate considered here to be 20 GHz, with fiber core diameter 0.4475 µm and nonlinearity coefficient γ=6642 W-1/km. The study has been extended to realize the supercontinuum generation.

8982-72, Session PWed

Nonlinear behavior of dispersive optics in ultrafast laser systems

Olga Razskazovskaya, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); Trang Trung Luu, Eleftherios Goulielmakis, Max-Planck-Institut für Quantenoptik (Germany); Ferenc Krausz, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); Vladimir Pervak, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany) and Ultrafast Innovations GmbH (Germany)

Dielectric multilayer dispersive mirrors (DMs) utilized for compensation of chromatic dispersion are a vital part of numerous nowadays ultrafast laser systems. Their flexibility of their dispersion characteristics yielding Fourier-transform-limited pulses and preserved high efficiency granted DMs an important place in multiple applications as ultrafast mode-locked Ti:Sapphire and disk oscillators, optical parametrical chirped pulse amplifiers, super continuum compression etc. It is recognized that except for the specially designed optical components (f.i. SESAMs), reflectivity of the multilayer optical components is intensity independent characteristics defined mostly by the multilayer stack design and chosen coating materials.

Our experiments showed that this statement should be reconsidered. In our studies we performed reflectivity measurements of DMs produced with Ta2O5/SiO2 and HfO2/SiO2 – some of the most used material pairs. Several designs deferred by amount of introduced negative dispersion and with different coating deposition techniques were produced. All mirrors were tested exploiting laser source producing 40fs pulses at 3kHz repetition rate centered at 400nm.

During our experiments we recorded non-linear intensity dependent reflectivity drop down to, in some cases, only 20% without evident damage of the structure. Similar trends were noticed for all cases, while exact slopes of reflectivity drops varied. The effect is reversible and reflectivity increases if intensity is decreased.

Comparison between DMs and quarter-wave dielectric multilayers of the same materials was also performed. Quarter-wave stacks did not show any evidences of similar behavior.

Discovered effect might affect functionality of not only existing, but still to be designed systems and should be studied and taken into consideration.

8982-73, Session PWed

Improving Shack-Hartmann wavefront sensor by using sub-wavelength annular apertures

Hao-Jung Chang, Ming-Han Chung, Chih-Kung Lee, National Taiwan Univ. (Taiwan)

Out of the many wavefront sensing techniques, Shack-Hartmann wavefront sensor configuration based on using a micro-lens array to measure the directivity of the light beam associated with each micro-lens remains the most popular and the most versatile. In this configuration, using smaller size of micro-lens could increase the angular resolution. However, smaller size of micro-lens is known to associate with shorter depth of focus and makes it difficult to focus highly aberrated wavefront on sensor array properly. Furthermore, the size of micro-lens array is limited by the diffraction limit. In today's technology, micro-lens with dimensions in the size of a few hundred of microns is possible. This dimension limits the angular resolution possible for the wavefront sensor.

To alleviate the compromise between the angular resolution and the depth of focus, we propose to use a subwavelength annular aperture (SAA) structure to enable the generation of Bessel light beams. That is, the SAA performs similar functions as that of the micro lens array in traditional wave front sensors. It will be shown that this design maintains a subwavelength focusing capability while achieves tens of micron depth of focus in the far-field region, which leads to an improved wavefront sensor. Both simulation and experimental results will be detailed in this paper.

8982-74, Session PWed

Large dynamic range silicon photomultipliers for high-energy physics experiments

Thomas Ganka, Christoph Dietzinger, Univ. der Bundeswehr München (Germany); Peter Iskra, Florian Wiest, Reinhard Fojt, KETEK GmbH (Germany); Walter Hansch, Univ. der Bundeswehr München (Germany)

Silicon Photomultipliers (SiPM) are very promising devices for high energy physics (HEP) experiments due to their high photon detection efficiency, miniaturized device size and insensitivity to high magnetic fields. For high energy particle physics experiments a large dynamic range is mandatory. Most often detectors are exposed to a high radiation dose for which reason the performance should degrade only minor under the applied radiation load. Decreasing the active depth of a SiPM micropixel should help to strengthen the radiation hardness. This was a further driving reason at KETEK to scale down the pixel pitch and thereby losing only small amount in geometrical efficiency. With these large dynamic range SiPMs a photon detection efficiency in blue spectral range of 32 % for 2500 pixels/mm? and 22 % for 4400 pixels/mm2 was achieved. With an improved manufacturing technology the dark noise level was decreased to about 250 kHz/mm2 at 20 % overvoltage. Further optimization of the depleted region increased the sensitivity in the output wavelength range of common scintillators (~515nm) by 20% compared to the standard devices. The performance of the KETEK SiPMs will be discussed in detail.

8982-75, Session PWed

Upconversion, size analysis, and fiber filling of NaYF4: Ho3+, Yb3+ crystals and nanocolloids

Darayas N. Patel, Ashley Lewis, Donald Wright III, Maucus Valentine, Danielle Lewis, Ruben Valentine, Oakwood Univ. (United States); Sergey Sarkisov, SSS Optical Technologies, LLC (United States)

Nano-colloids and nano-crystals doped with ions of rare-earth elements have recently attracted a lot of attention in the scientific community. This attention is due to unique physical, chemical and optical properties attributed to nanometer size of the particles. They have great potential of being used in applications spanning from new types of lasers, especially blue and UV ones, phosphorous display monitors, optical communications, sensors, and fluorescence imaging. In this paper we investigate the upconversion luminescence in bulk crystals and photonic crystal fibers filled with nanocolloids of ytterbium and holmium co-doped NaYF4 phosphor. The phosphor is prepared by using a simple co-precipitation synthetic method. The initially prepared phosphor has very week upconversion fluorescence. The fluorescence significantly increased after the phosphor was annealed at a temperature of 600 0C. Nanocolloids of this phosphor in 1-propanol were prepared using the laser ablation process. Then they were used as a laser filling medium in photonic crystal fibers. Under 980 nm diode laser excitation, strong upconversion emission was observed from the nanocolloids with spectral peaks at 541 nm, 646 nm and 751 nm. The particle size of the nanocolloids was estimated using the atomic force microscopy and dynamic light scattering. The reported nanocolloids are good candidates for fluorescent biosensing applications and also as a new laser filling medium in fiber lasers.

8982-76, Session PWed

Mitigating dispersive spectrometer size-performance limitations with HTVS optical components

Jeffery T. Meade, Bradford B. Behr, Yusuf Bismilla, Andrew T. Cenko, Brandon DesRoches, Arie Henkin, Elizabeth A. Munro, Jared Slaa, Scott Baker, Tornado Spectral Systems (Canada); David Rempel, Perimiter Medical Imaging (Canada); Arsen R. Hajian, Tornado Spectral Systems (Canada)

Traditional spectrometer design requires trading off between resolution and throughput (defining performance) and physical size. Increasing the internal beam diameter is the simplest method of improving the performance of an otherwise optimized spectrometer. Sadly, this increased beam size also directly translates into increased system volume, weight, and cost. Functional limitations on size (and thus performance) can also prevent spectroscopy from being used in applications where it would otherwise be a perfect fit.

Tornado Spectral Systems' (TSS) High Throughput Virtual Slit (HTVS) redefines the performance-size limit by replacing the traditional slit in a spectrometer, allowing for designs that exceed traditional limitations on size and performance. Spectrometers can be made smaller while maintaining performance or system performance can be increased without increasing spectrometer size.

We will briefly discuss the underlying HTVS technology and standard spectrometer performance metrics. This will lead into a discussion on traditional spectrometer size-performance limitations and how HTVS

technology enables us to overcome these limits. Theoretical and empirical examples showing performance improvements of 2-10x will be discussed.

8982-77, Session PWed

Robust long-wavelength infrared tellurium-based chalcogenide glass fiber produced by multimaterial coextrusion

Guangming Tao, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); He Ren, Jiangsu Normal Univ. (China); Soroush Shabahang, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Xunsi Wang, Ningbo Univ. (China); Zhiyong Yang, The Australian National Univ. (Australia); Ayman F. Abouraddy, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

The development of quantum cascade lasers that span mid-wave and long-wave infrared wavelengths necessitate developing new infrared fibers capable of transmitting light in the 5-12 micron range. The main infrared material candidates for fiber drawing that cover the 5-12 micron region are polycrystalline silver halides and glassy tellurium (Te)-based chalcogenide glass. Since halide materials are less chemically stable than Te-based chalcogenides, we have adapted a fiber fabrication methodology we recently developed for other chalcogenides to the latter glass family. We produce a novel long-wavelength infrared optical fiber with Te-based chalcogenide core and cladding, provided with a built-in polymer jacket by multimaterial coextrusion. We examine the extruded preforms using a high-resolution infrared camera to identify the interface between core and cladding materials. We characterize the optical performance of the fiber in the 5-12 micron spectral window and demonstrate the mechanical robustness of the fiber under bending and extensional forces.

8982-78, Session PWed

Scalable fabrication of digitally-designed spherical multimaterial particles enabled by in-fiber emulsification

Guangming Tao, Joshua J. Kaufman, Soroush Shabahang, Ayman F. Abouraddy, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

We report a scalable process that harnesses thermally driven fluid instabilities in multimaterial fibers to produce structured micro- and nanoparticles from a variety of material combinations. The starting point is producing a macro-scale fiber preform drawn into a fiber with the core combining the materials to be incorporated into the particles encased in a polymer cladding matrix. Thermal treatment of the post-drawn fiber induces the surface-tension-driven Plateau-Rayleigh capillary instability at the heterogeneous interfaces along the fiber length, resulting in the intact core breaking up into a necklace of spherical particles. By judicious design of the core structure, the morphing from a cylinder to spheres controllably produces desired complex geometries, including multilayer particles, 'beach ball' particles with complex azimuthal structure, and multilayer 'Janus' particles where the relative orientation of the different layers is brought under precise control. We describe potential applications of particles with such sophisticated structures in designer optical materials, drug delivery, and pathogen sensing.

8982-79, Session PWed

Fiber bragg grating filter using evaporated-induced self assembly of silica nano particles

Krister Hammarling, Zhang Renyung, Hans-Erik Nilsson, Mid Sweden Univ. (Sweden); Anatoliy Manuilskiy, Mid Sweden University (Sweden)

In the present work we present a study of optical fiber filters produced by evaporating silica particles upon a MM-fiber core. A narrow band filter was designed and theoretically verified using simulation. For the simulation, a 2D model of a 3D problem was used and numerically calculated in the frequency domain. The fiber filters were fabricated by stripping and chemically etching 10 cm in the middle of an MM-fiber (105 µm core and 125 µm cladding) until the core was exposed. To induce index perturbations in the fiber, a closely packed mono layer of silica nano particles was placed upon the core. The technique used for placing the particles evenly on the core, was Evaporation Induced Self-Assembly (EISA) method. The silica nano-particles will cause index perturbations close to the core edge. These index perturbations change the effective refractive index periodically, thus giving the fiber a Fiber Bragg Grating (FBG) like mechanism. By altering the size of the particles, one can build a filter to a specific center wavelength. The experimental results indicated a broader bandwidth than indicated by the simulations, this can be explained by the mismatch in the particle size distributions (normal distribution from manufacturing of particles), uneven particle packing and finally by effects from multiple mode angles. Thus, there are several closely connected Bragg wavelengths that build up a broad bandwidth. It is our belief that this technique can be used to fabricate low cost fiber filters of relatively high performance.

8982-80, Session PWed

Optomechanical optic modulator based on carbon nanotube coated fiber Bragg grating

Shivananju B. N., Ashish Suri, Sundarrajan Asokan, Abha Misra, Indian Institute of Science (India)

The tuning of the Bragg wavelength in fiber Bragg grating (FBG) based communication is generally achieved by using the techniques such as acousto-optic, electro-optic and magneto-optic. However, these contact based (except magneto-optic systems) techniques are of limited use and also generate noises resulting from electromagnetic interactions. The limitations associated with the existing techniques could be overcome by using a photo induced actuation characteristic of carbon nanotubes (CNTs) to tune the Bragg wavelength. CNTs respond to a wide range of optical wavelengths due to their near-perfect black body characteristics. A wide range of practical applications have been proposed such as infrared thermal detectors, optical modulators, sensors, transistors and diodes resulting from their high sensitivity towards infrared (IR), visible and ultraviolet (UV) radiations.

In our work, the photomechanical actuation in CNT coated FBG (optomechanical optical modulator) allows the tuning of the Bragg wavelength using a wide range optical wavelengths e.g. UV to IR (0.2 to 200 µm) by exposing them externally. It provides a very simple, compact, non-contact, and non-destructive method to tune the Bragg wavelength. The system response is not only stable over external sources of noise but also shown to be able to precisely tune the Bragg wavelength from picometer to nanometer (10-12 to 10-9) range. Reversible responses of the CNT-FBG system showed an optical switching behavior in milliseconds. This optomechanical optical modulator finds potential applications in the field of fiber optics and optical communications, especially in the area of optical add-drop multiplexers (OADM), filters, lasers, modulators, amplifiers, interrogators, etc.

8982-81, Session PWed

Simulation-based design of a pixel for backside-illuminated CMOS image sensor with thick photo-electric conversion element

Toshiki Arai, Hiroshi Shimamoto, Japan Broadcasting Corp. (Japan)

We simulated the conceptual design of a pixel for a backside-illuminated CMOS image sensor with thick (10 μm) photo-electric conversion element. The sensor is supposed to have a 1.8 times sensitivity than that of a front-side-illuminated sensor with thin (3 μm) element because of two reasons. One is the increased fill factor of 100% compared with that of 65% for front-side-illuminated sensor. The other is the increase in the optical utilization ratio defined as the integral of the output voltage over all visible light wavelengths divided by the ideal response. The ratio for the sensor with the thick element increase by 1.2 times compared with the one with the thin element.

The cross-sectional potential profile with photo-electric conversion element of 10 μm is calculated by a three-dimensional semiconductor device simulator. A pn double epitaxial layer structure is adopted to prevent migration of electrons into the p-well. The n- epitaxial layer is 4 μm thick and p- epitaxial layer is 6 μm thick. Doping concentrations of n- and p- epitaxial layers are optimized to minimize the transit time of electrons. The low concentration of the p- epitaxial layer is preferable; for the n- epitaxial layer, there is a range of optimum doping concentration. A minimum transit time of electrons of 1.41 nsec is achieved. All electrons including the ones generated on the corner of the backside of the pixel are collected in the charge integration region. Electrical pixel separation of this design is also confirmed by simulation.

8982-82, Session PWed

Low-loss coupling and splicing of standard single-mode fibers with all-solid soft-glass microstructured fibers for supercontinuum generation

Michal Murawski, Military Univ. of Technology (Poland) and InPhoTech Ltd. (Poland); Grzegorz St?pniewski, Institute of Electronic Materials Technology (Poland) and Univ. of Warsaw (Poland); Tadeusz Tenderenda, Marek Napierala, Zbigniew Holdynski, Military Univ. of Technology (Poland) and InPhoTech Ltd. (Poland); Lukasz Szostkiewicz, Mateusz Slowikowski, InPhoTech Ltd. (Poland); Michal Szymanski, Lukasz Ostrowski, Military Univ. of Technology (Poland) and InPhoTech Ltd. (Poland); Leszek R. Jaroszewicz, Military Univ. of Technology (Poland); Ryszard R. Buczynski, Institute of Electronic Materials Technology (Poland) and Univ. of Warsaw (Poland); Tomasz Nasilowski, Military Univ. of Technology (Poland) and InPhoTech Ltd. (Poland)

In this work we would like to present the results of low loss coupling of a novel soft glass fiber for super continuum generation with standard single mode fiber by a filament splicing method. For our experiment we used an all solid soft glass microstructured fiber (MSF) made from a composition of F2 lead-silicate glass and NC21 borosilicate glass. The structure and material properties of the fiber were optimized to achieve all normal dispersion (ND) flattened around 1560 nm, which offers two general advantages for supercontinuum generation. The ND supercontinuum avoids soliton dynamics, hence it is less sensitive to pump laser shot noise and has larger degree of coherence, than supercontinuum in the anomalous dispersion range. Furthermore flattening around 1560 nm indicates optimal supercontinuum pump wavelength, which is readily available from erbium doped femtosecond fiber lasers. Using Vytran splicing station (GPX3400) we were able to achieve repeatable splice losses between a standard fused-silica single mode fiber (SMF28) and the low-melting-temperature soft glass MSF as low as 2.12 dB @1310 nm and 1.94 dB @ 1550 nm. The developed very low loss splicing technology together with the above mentioned all solid soft glass MSF advantages give very promising perspectives for commercial applications.

8982-83, Session PWed

The novel dual-waveband SWIR InGaAs FPAs with monolithic integration filter microstructure

Heng-jing Tang, Xue Li, Yunji Wang, Weibo Duan, Xiumei Shao, Haimei Gong, Shanghai Institute of Technical Physics (China)

According to excellent photoelectric properties of InGaAs epitaxial material, and important application of the spectral bands at center wavelength of 1.38 μm and 1.60μm, the new-type monolithic dual-band InGaAs detector is studied in this paper. The detector was designed and fabricated with mesa structure and Fabry-Perot cavity by thermal evaporation. The current-voltage characteristics, response spectra of monolithic detector were measured. The bandwidths of 1.38 μm and 1.60μm waveband detector are 46nm and 54 nm respectively. 400x2 dual-waveband monolithic detector was connected with two 400x1 readout circuits, and 400x2 dual-waveband InGaAs focal plane arrays (FPAs) was obtained. The detectivity D*, non-uniformity, and the non-operative pixel ratio for 1.38 μm waveband FPAs are 7.71x10^11cmHz^1/2/W, 6.20% and 0.25%, respectively at room temperature, and the ones for 1.60 μm waveband FPAs are 6.06x10^11cmHz^1/2/W, 3.20% and 0.25%, respectively. The monolithic dual-waveband InGaAs focal plane arrays(FPAs) plays an important roles in developing compact, low-cost and high-precision photoelectric detection (imaging) system.

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8983-1, Session 1

Molecular engineering routes for quadratic nonlinear optics: the role of metal and lanthnide complexes for multifunctional nonlinear materials *(Keynote Presentation)*

Isabelle N. Ledoux-Rak, Joseph Zyss, Anu Singh, Ecole Normale Supérieure de Cachan (France)

The wealth of molecular structures and the exploitation of their multifunctional and structural flexibility open-up thoroughly renewed horizons in the domain of Molecular Photonics at the cross-road of physics, chemistry and device engineering

This presentation will point-out the specific interest of metal and lanthanide ion complexes for quadratic and cubic nonlinear optics (NLO), special attention being paid at multifunctional properties such as photochromism and luminescence properties.

A first example will be given by luminescent [PtLX] complexes, L being a 1,3-di(2-pyridyl) benzene ligand and X is an ancillary monodentate halide or acetylide ligand. The complementary use of electric-field-induced second-harmonic (EFISH) generation and harmonic light scattering (HLS) measurements demonstrates how the quadratic hyperpolarizability of this appealing family of multifunctional chromophores, characterized by a good transparency throughout much of the visible region, is dominated by an octupolar contribution.

A second example is illustrated by Phthalocyanines (Pc) form sandwich-type complexes with various lanthanide ions holding two Pc macrocycles closer than their van der Waals distance, resulting in strong pi-pi interactions and through-space three-dimensional delocalization. Huge quadratic hyperpolarizabilities (up to 5.10-27 esu) have been measured using HLS measurements at 1.9 µm. The influence of lanthanide ions and donor and acceptor substituent of the Pc ligand will be extensively discussed.

On another hand, we have investigated dithienylethene (DTE) photochromic metal complexes. We will report here on recent results about the photo-induced switching properties of octupolar (tetrahedral and octahedral) complexes, with different photochromic ligands displaying various electron-withdrawing properties. A highly efficient photo-triggered NLO enhancement (up to 50) has been evidenced.

8983-3, Session 1

Optimization of the electronic third-order nonlinearity of cyanine-like molecules for all optical switching

Honghua Hu, Trenton R. Ensley, Matthew Reichert, Manuel Ferdinandus, Davorin Peceli, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Olga V. Prjonskaia, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and National Academy of Sciences (Ukraine); David J. Hagan, Eric W. Van Stryland, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and Univ. of Central Florida (United States); Seth R. Marder, Georgia Institute of Technology (United States); Alex K. Y. Jen, Univ. of Washington (United States); Joel M. Hales, Joseph W. Perry, Georgia Institute of Technology (United States)

All optical switching (AOS) applications require a material with a large nonlinear refractive index (n2) but relatively small two-photon absorption (2PA) loss. A figure-of-merit (FOM) defined as the ratio between real and imaginary parts of the second hyperpolarizability (?) is used to evaluate the operating efficiency of the AOS material. By using an essential-state model, we describe the general dispersion behavior of ? of symmetric organic molecules and predict that the optimized wavelength range for a large FOM is relatively near its linear absorption edge for cyanine-like dyes. Experimental studies are normally performed on solution samples. The difficulty of separating solute nonlinearities from the dominating solvent background has been overcome using a dual-arm Z-scan to measure solution and solvent simultaneously on two identical Z-scan arms and discriminate their small nonlinear signal difference. This technique significantly reduces the measurement uncertainty by correlating the excitation noise in both arms, leading to nearly an order-of-magnitude increase in sensitivity. Here we investigate the nonlinear refraction and 2PA spectra of several classes of cyanine-like organic molecules and find that the results agree quantitatively with the essential-state model. Many cyanine-like molecules show a relatively small FOM due to the presence of detrimental 2PA bands near the linear absorption edge; however, an exception is found for a thiopyrylium polymethine molecule of which the maximum FOM can be >400, making it an excellent candidate for AOS. We also measured the nonlinearity of several common organic solvents, all of which show positive n2.

8983-4, Session 1

Second-order nonlinear susceptibilities in nonelectrically poled DR1PMMA guest-host polymers

Atsushi Sugita, Yasuaki Sato, Kazuma Ito, Yoshimasa Kawata, Shigeru Tasaka, Shizuoka Univ. (Japan)

The paper presents nonelectrical poling behaviors of guest-host nonlinear optical (NLO) polymers, consisting of Disperse Red1 as guest and poly (methyl methacrylate) (PMMA) as host and their consequent second-order NLO susceptibilities. Our experimental results discovered the emissions of the second harmonic generations (SHG) from the thin films of the guest-host polymers fabricated on SiO2 glass substrates after annealing them at the temperatures higher than Tg of the PMMA even in the absence of applied external electric fields. The film thickness dependence of the SHG intensities indicated that the polar alignments of the guests occurred not only in the vicinity of the substrate surface but also inside the polymer layers in a few micro meter ranges. The hydrogen bonds between the hydroxyl groups of the guests and the silanols of the substrate surfaces may lead to break the centro-symmetry in the alignments of the guests. The measurements were performed for the materials with the different film thickness as well as the different guest concentrations. The highest SHG conversion efficiency were recorded at 1500 nm-film thickness and 15wt.%-guest concentrations. The nonlinear constant of the materials with 10wt.% guest concentrations was approximately 0.3 pm/V. The nonelectrical poling procedure was also available for the guest-host polymers possessing other hydroxyl group-functionalized guests. Even though the nonlinearity induced with the present nonelectrical poling methods was much smaller than that with the electrical poling procedures, the simple techniques to induce the nonlinearity will be useful for further developing the fields of the polymer photonics, nanophtonics and plasmonics.

8983-5, Session 1

Surface-plasmon-enhanced third-order harmonic generation of organic materials

Fanghui Ren, Xiangyu Wang, Oregon State Univ. (United States); Zhong-An Li, Jingdong Luo, Sei-Hum Jang, Alex K. Y. Jen, Univ. of Washington (United States); Alan X. Wang, Oregon State Univ. (United States)

Extraordinarily high 3rd-order nonlinear effects have been demonstrated at visible wavelength using gold nanoparticle (NP)-doped composites. However, this approach faces two insurmountable challenges at telecom wavelengths: First, gold NPs do not have plasmonic resonances at telecom wavelengths, so the nonlinear enhancement is negligible; Second, metallic NPs-doped composites have strong optical scattering and absorption, which will induce very high optical loss, particularly at the resonant frequency. In this paper, we present to use hybrid organic-plasmonic nanostructures to enhance the nonlinearity of $\chi3$ polymers at telecom wavelengths. The device is based on a two-dimensional Au photonic crystal formed on a quartz substrate, which is embedded in a thin layer of spin-coated $\chi3$ polymer film (AJBC1725). The periodicity of the metallic photonic crystal and the thickness of the polymer film are fine-tuned such that the optical resonances of these two nanostructures will overlap and couple with each other to obtain extraordinary optical transmission and significantly enhanced electric field intensity. In our measurement, a femtosecond fiber laser is launched to pump the the nanostructure with a repetition frequency of 20 MHz. The output light centered at 1565 nm was collimated by a 40x objective lens. The THG emission at 522 nm is enhanced by ~100x due to the excitation of SPPs at the polymer/Au interface. The THG was imaged by a colored CCD camera at the far field after filtering the pump laser. With a high resolution image, we can observe the local field enhancement of each individual photonic crystal pixel.

8983-6, Session 2

Electronic structure and nonlinear optical response of polymethine dyes for all-optical switching applications *(Invited Paper)*

Jean-Luc Bredas, Georgia Institute of Technology (United States)

All-optical signal processing / switching applications require materials with large third-order nonlinearities and low nonlinear optical losses. Recently, a joint experimental / theoretical design approach was proposed, that involved enhancing the real part of the third-order polarizability (γ) of polymethine-type molecules through incorporation of heavy chalcogen atoms into terminal groups, while controlling the molecular length to obtain favorable one- and two-photon absorption resonances that lead to suitably low optical loss and to substantial dispersion enhancement of Re(γ). This approach was implemented in a soluble bis(seleno-pyrylium) heptamethine dye that exhibits a real part of γ that is exceptionally large throughout the wavelength range used for telecommunications, and an imaginary part of γ, a measure of nonlinear loss, that is two orders-of-magnitude smaller [1]. Such a combination is critical to enable low-power, high-contrast optical switching. In this presentation, we will first provide a quantum-chemical description of the real and imaginary nonlinear optical properties of relevant polymethine-type molecules [2]. We will then discuss the strategies that need to be followed in order to translate the properties of the isolated molecules into the solid state [3] and describe some recent very promising examples.

This work has been performed in the framework of the AFOSR MURI program (Award FA9550-10-1-0558).

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8983-7, Session 2

Second harmonic generation at liquid interface: molecular organization, supramolecular assemblies, and chirality *(Invited Paper)*

Emmanuel Benichou, Univ. Claude Bernard Lyon 1 (France); Pierre-Marie Gassin, Univ Claude Bernard Lyon 1 (France) and Institut de Chimie Séparative de Marcoule, UMR 5257 (CEA-CNRS-UM2-ENSCM) (France); Gaelle Martin-Gassin, Institut Charles Gerhardt Montpellier, UMR 5253 CNRS-UM2-ENSCM-UM1 (France); Aurélie Bruyère, Univ Claude Bernard Lyon 1 (France); Isabelle Russier-Antoine, Christian Jonin, Univ. Claude Bernard Lyon 1 (France); Olivier Diat, Institut de Chimie Séparative de Marcoule (France); Pierre-François Brevet, Univ. Claude Bernard Lyon 1 (France)

Second Harmonic Generation (SHG), the optical process whereby two photons at a fundamental frequency are converted into one photon at the harmonic frequency, has been shown to be an ideal tool to investigate molecular organization at interfaces. This sensitivity arises from its cancellation in centrosymmetric media like liquids within the electric dipole approximation. We have therefore investigated the possibility to probe this molecular organization in monolayer films formed at the air-water at the nanometer scale. Using this non linear optical process, we show that it is possible to monitor the formation of supramolecular assemblies. In particular, we reveal how chiral supramolecular assemblies forms from achiral amphiphilic molecules.

8983-8, Session 2

Production of waveguides on DR13-doped PMMA by femtosecond laser pulses

Paulo Henrique D. Ferreira, Renan Stefanutti, Felippe J. Pavinatto, Cleber R. Mendonça, Univ. de São Paulo (Brazil)

Femtosecond micromachining allows the fabrication of waveguides 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, such as glasses, to fabricate waveguide-based photonic devices. However, polymers are cheaper and easier to manufacture than glass, and have been used to fabricate devices with this technique in the last decade. Moreover, the optical properties of polymers can be tailored by doping or by chemical synthesis, providing easy customization for specific applications. In this work, we produced waveguides by extended-cavity femtosecond laser irradiation in PMMA doped with the chromophore Disperse Red 13 (DR13). This molecule (DR13) is often referred to as azoaromatic chromophore, or azochromophore, due to its molecular structure. Azochromophores possess interesting linear and nonlinear optical properties, which can be exploited for electro-optic modulators, second-harmonic generation, and birefringent devices. We studied the waveguide formation in function of the incident pulse energy. The formed waveguides, which have tubular structure and present good structural integrity, were characterized by confocal and transmission light microscopy. The tubular morphology is due to the thermal expansion of the polymer. Finally, we demonstrated their functionality by measuring the near-field intensity distribution at the waveguide output and their efficiency, which presented a guiding loss of 1.4 dB/mm. Moreover, we demonstrated that the birefringence properties of the DR13 azochromophore within the PMMA bulk were maintained after the fs-laser fabrication and a residual birefringence of approximately 40% was measured.

8983-9, Session 3

Progress and challenges in electrolyte-gated organic light-emitting transistors *(Invited Paper)*

Clara Santato, Francesca Soavi, Univ. degli Studi di Bologna (Italy); Jonathan J. Sayago, Ecole Polytechnique de Montréal (Canada)

Organic Light-Emitting Transistors (OLETs) are optoelectronic devices that couple the light-emitting function of OLEDs with the switching and amplifying functions of organic transistors. Electrons and holes injected from the drain and the source electrodes, upon application of a suitable gate bias, form excitons in the transistor channel, whose radiative recombination generates light. Despite the impressive progress experienced in the field of OLETs, their practical application requires improvements in their performance, in terms of operating voltage and electroluminescence efficiency.

Our research focuses on one strategy to achieve high performance OLETs, namely the coupling of light-emitting organic semiconductors and ionic species. The experimental configuration considered is the electrolyte-gated (EG) organic transistor. EG - OLETs represent an exciting opportunity to investigating the properties of organic materials under high charge carrier and exciton density as well as high current density conditions, to shed light onto the relationships between charge carrier density, mobility, and light emission in organic electroluminescent materials. In particular, we report EG - OLETs based on thin films of the light-emitting polymer MEH-PPV and, as the electrolyte, imidazolium based ionic liquids. The device performance are correlated with the electrochemical properties of the polymer film/ionic liquid interface as well as to the film morphology and structure.

8983-10, Session 3

On deoxyribonucleic acid (DNA) based BIOLEDs *(Invited Paper)*

Remigiusz Grykien, Beata Luszczynska, Ireneusz Glowacki, Jacek Ulanski, Technical Univ. of Lodz (Poland); Ileana Rau, Roxana Zgarian, François Kajzar, Univ. Politehnica of Bucharest (Romania)

Fabrication and characterization of deoxyribonucleic acid based bio light emitting diodes (BioLEDs) is reported and discussed. Using a Nile Blue luminophore a single layer BioLED was fabricated. It exhibits the voltage – current dependence characteristic typical for polymer based OLEDs. However the light emission was either very weak or nonexisting because of high find voltage necessary to operate it. In another approach DNA was used as the electron blocking layer in a structure using tris(2-phenylpyridine) iridium Ir(ppy)3 luminophore, embedded in the poly(N-vinylcarbazole) (PVK)/- (4-tert-Bbutylphenyl)-5-(4-biphenylyl)-1,3,4-oxadiazole (PBD) as light emitting layer. In that case a significant enhancement of the external conversion efficiency, depending on the thickness of DNA layer used was observed.

8983-11, Session 3

Alternating current electroluminescence with self-assembled low-dimensional nanomaterials/polymer blends *(Invited Paper)*

Cheolmin Park, Sung Hwan Cho, Seong Soon Jo, Yonsei Univ. (Korea, Republic of)

Field induced electroluminescence of either organic or inorganic fluorescent materials under alternating current (AC) has been of great attention as a potential candidate for next generation displays and lightings. Unique device architecture in which an emitting layer is separated with an insulator from electrode offers a new platform for designing and developing a variety of types of ELs based on novel nanoscale fluorescent materials such as collodial quantum dots, carbon nanotubes and their hybrids with organic/polymeric ones. Here, we demonstrate a high-performance field-induced AC electroluminescence (AC-EL) device consisting of four stacked layers: a top metal electrode/thin solution-processed nanocomposite film of low dimensional nanomaterials and a fluorescent polymer/insulator/transparent bottom electrode working under AC electric field. A small amount of carbon nanotubes that were highly dispersed in the fluorescent polymer matrix by a conjugate block copolymer dispersant significantly enhanced EL, and we were able to realize a solution-processed and color tunable AC-EL device with a light emission of a few thousand cd/m2 at an applied voltage of ?50V and an AC frequency of 300 kHz. The material design rules of our AC-ELs are much simpler than conventional light emitting diodes because there is no need to ensure energy band gap alignment between layers or to control carrier injection and transport, resulting in a very cost-effective device capable of full color emission.

8983-12, Session 3

Progress in OLED device with high efficiency at high luminance *(Invited Paper)*

Carmen Nguyen, Univ. of Toronto (Canada); Grayson Ingram, University of Toronto (Canada); Zhenghong Lu, Univ. of Toronto (Canada)

Over the last two decades, traditional inorganic semiconductor device physics has guided the OLED research community in device structure design and fabrication. Various layers of functional molecules have been progressively introduced, hoping to boost the efficiency. Many of these multilayered device structures have worked well, in particular for low luminance applications such as small size displays. However, efficiency roll off (similar to efficiency droop in LED) at high luminance and high injection current become a major challenge for OLED lighting applications. In this talk I will review fundamental problems in these multilayered devices and it correlation with efficiency droop. In order to reduce or eliminate this efficiency droop, considerations in design of device structure and in selection of materials will be discussed.

8983-13, Session 4

Optical properties of Sulfur copolymers for Infrared applications

Soha Namnabat, College of Optical Sciences, The Univ. of Arizona (United States); Jared J. Gabriel, Jeffrey Pyun, The Univ. of Arizona (United States); Robert A. Norwood, College of Optical Sciences, The Univ. of Arizona (United States)

The development of organic polymers with high refractive indices has been widely investigated, as a possible alternative to inorganic metal oxide, semiconductor, or chalcogenide-based materials for a variety of optical devices and components, such as waveguides, anti-reflective coatings, charge-coupled devices and fiber optic cables. In principle, organic-based polymers are attractive for these applications because of their light weight, ease of processing, mechanical toughness, and facile chemical variation using commercially available precursors. However, one of the fundamental challenges associated with organic polymers is their generally low refractive indices in comparison to their inorganic counterparts. Herein we report on the optical characterization of a new class of sulfur copolymers that are readily moldable, transparent above 500nm, possess high refractive index ($n > 1.8$) and take advantage of the low infrared absorption of S?S bonds for potential use in the mid-infrared at 3-5 microns. These materials are largely made from elemental sulfur

by an inverse vulcanization process; in the current study we focus on the properties of a chemically stable, branched copolymer of poly(sulfur-random-1,3-diisopropenylbenzene) (poly(S-r-DIB). Copolymers with elemental sulfur content ranging from 50% to 80% by weight were studied by UV-VIS spectroscopy, FTIR, and prism coupling for refractive index measurement. Clear correlation between material composition and the optical properties was established, confirming that the high polarizability of the sulfur atom leads to high refractive index while also maintaining low optical loss. Applications of the materials for bulk optics, high-density photonic circuits, and infrared components will also be discussed.

8983-14, Session 4

Multidirectional waveguide arrays: an artificial compound eye in a planar architecture

Ian D. Hosein, Hao Lin, Matthew R. Ponte, Dinesh Baskar, Kalaichelvi Saravanamuttu, McMaster Univ. (Canada)

Current artificial compound eyes adapt hemispherical geometries to achieve the wide field of view (FOV) characteristic of their naturally occurring counterparts. We now present the fundamentally new concept of generating this functionality within planar and flexible architectures. Our technique exploits the modulation instability of white light and the spontaneous generation of tens of thousands of cylindrical waveguides in photopolymerizable media. By simultaneously eliciting the modulation instability of multiple white light beams, we have generated planar films comprising up to 5 non-parallel and intersecting waveguide arrays; each array is oriented at a different angle with respect to the film surface. Their efficient light collection and guiding properties as well as their cumulative angular acceptance ranges results in a wide FOV, like spherical compound eyes, but now in a planar geometry. Because waveguides are the functional subunit, the plane of imaging is not restricted by a focal length as in the case of micro-lenses. Critically, the cylindrical waveguides in our system are multimodal and support wavelengths spanning the entire visible spectrum. This enables operation with quasi-monochromatic laser and polychromatic, incandescent sources. We demonstrate that our multidirectional waveguide arrays collect images over a wide range of view angles, (-50 to 50°), confirming that information is transmitted as waveguided modes with preservation of image quality, relative to a homogeneous, unstructured film. Our multidirectional waveguide arrays have potential application for imaging in medical, sensing and smart-phone applications. Their planar geometry makes these systems particularly amenable to thin-film device fabrication, which can significantly reduce device sizes.

8983-15, Session 4

Mode-coupling mechanism in poly(methyl methacrylate)-based graded-index plastic optical fiber

Takahiro Kashiwazaki, Azusa Inoue, Yasuhiro Koike, Keio Univ. (Japan)

A graded-index plastic optical fiber (GI POF) is a promising candidate for a transmission media in home-network because of its flexibility and large core. POF core base-polymers such as poly(methyl methacrylate) (PMMA) intrinsically have microscopic heterogeneous structure with larger-sized dielectric constant fluctuations, which can result in mode coupling due to more forward scattering, than those of optical glasses. Recently, we theoretically developed coupled power equation to correlate microscopic heterogeneities in POF cores to optical transmission characteristics of GI POFs. In this study, we investigated influence of the intrinsic material properties on optical pulse transmission of an actual PMMA-based GI POF based on the analysis with the developed coupled power equation. We fabricated a GI POF by the interfacial gel polymerization and measured the output pulse response from the GI POF under restricted mode launching condition. We estimated spatial correlation characteristics of dielectric constant fluctuations by measuring the light scattering profile of the POF core bulk-polymer. Using the determined correlation characteristics in the developed coupling power equation, we evaluated the optical pulse broadening in the GI POF. The results show that the intrinsic mode coupling due to microscopic heterogeneous structure can affect the optical pulse response of the GI POF even for a fiber length of 100 m, which is much shorter than coupling lengths for extrinsic mode couplings in glass multimode fibers. In the conference, we will also discuss the mode coupling effect in GI POFs with various core materials.

This work has been sponsored by the Japan Society for the Promotion of Science (JSPS) through its "Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program)."

8983-16, Session 4

Longitudinal versus transversal excitation in doped graded-index polymer optical fibers

María Asunción Illarramendi, Jon Arrue, Igor Ayesta, Univ. del País Vasco (Spain); Felipe Jimenez, Univ del País Vasco (Spain); Joseba Zubia, Iñaki Bikandi, Univ. del País Vasco (Spain); Akihiro Tagaya, Yasuhiro Koike, Keio Univ. (Japan)

Polymer optical fibers (POFs) are well known in the field of fiber optics thanks to their robustness, large core diameters, high numerical apertures and low cost. The lower manufacturing temperatures of POFs as compared to glass fibers make it possible to embed a wide range of available materials into the fiber core. In addition, the fiber structure provides several advantages, such as optical confinement in the core area, long interaction distance between the light and the gain medium, symmetric output of the beam profile, good adaptability to fiber-optic communications systems and high ratio between surface area and volume, which allows efficient heat dissipation and minimization of thermal degradation of performance. These facts provide new applications for POFs in the fields of lasers, amplifiers, switches and sensors in the visible region.

In this work we perform a theoretical and experimental analysis of the optical characteristics of amplified spontaneous emission (ASE) in a rhodamine-6G-doped graded-index polymer optical fiber when the fiber is pumped either longitudinally or transversally with respect to the fiber axis. The theoretical model has been carried out by means of the rate laser equations as functions of time, distance traveled by light and wavelength for both schemes of excitation. In the analysis, it has been taken into account that the fiber analyzed is a typical graded-index POF in which the radial distributions of light power density and dye density are not uniform. The dependence on the overlapping between light power distribution and dopant concentration and the dependence on fiber length of ASE thresholds and slope-efficiencies have been compared for both excitations. The theoretical calculations are in satisfactory agreement with the experimental results.

8983-17, Session 4

Graded-index plastic optical fiber based on a novel partially-fluorinated polymer

Hiroki Yamamoto, Yasuhiro Koike, Atsushi Kondo, Kenji Makino, Azusa Inoue, Keio Univ. (Japan)

Graded-index plastic optical fiber (GI POF) is expected to be transmission medium in very short-reach optical communications, because GI POF allows for easy handling and high-speed transmission of digital data. GI POFs based on poly(methyl methacrylate) (PMMA) or a perfluorinated polymer have been proposed as the transmission media. However, GI POF based on PMMA had a problem of high material dispersion and low transmittance at a wavelength of 850 nm, and GI

POF based on the perfluorinated polymer had a problem of high material cost. In this study, we proposed a novel partially fluorinated polymer (PFP) as the inexpensive base material of GI POF. The PFP has lower material dispersion at 850 nm than PMMA. Therefore, it was indicated that the PFP-based GI POF had higher bandwidth than PMMA-based GI POF, allowing for a bandwidth of 8.0 GHz for 100 m at 850 nm. The PFP has lower intensities and longer peak wavelengths of the molecular vibrational absorptions than PMMA. Therefore, it was indicated that the PFP-based GI POF had lower loss at 850 nm than PMMA-based GI POF. Because of high heat resistance of the PFP, we could fabricate the PFP-based GI POF by co-extrusion process, and confirm that the refractive-index distribution was successfully formed in the core region of the obtained GI POF. It is expected that the PFP-based GI POF has high bandwidth and low loss at 850 nm, which is just suitable for use with very short-reach optical networks.

8983-18, Session 4

Proteins detection by polymer optical fibers sensitised with overlayers of block and random copolymers

Alexandros El Sachat, Anastasia Meristoudi, Christos Markos, Stergios Pispas, Christos Riziotis, National Hellenic Research Foundation (Greece)

A low cost and low complexity scheme for optical detection of proteins, based on fast electrostatic interaction, was implemented by the sensitization of Polymer Optical Fiber - POFs' surface by overlayers of copolymers with properly designed charge distribution. This method allows the sub-second response to opposite charged proteins and also the effective discrimination of differently charged biomolecules like lysozyme (LSZ) and bovine serum albumin (BSA). As sensitive materials were used the block and the random forms of the same copolymer poly(styrene-2vinylpyridine), namely the block co-polymer PS-b-P2VP and the corresponding random co-polymer PS-r-P2VP of the same molecular weight. The evaluation performance of the active materials was conducted using large core poly(methyl-methacrylate) PMMA POFs where the deposition of polymeric thin films and the functionalization of the PMMA fiber region was performed using a common dip coating technique by removal of the fluorinated polymer cladding followed by proper chemical treatment for improved layer adhesion and bio-contact properties. The employed polymers induce a positively charged coated PMMA sensing region that strongly adsorbs negatively charged BSA. In contrast as it was anticipated positively charged lysozyme exhibited drastically lower adsorption, suggesting thus an intrinsic electrostatic discrimination and selective detection mechanism. Results show also systematically different response between the block PS-b-P2VP and the random PS-r-P2VP materials, although at the same order, drawing thus important conclusions on their applications' techno-economic aspects given that they have much different associated manufacturing costs, as block co-polymers often require laborious high vacuum techniques for their production in contrast to random polymers.

8983-19, Session 5

Laser trapping studies toward fabrication of organic materials and devices *(Keynote Presentation)*

Hiroshi Masuhara, National Chiao Tung Univ. (Taiwan); Teruki Sugiyama, Instrument Technology Research Ctr. (Taiwan); Ken-Ichi Yuyama, National Chiao Tung Univ. (Taiwan); Anwar Usman, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Upon focusing intense CW and femtosecond lasers with a few hundreds mW into a diffraction limit, small nano-objects such as molecular clusters, polymers, and particles can be trapped in solution at room temperature, opening new applications for organic photonic materials.

Laser trapping induces unique molecular association, which was confirmed for pseudo-isocyanine J-aggregates. The formed J-aggregate shows a narrower fluorescence bandwidth compared to those obtained by solvent vaporization, indicating that the highly ordered J-aggregates is preferentially fabricated at the laser focus. Laser trapping localizes photo-polymerization and confines solidification, enabling the production of tiny polymeric structures that are smaller than the diffraction limit of the trapping light. Also laser trapping crystallizes amino acidsand controls crystal growth of proteins in solution. Crystallization is only achieved when CW laser is focused at solution surface, and one single crystal is always prepared at the focal point upon irradiation. This crystallization is realized even for unsaturated solution, and its polymorph can be controlled by laser polarization and power. Laser trapping by femtosecond pulses is more efficient than CW laser trapping and, for example, quantum dots with size of a few nm can be gathered at the focal point. In addition unique scattering dynamics was observed for polystyrene nanoparticles, which we explained by taking into account the impulsive peak power and the axial component of electric light field produced by high numerical aperture of objective lens. Organic photonic materials have high polarizability and are recognized as nice molecular targets for laser trapping, promising potential developments.

8983-20, Session 5

Studies of functionalized nanoparticles for photonic and sensing applications *(Invited Paper)*

Katarzyna Matczyszyn, Wroclaw Univ. of Technology (Poland); Marta Gordel, Wroclaw Univ. of Technology (Poland) and Ecole Normale Supérieure de Cachan (France); Aleksandra Bednarska, Claude Nogues, Ecole Normale Supérieure de Cachan (France); Joanna Olesiak-Banska, Dominika Wawrzynczyk, Wroclaw Univ. of Technology (Poland); Pawel Jaworski, Polish Academy of Science (Poland); Marcin Nyk, Wroclaw Univ. of Technology (Poland); Krzysztof Pawlik, Polish Academy of Science (Poland); Macolm Buckle, Ecole Normale Supérieure de Cachan (France); Marek Samoc, Wroclaw Univ. of Technology (Poland)

A range of the nanoparticles varying from the plasmonic ones to the rare-earth luminescent nanocrystals have been synthesized and functionalized for applications in the field of biophotonics. Gold nanorods of 10x36 nm dimensions stabilized by the CTAB ligand, were prepared by the wet-chemistry method. Measurements of the nonlinear optical properties of those nanostructures were conducted with the use of the open-aperture and closed-aperture Z-scan technique, and the real and imaginary part of the cubic hyperpolarizability γ $(-\omega;\omega,-\omega,\omega)$ in the range from 550 to 1600 nm were measured. The wavelength dependencies of the nonlinear refractive index and the two-photon absorption cross-section were determined, taking into account the observed saturable absorption effects [1]. The irradiation of the nanorods with the femtosecond laser caused the re-shaping of the anisotropic structures into nanobananas, the shape which is not possible to obtain by other means. The thermal analysis of the nanostructures unveiled the composition of the gold nanorods, the ligand amount and the temperature of the gold melting, much below the temperature characteristic for the bulk gold counterparts.

The rare-earth doped nanocrystals of average size in the range from 7 nm to 30 nm were prepared by the method described in [2,3]. The nanoparticles were transferred into water and the DNA strands were attached. The complementary strands of various length, marked with the fluorescent dye Cy5, were added into the solution and the optimal distance for the energy transfer in such systems was achieved at about 26 base pairs. The fluorescence life-time measurements confirmed the appearance of the Förster energy transfer in those systems.

All the nanostructures were characterized by the TEM and AFM techniques before and after functionalization with the DNA and no significant changes in the morphology of the nanoparticles were observed. In summary, these nanoprobes can be considered as ideal candidates for a new generation of gene diagnostic probes in the field of DNA-based sensing.

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8983-21, Session 5

Laser inscription of surface structures and induction of optical anisotropy in azo-benzene substituted photochromic polymers and other systems *(Invited Paper)*

Andrzej Miniewicz, Lech Sznitko, Ewa Szlapa, Pawel Karpinski, Antoni C. Mitus, Grzegorz Pawlik, Wroclaw Univ. of Technology (Poland); Ewa Schab-Balcerzak, Instiute of Polymer Chemistry (Poland)

A growing demand for advanced materials and technologies for modern photonics, e.g. optical data storage and light processing, stimulates development of novel materials and tools for material modifications. Photochromic materials, such as azo-functionalized polymers have been widely investigated [1-3] because of their unique features to undergo inducement of optical anisotropy and surface mass transport upon suitable laser light irradiation. We report how using microscope and tightly focused laser beam different structures can be recorded in azofunctionalized polymer showing both light induced birefringence and surface modification. The latter was analyzed with Atomic Force Microscope. The chiral symmetry of light can be mapped via mass transport and surface pattern formation [4]. By applying a systematic approach to the inscription experiment such as used light intensity, cw or pulsed laser light, its polarization with respect to the direction of inscription, beam scan speed and the position of objective focal point with respect to the surface we can reveal the dynamics of birefringence change and its relation to mass transport [5]. We also report how azo-benzene molecules can work in other systems i.e. azo-benzene functionalized POSS molecules embedded in liquid crystals. We discuss also properties of holographically inscribed polarization gratings and analyze them spatially with the help of microscopic local diffraction efficiency recording.

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8983-22, Session 5

Epitaxial growth of a methoxy-functionalized quaterphenylene on dielectric surfaces

Frank Balzer, Rong Sun, Horst-Günter Rubahn, Univ. of Southern Denmark (Denmark); Manuela Schiek, Carl von Ossietzky Univ. Oldenburg (Denmark); Arne Lützen, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany)

Small rod like conjugated organic molecules such as the para-phenylenes, acenes, and thiophenes have been investigated extensively in the past due to their potential in optoelectronic devices. Depending on the application either the formation of continuous films or the growth of nanoaggregates (nanoclusters, nanofibers) is preferred. Functionalization of the molecule can be used to change the growth mode, somehow preserving the optical properties. In this work the substitution of para-quaterphenylene in the 4,4''' positions by methoxy groups is investigated. The epitaxial growth of the methoxy functionalized molecule (MOP4) on the (001) faces of the alkali halides NaCl and KCl is observed by a combination of low energy electron diffraction (LEED), polarized fluorescence microscopy (PFM), birefringence / bireflectance microscopy, atomic force microscopy (AFM) and X-ray diffraction (XRD). XRD together with AFM and PFM shows that both islands from upright molecules as well as needle like crystallites form. For the upright molecules optical microscopy and LEED demonstrate that the MOP4 [100] direction is parallel to the substrate [110] direction. This is compared to the deposition on muscovite mica and on graphite, where mostly fibers form. For MOP4 on graphite Kelvin probe force microscopy (KPFM) is used to detect the difference in electric surface potential between upright and laying molecules.

8983-23, Session 6

2D- and 3D-patterned organic-inorganic hybrid systems for photonic applications *(Invited Paper)*

Kwang-Sup Lee, Sumin Jeon, Hannam Univ. (Korea, Republic of); Yoon Deok Han, Korea Univ. (Korea, Republic of); Redouane Krini, Rudolf Zentel, Johannes Gutenberg Univ. Mainz (Germany); Jinsoo W. Joo, Korea Univ. (Korea, Republic of)

Chemical protocols for incorporation of silver nanoparticle and quantum dots into structures fabricated with two-photon lithography were recently developed in our group [1-3]. This maskless lithographic technique allows fast prototyping of complex microstructures by nonlinear optical initiation of chemical processes. An ordered arrangement of high and low refractive index materials is required for many optoelectronic components like waveguides and photonic crystals. Incorporating inorganic nanoparticles with superior optical and electronic properties into polymeric microstructures is a popular method for achieving such structures. In-situ generation of silver nanoparticles as well silver coating of microstructures have been studied for the incorporation of silver into microstructures. To incorporate semiconductor quantum dots into 3D microstructures we have pursued a surface functionalization strategy. Cadmium selenide (CdSe) as well as core-shell CdS/ZnS, CdSe/ZnS and CdSe/ZnSe were functionalized with photosensitive monolayer to make them solution processable and photopatternable. The core-shell nanoparticles show more efficient flourecence and can be useful in display applications. These functionalized quantum dots can be easily dispersed in photopolymerizable resins to fabricate 3D structures.

8983-24, Session 6

Fully updatable holographic stereogram display device based on organic monolithic compound

Naoto Tsutsumi, Kenji Kinashi, Kyoto Institute of Technology (Japan); Kazuhiro Tada, Kodai Fukuzawa, Yutaka Kawabe, Chitose Institute of Science and Technology (Japan)

We have successfully demonstrated updatable three dimensional (3D) holographic display device based on organic monolithic compound [1]. Recently further progress of 3D display device is achieved using updatable holographic stereogram with organic monolithic compound

[2]. We present fully updatable holographic 3D display system using a holographic stereographic technique with a transparent optical device of PMMA doped organic monolithic compound. 100 elemental holograms which are a series of pictures of object took from different angles can completely reproduce updatable entire hologram of object. Immediately after recording one holographic stereogram, another holographic stereogram can be over-recorded without erasing. Recorded updatable 3D hologram can be viewable for up to a couple of hours directly on a device without any eye glasses and other tools to magnify images. Hologram can be easily refreshed by overwriting without erasing process. Spin coating technique and roll to roll fabrication technique are preferred to make the large size devices. The possibility of spin coated device to the holographic display application is investigated. In the case of spin coated device, clear holographic images can be recorded and updated without erasing process. Using 1.5 W palmtop green laser, updatable 3D hologram can recorded every 200 – 300 ms/step (20 – 30 s for total 100 steps) with only interference beams.

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8983-25, Session 6

Numerical studies on self-organized liquid crystal microphotonic systems

Tatsunosuke Matsui, Mie Univ. (Japan) and Mie CUTE (Japan); Masahiro Kitaguchi, Akiko Okajima, Mie Univ. (Japan)

The liquid crystals (LCs) form various types of nano- and micro-structures in a self-organized manner. In recent years, numerous studies have been carried out to develop novel types of optical functional materials and devices utilizing such self-organizing characteristics of the LCs. Based on the finite-difference time-domain (FDTD) method or its extended version, auxiliary differential equation FDTD (ADE-FDTD) method, we have been numerically studying on the optical characteristics and functionalities of the self-organized LCs such as: (1) lasing from the cholesteric LCs (CLCs) and (2) photonic nanojet (PNJ) from LC micro-systems.

Based on the ADE-FDTD method incorporating the equation of motion of the macroscopic polarization and the rate equations at the four level energy structures, we have successfully reproduced circularly polarized lasing from CLC at the edge energy of the stop band. It has also been clarified that the introduction of the defect is effective to lower the lasing threshold. Our technique can be utilized to design the CLC laser devise architecture for much lowered lasing threshold.

The PNJ from LC micro-systems are uniquely polarized reflecting birefringence of LCs, which cannot be obtained using optically isotropic microdroplets or microcylinders. A small degree of birefringence drastically changes the optical characteristics of the obtained PNJ. Our findings may open the way for the development of the novel optical functional materials and devices.

8983-26, Session 6

Photorefractive device using self-assembled monolayer coated indium-tin-oxide electrodes

Kenji Kinashi, Kento Masumura, Wataru Sakai, Naoto Tsutsumi, Kyoto Institute of Technology (Japan)

Dynamic holographic displays using the PR effect have recently received considerable attention because the diffracted images through the PR device will be able to produce realistic 3D images without requiring special eyeglasses; therefore, the characteristics of high diffraction efficiency and fast response time are required for practical applications. With the recent widespread use of displays users have more opportunities to see moving images on screen. Manufacturers and IT publications often refer a fast response time as an indication that a display can play videos with little or no blurring. If response time is slow, the change from one image (or frame) to another can produce an afterimage or blurring effect. This problem occurs when looking at motion images. Displays are required response times of 30 ms (equivalent to 33 fps) (national television system committee (NTSC)), or 16 ms (equivalent to 63 fps) (high-definition television (HDTV)); furthermore the 3D PC game requires 8 ms (equivalent to 125 fps).

We have first demonstrated the PR quantities of PTAA-based PR device with the SAM-ITO electrodes. The PTAA-based PR device shows a significantly fast response time of 5.0 ms and high sensitivity of 43 cm2 J-1, which are greater values than the results achieved so far. It is noteworthy that the remarkable fast response can only be obtained by using the PR device with SAM-ITO electrodes. We believe that this new approach will provide the useful technology for dynamic holographic displays and for the future PR investigations.

8983-27, Session 7

Two-photon solvatochromism of 4-dimethylamino-4'-nitrostilbene (DANS)

Geoffrey R. Wicks, Aleksander K. Rebane, Mikhail Drobizhev, Montana State Univ. (United States)

Variation of two-photon absorption (2PA) of organic chromophores as a function of the environment such as different solvent polarity has important implications for practical applications of NLO materials but could be also used as a sensitive probe of local inter- and intra-molecular interactions. We report the measurement of 2PA spectrum in the broad wavelength range 700-1050 nm of a benchmark NLO chromophore 4-dimethylamino-4'-nitrostilbene (DANS) in a series of solvents and solvent mixtures with varying polarity by using a novel femtosecond nonlinear-optical transmission method with a nearly-collimated laser beam. The 2PA peak of DANS shifts from 834 nm in a low dielectric constant solvent isobutyl isobutyrate (dielectric constant 4) to 892 nm in a highly polar solvent DMSO (dielectric constant 48), which quantitatively follows the corresponding solvatochromic shift of the S0 -> S1 transition peak in the linear absorption spectrum, and indicates that DANS has a large ground state permanent electric dipole moment that interacts with the solvent environment. On the other hand, the S0 -> S1 transition peak 2PA cross section also changes in a surprisingly large range from 190 GM in DCM to 270 GM in acetone, but this variation exhibits no direct correlation with the solvent polarity. This effect may be tentatively attributed to the change of the excited state permanent electric dipole moment due to the instantaneous S0 -> S1 transition. Our results confirm that accurate measurement of 2PA spectra may serve as a probe of local molecular-level interactions.

8983-28, Session 7

Mechanisms of the three- and four-photon induced photobleaching of red fluorescent proteins

Mikhail Drobizhev, Caleb Stoltzfus, Aleksander K. Rebane, Thomas Hughes, Montana State Univ. (United States); Igor Topol, SAIC-Frederick, Inc. (United States); Lauren M. Barnett, The Univ. of Montana (United States)

Two-photon laser scanning microscopy (TPLSM) has several advantages over one-photon confocal microscopy, including deeper tissue penetration, higher signal-to-background ratio, and less photodamage in the out-of-focus volume. However, due to very high instantaneous

light intensities in the focal volume, the probability of further, stepwise resonant photon(s) absorption increases dramatically, leading to very efficient bleaching of a probe. To deal with this challenge one has to understand the underlying mechanisms. Here we measured the power dependence of multiphoton bleaching rates of several red fluorescent proteins expressed in live E. coli cells under two-photon microscope conditions. To clarify the photophysical mechanisms, we also used much lower repetition rate (1 kHz) and different pulse durations in experiments in vitro with Ti:Sa amplifier excitation. Our experimental data supported by quantum mechanical calculations of the chromophore in protein environment are consistent with the mechanism of ultrafast (<150 fs) singlet-singlet stepwise absorption of one or two additional photons following initial simultaneous two-photon absorption. In the DsRed2 protein, the third photon absorption most probably results in an ultrafast electron transfer (ET) from the anionic chromophore to an excited Rydberg state of a nearby positive amino acid residue (e.g. K163+). The transient radical state of the chromophore tends to accept an electron from the deprotonated E215- amino acid, thus promoting the first step of the recently established decarboxylation reaction. In mFruits proteins, the third photon promotes an ET from the chromophore to the 4S Rydberg state of nearby K70+ with its subsequent photoionization by the fourth photon.

8983-29, Session 7

Breaking of two-photon absorption inversion symmetry in trans- versus cis- platinum(II) acetylide complexes

Aleksander K. Rebane, Geoffrey R. Wicks, Montana State Univ. (United States); Abigail H. Shelton, Univ of Florida (United States); Mikhail Drobizhev, Montana State Univ. (United States); Randi S. Price, Khalil A. Abboud, Univ. of Florida (United States); Charles F. Campana, Bruker AXS, Inc. (United States); Kirk S. Schanze, Univ. of Florida (United States)

Among chromophores with enhanced two-photon absorption (2PA) platinum(II) acetylide complexes exhibit unique combination of NLO properties rendering these organo-metallic compounds especially suitable for broad-band optical power limiting and other applications that require efficient ultrafast all-optical switching. We report femtosecond 2PA spectra of cis- and trans versions of three Pt-acetylides bearing phenylethynyl phenylethynylene (PE2), diphenylaminofluorene (DPAF), and benzothiazolefluorene (BTF) two-photon absorbing chromophores. The 2PA spectra were measured in toluene solution in the broad 540-900 nm range by using a novel nonlinear-optical transmission method utilizing nearly-collimated femtosecond laser beam. Direct comparison between 2PA in the S0 -> S1 transition peak in the nominally certrosymmetric (trans) and non-centosymmetric (cis) versions reveals that isomers behave in a quantitatively as well as qualitatively different manner depending on the electron-donating or electron-withdrawing strength of the substituents. In accordance with parity selection rules, in centrosymmetrical trans-DPAF the peak 2PA cross section in the one-photon allowed S0 -> S1 transition is low, sigma2<100 GM, but increases to a higher value, sigma2 ~250 GM, in non-centrosymmetrical cis-DPAF. In a stark contrast to the above, 2PA of both trans- and cis-BTF show a distinct 0-0 component with high peak cross section, sigma2 ~600 GM and ~1000 GM, respectively. This result indicates that decorating a slightly electron-donating centrosymmetric Pt-core with strong electron-withdrawing groups may lead to breaking of the inversion symmetry, whereas in case of similar electron-accepting end-groups the center of inversion is preserved. Our results shows that 2PA spectroscopy is an effective tool to study molecular-level interactions.

8983-30, Session 7

Pushing the limits of vertical external-cavity surface-emitting organic lasers

Zhuang Zhao, Tatiana Leang, Univ. Paris 13 (France); Sébastien Chenais, Sébastien Forget, Univ. Paris 13 (France) and Ctr. National de la Recherche Scientifique (France)

The limits in terms of efficiency and output energy are examined in Vertical External Cavity Surface Emitting Organic Lasers (VECSOLs), a distinctive type of organic solid-state laser (OSSL), developed as a counterpart of VECSELs with organic thin films. OSSLs represent a low-cost attractive solution for building widely-tunable coherent sources in the visible spectrum. They usually deliver ns pulses with energies ~ nJ to µJ at low repetition rates (< kHz) with modest efficiencies. We show that thanks to a good pump-to-laser mode matching and long enough pump pulses, conversion efficiencies can be higher than 60% with a VECSOL device based on Pyrromethene 597 in PMMA, with 30µJ (25 ns) per pulse at 10 Hz. Achieving higher energies is at the expense of a faster degradation rate, and since many photodegradation mechanisms are thermally activated, the question is raised whether power scaling of organic lasers can be realized through a better thermal management. We have performed thermal infrared (8-12µm) microscopy on operating VECSOLs in order to get time-averaged temperature maps, coupled with time-resolved Finite-element thermal simulations, and visible microscopy to monitor bleaching and irreversible damage during laser action. It is shown that for a 100 µJ pump pulse focused onto a 100µm-in-diameter spot, the steady-state temperature at the center of pumped zone reaches 2 K above ambient at 10 Hz and 15 K above ambient at 1 kHz repetition rate, in good accordance with simulations. These observations suggest new strategies towards high-energy, high-repetition rate organic lasers.

8983-31, Session 7

Random lasing in liquid and solid solutions oversaturated with organic laser dye

Lech Sznitko, Konrad Cyprych, Adam Szukalski, Andrzej Miniewicz, Jaroslaw Mysliwiec, Wroclaw Univ. of Technology (Poland)

Classical laser operation that occurs in liquid or solid dye solution requires particular dye concentration. Mainly the concentration of laser dye in liquid or solid matrix should be precisely selected and the choice of proper concentration depends on gain media size, designed lasing threshold and maximal power, excitation manner, gain material, etc [1]. Therefore optimal laser dye concentration can be found at the level of 10-4 moles per liter. Such concentration of dye is high enough to provide sufficient gain and small enough to suppress quenching effect.

We present the results of studies carried out for oversaturated solutions with common laser dye 4-(Dicyanomethylene)-2-methyl-6-(4-dimethylaminostyryl)-4H-pyran (DCM) and 3-(1,1-Dicyanoethenyl)-1-phenyl-4,5-dihydro-1H-pyrazole (DCNP) nonlinear chromophore. We show that oversaturating the solution leads to formation of crystallites suspension resulting in strong Mie scattering and thus random laser operation can be observed. The crystallites formation can be induced be oversaturating the solution or by injection of non-solvent to the dye solution, leading to reduction of solubility limit. Similar situation can be obtained for polymeric matrices for which crystallites are precipitated during layer formation (solvent evaporation) when film is casted from the solution.

Acknowledgements:

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8983-32, Session 7

Polymeric waveguide Fabry Perot resonators

Mohammad Amin A. Tadayon, Univ. of Minnesota (United States); Martha- Elizabeth E. Baylor, Carleton College (United States); Shai Ashkenazi, Univ. of Minnesota (United States)

Optical microcavities are used in variety of applications ranging from sensors to lasers and signal routing in high volume communication networks. Achieving a high quality factor (Q) is necessary for achieving the higher sensitivity in sensing applications and for narrow linewidth light emission in most lasing applications. In this work, we propose a new way for achieving a higher quality factor in thin film, Fabry-Perot polymeric optical resonators. We show that lateral photon confinement in a vertical Fabry-Perot microcavities can be achieved by optical writing of a refractive index profile utilizing our UV-sensitive polymer. Our theoretical modeling shows that up to 100% increase in cavity finesse can be achieved in this way. In order to demonstrate this improvement, the device has been fabricated. The fabricated device consists of two dielectric Bragg reflectors with a layer of 7 um thick polymer layer between them. The polymer is a thiol-ene/methacrylate photopolymer whose optical index can be modified utilizing standard photo-lithography processes. Although the attained finesse is lower than the finesse achieved in high Q non-polymeric microcavities (e.g., optical micropost cavities), the achieved finesse combined with the flexible polymer layer allows this device to be used as an ultrasound detector in optical micromachined ultrasound transducers (OMUT).

8983-33, Session 8

Electroactive vibrantly-colored processable conjugated polymers in display- and window-type devices *(Keynote Presentation)*

John R. Reynolds, Georgia Institute of Technology (United States)

Electrochromic materials are potentially useful for color-changing displays and dynamic windows with the active materials varying from transition metal oxides, ionic metal complexes, conjugated organic molecules, and conjugated polymers. With their relatively fast switching rates, mechanical flexibility, low redox potentials, and highly transmissive oxidized states, soluble and processable conjugated polymers provide a suite of properties desirable for both application types. Our group has created a set of conjugated polymers with a complete color palette that spans the visible spectrum with neutral state colors that range from yellow, orange, red, magenta, green, cyan, blue, and black. Their high level of solubility allows for processing using a variety of methods including roll-to-roll coating, inkjet printing, and spray-coating. This presentation will outline our efforts in developing this full family of electrochromics polymers. We will overview advanced characterization methods for measuring the electrochemical, spectroscopic, and colorimetric properties of these polymers, including monitoring color properties during dynamic switching, along with rapid spectral recording for definition of switching speeds. Using electrochromic devices (absorptive/transmissive and absorptive/reflective types) as a characterization platform, we demonstrate how these colored-to-transmissive switching polymers behave in regards to color, spectra, switching speed, lifetime, durability, and bistability.

8983-34, Session 8

Near-IR photothermal properties of conjugated polymers *(Invited Paper)*

Eunkyoung Kim, Yonsei Univ. (Korea, Republic of)

Conjugated polymers (CPs) have been collected strong interests for their tunability of colors, and low cost of preparation for flexible organic devices. In particular, conjugated polymers for photon energy harvesting is promising because their aborption energy is easily controlled by doping. CPs from thiophene monomers are obtained by oxidative polymerizations, which grow conductive channels as polymerization proceeds. Herein we report preparation of CPs for near IR energy tuning and photon harvesting. Upon exposure to an NIR source, the doped CP film resulted in a temperature rise confirming photothermal conversion. This photothermal effect by NIR light exposure was switchable between the colored and bleached state by simply dedoping and doping the film electrochemically, respectively. The absorption of CP films in the NIR region was effectively triggered cell harvesting and electricity generation. By controlling the NIR absorption of the CP film through electrochemical doping or growing CP with different thin film thickness, the proliferation and harvesting of MSCs on the CP surface were controlled quantitatively. This light-induced cell detachment method based on CP films provides the temporal and spatial control of cell harvesting, as well as cell patterning. The photothermal effect was optimized by precisely controlling the morphology and doping state of CPs. Efficient visible to near-infrared absorption and heat to electric conversion have been realized in one film that could benefit in exploiting multifunctional film displays, invisible NIR sensors, photodynamic theragnosis, and thermoelectric devices.

8983-35, Session 8

Janus tectons: a versatile platform for decoupling self-assembled chromophores from metallic substrates *(Invited Paper)*

André-Jean Attias, Ping Du, Antoine Colas, Fabrice Mathevet, David Kreher, Univ. Pierre et Marie Curie (France); Fabrice Charra, Commissariat à l'Énergie Atomique (France)

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

8983-37, Session 9

Efficient small-molecule photovoltaic cells using nanostructured template *(Invited Paper)*

Tetsuya Taima, Ying Zhou, Takayuki Kuwabara, Kohshin Takahashi, Kanazawa Univ. (Japan)

To improve the efficiency of organic photovoltaic cell (OPV), the control of the crystallinity and morphology of organic thin films is important. We reported the introduction of 3D nano-pillars or 2D nano-sheets of copper iodide on ITO in order to control the organic films at molecular level . 1,2) These pillars and sheets realize ideal phase-separation morphology in bilayer or co-evaporated blend films, which have significantly improved the PCE to above 4%.

Here we report the introducing of the organic templating film (diindenoperylene DIP organic semiconductor) for realizing organic nano-pillars, which significantly improves the cell performances. We introduced tetraphenyldibenzoperiflanthene (DBP) as p-type semiconductor, which is a non-planar molecule, and vacuum-evaporated DBP film generally

exhibits amorphous state with smooth morphology. Patterning DIP nanocrystals on ITO substrate leads to the formation of nanostructured DBP. Finally, we obtained a two-fold increase in power conversion efficiency from 2.6% to 5.2 % at planer heterojunction OPV cells with DIP organic template.

1) Y. Zhou, T. Taima, et al. Nano Lett. 12 (2012) 4146.

2) Y. Zhou, T. Taima, et al. Appl. Phy. Lett. 100 (2012) 233302.

8983-38, Session 9

Plasmonic and morphological effects of metal nanoparticle inclusions in organic photovoltaics

Christopher E. Tabor, Dennis P. Butcher Jr., Air Force Research Lab. (United States); Chun-Wan Yen, Massachusetts Insitute of Technology (United States); Michael F. Durstock, Air Force Research Lab. (United States); Laura Fabris, Robert C. Wadams, Rutgers, The State Univ. of New Jersey (United States); Hilmar Koerner, Air Force Research Lab. (United States); David W. McComb, Imperial College London (United Kingdom); Frank J. Scheltens, The Ohio State Univ. (United States)

Organic photovoltaics (OPV) provide the possibility to rapidly print large area flexible energy harvesting components in a cost effective manner. Unfortunately the requirement that the film be ultrathin (50-200nm) in order to efficiently collect excited charge carriers prior to internal loss mechanisms limits the overall photoconversion efficiencies of these devices. To more effectively collect and manage the incoming electromagnetic energy in such a thin film, we report on the effects of including plasmonic metal nanoparticles with the devices. We present results on the influence that metallic nanoparticles have on the device performance from both plasmonic mechanisms and induced morphological changes in the film.

Control of the nanoparticle / OPV composite architecture and the related effects on device performance will be discussed, including particle spacing and ligand thickness, particle size and shape, and inclusion effects on polymer morphology and domain parameters. Detailed analysis of the nanoparticle / OPV composites will be presented, including device characterization (EQE, J-V curves, mobility) and compositional analysis (HRTEM, X-Ray).

8983-40, Session 9

Optical intensity analysis of organic solar cell with metallic nanoparticles in the photoactive layer

Kwan-Yong Lee, Sun-Joo Park, Do-Hyun Kim, Young-Joo Kim, Yonsei Univ. (Korea, Republic of)

To increase the photon harvesting efficiency in an organic solar cell, it is required to maximize the optical intensity in the photoactive layer for the desired absorption range of wavelengths. Recently, the localized surface plasmon resonances (LSPR) of metal nanoparticles have been used widely to enhance light intensity in the photoactive layer. In this case, the shape and distribution of metal nanoparticles must be optimized to improve LSPR efficiency and reduce the incident light blocking. The bulk heterojunction structure, comprised of PEDOT:PSS, PTB7:PCBM and silver electrode, was computationally analyzed how metal nanoparticles influence the optical absorption in the photoactive layer by the electromagnetic field analysis in this study. The absorbed optical power in the photoactive layer as a function of three particle shapes such as sphere, hexagon and polygon were calculated by the Poynting's theorem. In addition, the effects of metal nanoparticle location and distribution were also studied. It was observed that the absorbed optical power in the photoactive layer for the case of sphere, hexagon and polygon metal nanoparticles can be enhanced up to 8.5%, 9.8% and 13.6%, respectively, compared to the bare device. We also understood that more light concentration on the corner of polygon metal nanoparticles contribute to the improvement of the LSPR efficiency. Furthermore, it was confirmed that the location of metal nanoparticles on the vertically central area of photoactive layer could be more advantageous to improve the electric field enhancement and reduce the diffusion length of charged carriers.

8983-41, Session 9

Patterning of photoelectrode for I2-free solid-state dye-sensitized solar cells

Byeonggwan Kim, Jeonghun Kim, Jong Kwan Koh, Jong Hak Kim, Eunkyoung Kim, Yonsei Univ. (Korea, Republic of)

Patterning of light reflecting photonic photoelectrodes has received a lot of attention as a means of enhancing the photoconversion efficiency of solar cells. In particular, nanopatterning by soft imprinting method provides a simple and facile process for a large area well-arrayed mesoporous inorganic oxide films at low cost by using readily available pastes and elastomeric stamps. The nanopatterned photoelectrode enhanced the light-harvesting efficiency of dye-sensitized solar cells (DSSCs) according to light-trapping principles. The I2-free solid-state DSSCs showed a 40% increase in the short-circuit current density and high photoconversion efficiency (7.03%) which is one of the highest values reported for N719-dye-based, I2-free solid-state DSSCs. This universal patterning method will improve performance in various photovoltaic cells and optoelectric devices using mesoporous inorganic oxide films.

8983-42, Session 10

All EO polymer waveguide devices for next-generation optical communication network *(Invited Paper)*

Akira Otomo, Toshiki Yamada, Shin-ichiro Inoue, Yoshinari Awaji, Tetsuya Kawanishi, National Institute of Information and Communications Technology (Japan)

Integration of many modulators in PLCs becomes crucial technology because they play important role in next generation large-capacity optical communication systems, such as digital coherent communication and space division multiplexing. The modulators in such communication systems have to modulate amplitude, phase and polarization independently. Therefore materials that exhibit true electro-optic effect, such as LiNbO3 and EO polymers have advantages in these applications over the Si-based modulators that works based on electro-absorption effect. In addition, EO polymers have advantages in high-speed modulation exceeding 100 GHz and in process flexibility. We have made UV cross-linkable EO polymer materials and fabricated channel waveguides using EO polymers as both core and clad materials. Since the UV cross-linkable EO polymers become insoluble after coating, multilayer structures can be made simply by spin coating one after another. The waveguide lateral structure was fabricated by using RIE, and symmetric channel structure for TE and TM modes was formed. The all EO polymer waveguides are expected to reduce drive voltage or device length comparing to conventional EO polymer waveguides in which EO inactive materials are used as clad of the waveguides because overlap integral between modulation field and optical field is almost unity for the all EO polymer waveguide. Also a vertical EO switch can be fabricated using the multilayered EO waveguide system. Therefore high-density 3D integration of EO devices is possible in all EO polymer waveguide system. We will present recent progress of our research on EO polymer materials and devices towards 3D integration of modulators and switches for the next generation optical communications.

8983-43, Session 10

Efficient poling in TiO2/electro-optic polymer/ TiO2 multilayer slot waveguide modulators

Yasufumi Enami, Kochi Univ. of Technology (Japan); Jingdong Luo, Alex K. Y. Jen, Univ. of Washington (United States)

We examined low index material to improve mode confinement in the modulator to increase mode confinement and poling efficiency for the EO polymer in the slot waveguide. The poling current was increased by a factor of ten, which indicates more efficient poling of the EO polymer.

8983-44, Session 10

All-polymer electro-optic modulator design, characterization, and application integration

David L. K. Eng, Stephen T. Kozacik, Shouyuan Shi, Benjamin C. Olbricht, Dennis W. Prather, Univ. of Delaware (United States)

Organic electro-optic material based optical modulators have been fervently pursued over the past two decades. The material properties of organic materials over crystalline electro-optic materials such as LiNbO3 have yielded devices with record low drive voltages and significant promise for high frequency operation that are ideal for implementation in many developing telecommunication technologies. This paper will discuss a TM electro-optic phase modulator based on a recently developed material IKD-1-50. A simple fabrication process that is compatible with wafer scale manufacturability using commercially available cladding materials, standard photolithography, dry etching, and spin deposition will be presented. Non-centrosymmetric order is induced in the core material via a thermally enabled poling process that was developed based on work in simple slab waveguide material characterization devices, and optimized for polymer stack waveguide architectures. Basic phase modulators are characterized for half wave voltage and optical loss. In device r33 values are estimated from a combination of measured and simulated values. Additional work will be discussed including amplitude modulation and high frequency applications. The design for a Mach-Zehnder interferometer amplitude modulator that implements a multi mode interference cavity splitter will be presented along with push-pull poling and device operation for decreased half wave voltage. Work towards integrating a TM phase modulator into a subwavelength scale bowtie antenna structure for efficient coupling of RF radiation onto an optical carrier is being pursued. Such an integration is the basis for developing highly sensitive wide bandwidth metamaterials for RF receiver applications.

8983-45, Session 10

Progress towards dual-slot modulator for millimeter-wave photonics

Matthew R. Konkol, Stephen T. Kozacik, David L. K. Eng, Maciej Murakowski, Brock M. Overmiller, Mathew J. Zablocki, Benjamin C. Olbricht, Janusz A. Murakowski, Shouyuan Shi, Dennis W. Prather, Univ. of Delaware (United States)

Dual slot amplitude and phase modulators leverage the field enhancement provided by the continuity of normal electric flux density across a boundary between two dielectrics to increase modal confinement and overlap for the propagating optical and RF waves. The effect is achieved by aligning a conventional silicon based optical slot waveguide with a titanium dioxide RF slot. The TiO2 has an optical refractive index lower than silicon, but a significantly higher index in the RF regime. Thus the dual slot design confines both the optical and RF modes to the same void between the silicon ribs of the optical slot waveguide without the need for a doping scheme. To obtain modulation of the optical signal, the void is filled with an organic electro-optic material (OEOM) with optical and RF indices lower than those of silicon, which offers significantly higher electro-optic activity and bandwidth than traditional optical modulation materials such as lithium niobate. The tight mode concentration and overlap in the slot allow the infiltrated OEOM material to experience enhanced nonlinear interaction with applied electric field, which can result in a device with an ultralow Vpi and high operational bandwidth. We present work towards achieving various prototypes of the proposed device, and we discuss the fabrication challenges inherent to its design.

8983-46, Session 10

High-refractive index core/EO polymer cladding waveguide for 100 pm/V modulator

Shiyoshi Yokoyama, Feng Qiu, Andrew M. Spring, Feng Yu, Kazuhiro Yamamoto, 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. In this study, we fabricated a TiO2 waveguide on silicon based substrate, and used EO polymer as the cladding to demonstrate its optical modulation at 1550 nm. This system can be realized by a straightforward fabrication process, which consists of a sputtering, a photolithography, and two times spin-coating. The fabricated waveguide showed a large figure of merit for the light moderation due to the improved r33 of 120 pm/V. This level of EO activity is 80% higher than that in a thin film. We attributed such an enhancement to the effective poling of EO polymer through the TiO2 layer. The minimum VL was measure to be 3.3 Vcm. The TiO2 core / EO polymer cladding hybrid waveguide has been explored to the ring resonator application. In this application, because of the high-refractive index of the TiO2 layer, the ring radius can be down to 100 ?m with the Q-factor of 5,000 and propagation loss smaller than 2 dB/cm. The low-frequency moderation experiment indicated that the ring modulator showed an extinction ratio >3dB with 2V peak-to-peak driving. High tuning efficiency of 0.02 nm/V was obtained due to the enhanced EO activity in the present device structure.

8983-47, Session 11

Conjugated polymer biomedical sensors *(Invited Paper)*

Ifor D. W. Samuel, Ashu K. Bansal, Shuoben Hou, Mario E. Giardini, Univ. of St. Andrews (United Kingdom)

Conjugated polymers are important optoelectronic materials that are now of growing interest for sensing applications. They offer the potential for compact, light and flexible sensors that are simple to fabricate. Building on our demonstration of a wearable light source for skin cancer treatment, we will present recent progress using organic light-emitting diodes and photodiodes for biophotonic applications. We have developed a sensor using organic LEDs and photodiodes to measure changes in tissue oxygenation. The results of tissue oxygenation during a forearm ischemia experiment are presented. In this experiment a tourniquet is used to restrict blood flow, and the resulting changes in oxygenation of forearm muscles are measured. These results provide another interesting direction for polymer optoelectronics, and the possibility of measuring a range of important biomedical processes.

8983-48, Session 11

Latest advances in biomaterials: from deoxyribonucleic acid To nucleobases *(Invited Paper)*

Fahima Ouchen, Air Force Research Lab. (United States); Eliot F. Gomez, Univ. of Cincinnati (United States); Donna M. Joyce, Adrienne Williams, Emily M. Heckman, Carrie M. Bartsch, Air Force Research Lab. (United States); Perry P. Yaney, Univ. of Dayton (United States); Narayanan Venkat, Univ. of Dayton Research Institute (United States); Matthew B. Dickerson, Kristi M. Singh, Steve S. Kim, Air Force Research Lab. (United States); Andrew J. Steckl, Univ. of Cincinnati (United States); Guru Subramanyam, Univ. of Dayton (United States); Henry D. Young, Rajesh R. Naik, James G. Grote, Air Force Research Lab. (United States)

Bio Materials hold great promise for photonics and electronics applications. To be presented will be the latest on-going research with deoxyribonucleic acid (DNA), silk and nucleobase materials, including their similarities, advantages and differences, along with their use in electro-optic modulators, light emitting diodes, transistors and capacitors.

8983-49, Session 11

Biopolymer conformations and dopant aggregation in DNA-based complexes for photonics application *(Invited Paper)*

Ileana Rau, Gratiela Tihan, Mihaela Mandroiu, Roxana Zgirian, François Kajzar, Univ. Politehnica of Bucharest (Romania)

Biopolymers in general, and the deoxyribonucleic acid (DNA) in particular, appear to be the choice materials for the next generation photonic and electronic devices. There are several arguments for the practical use of these materials, such as their origin from renewable resources, abundance, biodegradability, versatility and ease of processing. The DNA biopolymer can be extracted from the waste of food processing industry, thus can be cheap and is ecofriendly. Although the pure DNA represents a limited interest for practical applications (water solubility only, weak [pi] electron conjugation, low ionic conductivity) it can be functionalized with surfactants and with active molecules, providing desired optical and electrical properties. Some of these properties, like fluorescence, are enhanced due to the specific environment it offers. The DNA-surfactant complexes are insoluble in water and soluble in a number of organic solvents, offering large possibilities for functionalization. They form high optical quality thin films, which can be obtained by spin coating. In this talk the particular and important problems of biopolymer conformations and aggregation of doping chromophores will be addressed Experimental results obtained by diffuse light scattering will be presented and discussed.

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8983-50, Session 11

Bio-hybrid integrated system for wide-spectrum solar energy harvesting

Kathleen E. Martin, Matthew K. Erdman, Hope Quintana, The Univ. of New Mexico (United States); John A. Shelnutt, Univ. of Georgia (United States); Julio Martinez, Olga Lavrova, Tito L. Busani, The Univ. of New Mexico (United States)

An integrated hybrid photovoltaic-thermoelectric system has been developed using multiple layers of organic photosensitizers on inorganic semiconductors in order to efficiently convert UV-visible and IR energy into electricity.

The hot anode of n-type ZnO nanowires or nano-ribbons was fabricated using a thermal process on pre-seeded layer and results to be crystalline, with a transmittance up to 95 % and a bandgap of 3.32 eV. The optoelectronic properties of the nanowires from experimental studies were related to the aspect ratios and the crystal surface defects. Conductivity measurements reveal diode-like behavior for the ZnO nanowires.

The visible-UV light-active organic layer was deposited between the anode and cathode at room temperature using a layer-by-layer deposition onto ITO and SiO2 substrates and ZnO and Bi2Te3 nanowires from aqueous solution. The organic layer is composed of oppositely charged porphyrin metal (Zn(II) and Sn(IV)(OH?)2) derivatives that are separately water soluble, but when combined form a virtually insoluble solid. The electron donor/acceptor properties (energy levels, band gaps) of the solid can be controlled by the choice of metals and the nature of the peripheral substituent groups of the porphyrin ring.

The highly thermoelectric structure, which acts as a cold cathode, is composed of p-type Bi2Te3 nanowires with a thermoelectric efficiency (ZT) between 0.7 to 1, values that are twice that expected for bulk Bi2Te3.

Efficiency of the integrated device, compared to the single PV or thermoelectric device, is presented in terms of photo- and thermo-generated current and advantages of the low cost fabrication process is discussed

8983-65, Session 11

A general approach of chromophores biocompatibilization for in vivo applications in biophotonics *(Invited Paper)*

Chantal Andraud, Ecole Normale Supérieure de Lyon (France)

An ideal probe for in vivo biophotonics must fulfill many salient requirements, such as: good absorption and emission in the biological transparency window, solubility in the physiological medium, non-toxicity, synthetic availability on relatively large scales, specificity and moderate cost. We have recently reported on a polymer-based strategy that enabled us to fulfill most, if not all, of the abovementioned requirements.

In this presentation, we will introduce this approach, and discuss its benefits compared to other existing strategies. We will illustrate its interest for many applications in the field of biophotonics, through several examples including: nonlinear cellular imaging, one and two-photon PDT, cerebral vascular imaging, and discuss possible improvements and future perspectives.

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8983-51, Session PWed

Triphenylamine-based acrylate polymers for photorefractive composite

Ha N. Giang, Kenji Kinashi, Wataru Sakai, Naoto Tsutsumi, Kyoto

Institute of Technology (Japan)

Photorefractive (PR) polymer and composite have attracted many attentions owing to their updatable holographic properties. The typical components for PR effect include a photoconductive polymer, a nonlinear optical chromophore, a plasticizer, and a sensitizer. Among them, the polymer matrix plays a main role to provide a photoconductivity. Poly(vinyl carbazole) (PVK) has been successfully applied as a polymer matrix for PR composite. The plasticizer is added to the composite to reduce the glass transition temperature. However, the method is along with reducing the photoconductive component. To make the composite less inert, the photoconductive plasticizer ethyl carbazole (ECZ) is widely used with PVK. Recently, photoconductive polymers based on triphenylamine have been utilized for fast response PR application because of their fast hole mobility. In this study, two kinds of triphenylamine photoconductive polymers with the same acrylate structure and a similar glass transition temperature are synthesized. One of the polymer possesses a triphenylamine modified with a methoxy group at para position to vary ionization potential (IP). 2-(4-(azepan-1-yl) benzylidene)malononitrile (7DCST) is a plasticizer. Phenyl-C61-butyric acid methyl ester (PCBM) is a sensitizer. A triphenylamine-based plasticizer is used instead of the conventional plasticizer of ECZ to utilize the fast hole mobility. The study reveals that the composite with modified-triphenylamine polymer shows significant improvement over the one with non-modified triphenylamine polymer. By using modified-triphenylamine polymer, high diffraction efficiency of 80% can be achieved. A small difference of IP values between polymer matrix and plasticizer might be the main reason of the enhancement.

8983-52, Session PWed

FDTD analysis of photonic nanojet from self-organized liquid crystal microsystems

Akiko Okajima, Mie Univ. (Japan); Tatsunosuke Matsui, Mie Univ. (Japan) and Mie CUTE (Japan)

Since Chen et al. reported on the photonic nanojet (PNJ), many researches have been carried out from various viewpoints such as fundamental physics and device applications. Upon illuminating micron-sized lossless dielectric microcylinder or microsphere with a plane wave light, a propagating light beam which is narrow, bright and can propagate over a distance longer than the wavelength can be obtained from the shadow-side surface of them. It has also been reported that the performance of the PNJ can be improved by incorporating multilayered graded-index structure. This suggests that designing appropriately non-uniform distribution of dielectric constant in the microcylinder or microsphere can be effective to obtain PNJ with higher performance.

The liquid crystals (LCs) can form micron-sized droplets with a characteristic molecular orientation in a self-organized manner when dispersed in polymer or liquid matrices, and various kinds of optical devices have been proposed using such LC microdroplets. We have numerically analyzed, based on the finite-difference time-domain (FDTD) method, generation of PNJ from microcylinder incorporating LCs with various types of molecular orientations such as tangential or radial hedgehog. The PNJ from LC micro-systems are uniquely polarized reflecting birefringence of LCs, which cannot be obtained using optically isotropic microdroplets or microcylinders. Detailed analysis of the polarization of PNJ will be reported. A small degree of birefringence drastically changes the optical characteristics of the obtained PNJ. By using LC microcylinder or microsphere, we may obtain rich variety of PNJ with electrical tunability.

8983-53, Session PWed

Room-temperature working NIR sensor by solution-processed networked SWNT FET

Ihn Hwang, Yonsei Univ. (Korea, Republic of)

Room-temperature FET-NIR detector with a solution-processed networked SWNT/conjugated block copolymer nanocomposite channel consisting of a mixture of metallic and semiconducting nanotubes. Reliable arrays of the detectors were readily fabricated in which each device showed gate controlled p-type current modulation, which arose from Schottky barriers (SBs), evolved between individual metallic and semiconducting SWNTs in the network. This allowed extremely high current gain for NIR detection sufficient for room temperature operation. The OFF state dark current of a device was significantly enhanced more than 50 times and a maximum of 100 times upon illumination of a 1064 nm NIR laser. This was due to facile photo-carrier generation and separation at multiple SB junctions of the networked SWNTs. At a power of a 7mW the device exhibited excellent ON/OFF endurance for over 60 cycles, with fast switching of less than 0.75 seconds.

We calculated the specific detectivity (D*) .The D* value was an order of 109 Jonse.

And we also find the contribution of NIR exposure Photo and thermal effect on the film at high temperature (RT to 65'c). Based on the dark current results at various temperature, we were able to separate total photocurrent into current arising from exciton dissociation and one from thermal effect. The results show that the thermal contribution is approximately 10% of the total current even at the temperature of 65'c. The results clearly implies that bolometric contribution to the photocurrent of our device was insufficient and our device worked with effective exciton dissociation mechanism.

8983-54, Session PWed

Diffraction can mimic saturation in multiphoton absorbers

Mary J. Potasek, Evgueni Parilov, Simphotek Inc. (United States); Mark Walker, General Dynamics (United States)

Many traditional investigations of saturation in multiphoton absorbers with the z-scan method use an approximate analytical formula that assumes a steady-state approximation. Using a numerical simulation for Maxwell's equations for laser propagation including diffraction and coupled electron population dynamics, we show that the commonly used analytical formula for determining saturation in multiphoton absorbers is often incorrect, even when the sample thickness is only one diffraction length.

Using published experimental data on an organic chromophore, we show that saturation, in fact, does not occur at the laser intensity values predicted for these two and three photon absorbers. We numerically fit the published experimental z-scan data and obtain new absorption coefficients for multiphoton absorbers that accurately reflect their intrinsic values. The new values are from three to ten times larger than the published values.

Because multiphoton absorbers are being used more extensively in many applications such as optical limiter, medical diagnostics and microscopy, it is important to have accurate values for the two and three-photon absorption coefficients. Knowing the real value of the multiphoton absorber coefficients, even for a single diffraction length, is therefore of the utmost importance. In particular, the laser intensity at which the absorber saturates can determine which absorber is useful for a particular application.

8983-55, Session PWed

Tunable photonic band gap of photonic crystal cell fabricated using block copolymer and hydrogel with electric field

Youngbin Baek, Sung Nam Lee, Dongmyung Shin, Hongik Univ. (Korea, Republic of); Nakjoong Kim, Hanyang Univ. (Korea, Republic of)

The photonic gel film has a problem that evaporation speed of swollen deionized water is fast. The hydrogel with deionized water can solve this problem. Poly(styrene-b-2-vinyl pyridine) (PS-b-P2VP) lamellar film with alternating hydrophobic block-hydrophilic polyelectrolyte block polymers (52 kg/mol-b-57 kg/mol) were prepared for the photonic gel film. Poly(acrylamide-co-acrylic acid)sodium salts (PAAm-co-PAAc) were synthesized with acrylamide and acrylic acid by thermal initiator for hydrogel. This hydrogel has an electrical sensitivity. The hydrogel was synthesized with flat and tetragonal shape. Photonic gel was spin coated onto Indium Tin oxide (ITO) glass for electric fields. The cells are fabricated with photonic gel layer and hydrogel layer consisting two electrodes which have cell gaps about 1.1mm using spacer. The wavelength of reflected color is a few changed when electric fields occurred in cells. This experiment showed that effect of electric fields on the hydrogel-photonic gel hybrid devices.

8983-56, Session PWed

NIR-sensitive conductive polymers for transparent electrochromic photo-thermo-electric converters

Byeonggwan Kim, Haijin Shin, Teahoon Park, Hanwhuy Lim, Eunkyoung Kim, Yonsei Univ. (Korea, Republic of)

Conductive polymers have received significant attention for applications in optoelectronics such as electrochromic devices (ECDs), photovoltaic cells, organic light emitting diodes, and light sensors due to their controllable optical and photo-thermo-electrical properties by external electrical stimuli. These properties of hexyl-derivatized poly(3,4-ethylenedioxyselenophene) are clearly demonstrated by precisely controlling the doping state and the surface morphology from applying potential of the flexible polymer films. Especially, the doped polymer film at –0.1 V reveals the highest photothermal conversion efficiency and a power factor of 42.5% and 354.7 μW m-1 K-2, respectively. Efficient visible to near-infrared absorption, photon to heat, and heat to electric conversion has been realized in one transparent and potentially optimized film that could benefit in exploiting invisible NIR sensors, multifunctional film displays, day and night vision display, optical attenuators, and photodynamic theragnosis.

8983-57, Session PWed

Nanostructured conductive polymer/GaAs epilayer hybrid heterojunction solar cells

Yi-Chun Lai, Huai-Te Pan, Kai-Yuan Cheng, Peichen Yu, Hsin-Fei Meng, Gou-Chung Chi, National Chiao Tung Univ. (Taiwan)

Recently, hybrid solar cells combining organic materails and inorganic semiconductors are extensively researched because of their relatively inexpensive cost and low temperature fabrication processes. In this work, we demonstrate organic/inorganic hybrid heterojunction photovoltaic devices based on gallium arsenide (gaas) substrate and conjugated polymer poly(3,4-ethylenedioxy-thiophene):poly(styrenesulfonate) (PEDOT:PSS). We started with a one-dimensional device simulation based on a self-consistent poisson and drift-diffusion solver to investigate the band alignment between PEDOT and GaAs for achieving a practical device design. Next, for device fabrication, we prepare a cleaned and oxide-removed one-side-polished (100) GaAs wafer with a low doping epitaxial layer, followed by thermal evaporation of aluminum as back-side electrode. After that, PEDOT:PSS is spun-cast onto the substrate and then annealed. Finally, shading-ratio-optimized silver fingers are deposited as the anode. In addition to planar ones, we also use self-assembled polystyrene (PS) nanosphere lithography technique to form the sacrificial mask layer, and perform anisotropic inductively coupled plasma reactive ion etching (ICP-RIE) on GaAs substrates. It has been revealed that nanostructures such as nanowires or nanorods allow the conformal p-n heterojunction formation at the interface of organic/inorganic semiconductors, which can be beneficial for both light absorption and carrier collection. The optical and electrical characteristics such as reflectance, current voltage, and external quantum efficiency are measured. Currently, for planar/nanorod devices, we achieve 7.54/7.74 % power conversion efficiencies with open-circuit voltages of 0.662/0.639 V, short-circuit currents of 15.34/20.65 mA/cm2, and fill factors of 74.20/58.67 % under simulated AM1.5G illumination.

8983-58, Session PWed

Characteristics of periodic silicon nanorods arrays for conductive polymer/silicon heterojunction solar cells

Yi-Chun Lai, Yang-Yue Huang, Wei-Sheng Weng, Peichen Yu, National Chiao Tung Univ. (Taiwan); Martin D. B. Charlton, Univ. of Southampton (United Kingdom); Hsin-Fei Meng, Gou-Chung Chi, National Chiao Tung Univ. (Taiwan)

Mono- and multi-crystalline silicon photovoltaics currently still hold more than 80% market share because of the non-toxic, abundant material resources used, and their long-term stabilities. However, the cost of solar power is still more than three times that of fossil fuels, which necessitates a further reduction to accelerate its widespread use. It has been estimated that cell fabrication consumes 30% of the total manufacturing cost due to energy intensive semiconductor processes, such as high temperature furnace for doping, electrodes co-firing, high-vacuum chemical deposition, etc. Therefore, the organic-inorganic hybrid cell concept has been proposed to take advantage of the solution-based processes for rapid and low-cost production and the wide absorption spectrum of silicon. In this work, we demonstrate a hybrid heterojunction solar cell based on the structure of conductive polymer PEDOT:PSS spun cast on n-type crystalline silicon nanorod (SiNR) arrays with periodic arrangements. The nanorod arrays are fabricated by electron beam (E-beam) lithography followed by reactive-ion etching (RIE), which show capability to enhance light harvesting. In addition, SiNRs and PEDOT:PSS can form core-shell structure that provides a large p-n junction area for carrier separation and collection. However, the reactive-ion etching cause a lot of surface damages on the surface of the rod which cause a lot of interface defect between Silicon and PEDOT:PSS. A post-RIE damage removal etching (DRE) is subsequently introduced in order to mitigate the surface damages issues . Finally, we map the weighting reflection of silicon nanorod arrays with different periods and filling ratio, which explain the reason of lowing reflection of device after DRE treatment and indicate that arrays with 330nm period and 0.25 filling ratio have the minimum weighting reflection.

8983-59, Session PWed

White-light-amplified spontaneous emission

Kin Long Chan, Guixin Li, Kok-wai Cheah, Hong Kong Baptist Univ. (Hong Kong, China)

Semiconducting (conjugated) polymer draws much attention nowadays as it is a promising possible application. With increasing emission efficiency, excited emission such as ASE (amplified spontaneous emission) and lasing have been achieved. Recently, the white ASE has been reported but with one ASE spectrum and one much broader spectrum. In this research, the gain media in optical amplifiers will be studied. Two individual shape ASE spectra in one sample will be demonstrated.

This work aims at getting white light ASE with two different color ASE spectra that have near-equal spectral profile. Two materials, Poly (9, 9-di-n-dodecylfluorenyl-2, 7-diyl) (PFO) and Poly [(9, 9-di-n-octylfluorenyl-2, 7-diyl)-alt-(benzo[2,1,3]thiadiazol-4,8-diyl)] (F8BT) were selected. The correspond peaks of PFO and F8BT are at 450nm and

575nm respectively, and the full width half maximum are 5nm and 10nm. Therefore they are suitable to combine to give a white ASE. PFO thin film is first deposited onto a galss substrate, then a high transmittance optical clear adhesive (over than 90% transmittance in visible range) was added as a spacer that separate it from the F8BT thin film. The sample successfully demonstrated white light ASE when pumped by 355nm third harmonic laser from YAG-Nd. The CIE achieved is (0.36, 0.45) and a comparable threshold.

In conclusion we have shown that a simple thin film configuration that can produce white light ASE was achieved and it is possible to tune the CIE from the thin film thickness. Such device can be used as strong white light source in spectroscopy experiments.

8983-60, Session PWed

Surface charge measurements and (dis)charging dynamics of organic semiconductors in various media using optical tweezers

Rebecca Grollman, Kyle Peters, Oksana Ostroverkhova, Oregon State Univ. (United States)

Optical tweezers, which use a tightly focused laser beam to trap microscopic particles, have many applications due to their ability to measure forces on the order of piconewtons. One exciting recent application is the measurement of the surface charge on a trapped particle, as well as of the dynamics of charge exchange with the environment with a single charge resolution. The purpose of our study is to both develop an optical tweezer-based method to measure the charging and discharging dynamics of organic semiconductor molecules and to establish effects of environment on these dynamics depending on the molecule. For our experiments, we chose high-performance functionalized anthradithiophene (ADT) and pentacene (Pn) derivatives that exhibit high charge carrier mobilities in thin-film transistors and are promising for organic solar cells. Functionalization of the molecules enables tunability of their optical and solid-state packing properties, which also manifests in differences in the charging and discharging dynamics, depending on the molecule, that we seek to establish. Our samples are 1 um silica spheres coated with ADT or Pn derivatives suspended in media of various polarity and viscosity. The particles are trapped with an 800 nm trapping laser, and their position is tracked with a 633 nm detection laser and quadrant photodetector as a function of applied electric field. Surface charge density on the coated particles and its time evolution due to interactions with the environment are presented as a function of various parameters of the surrounding medium for various ADT and Pn derivatives.

8983-61, Session PWed

Sustainable UV-curable low refractive index resins with novel polymers for polymer cladding materials

Hiroki Tokoro, Takako Ishikawa, Nobuyuki Koike, Yohzoh Yamashina, DIC Corp. (Japan)

Low refractive index polymers are used as cladding materials for the polymer clad silica fibers. Since transparent fluoro polymers are ideal for this application, those materials have been used for a longtime. However, some fluoro chemicals face an issue related to perfluoro octanoic acid (PFOA) which is caused by its longtime persistence in the environment and human body.

Here, non-PFOA type UV curable fluoro resins for the claddings were developed with newly designed and synthesized polymers and monomers. The viscosity of the developed materials can be adjustable between 20 mPas and 5,000 mPas for without any changes of optical and physical properties. The cured materials are colorless even after thermal resistant tests, highly transparent: more than 92% in visible light region and have low refractive index range from 1.359 to 1.386 at 850 nm which means numerical aperture of 0.51 to 0.43. Moreover, the cured material with refractive index 1.386 has Young modulus of 229 MPa which is rigid enough to be used for hard clad fibers. Besides, both materials showed excellent adhesion to glass substrate even though without adhesion promoters, as a matter of course, it was improved by the promoter like 3-acryloxypropyltrimethoxysilane. Properties of the materials itself and optical fibers with these cladding materials will be discussed in detail at the conference.

8983-62, Session PWed

Synthesis and electro-optic properties of the chromophore-containing NLO polyarylate polymers

Haohui Ren, Technical Institute of Physics and Chemistry (China); Chengcheng Peng, Technical Institute of Physics and Chemistry (China) and Chinese Academy of Sciences (China); Shuhui Bo, Guofang Fan, Guangming Xu, Hui Zhao, Zhen Zhen, Xinhou Liu, Technical Institute of Physics and Chemistry (China)

Base on the same two monomers, diphenolic acid (DPA) and isophthaloyl chloride (IPC), three chromophore-containing nonlinear optical (NLO) polyarylate polymers were prepared. A tricyanofuran (TCF)-acceptor type chromophore group was in main-chain (mPAR-chr1), side-chain (sPAR-chr1) and side-chain with a 1,1-bis(4-hydroxyphenyl)-1-phenyl-2,2,2-trifluoroethane (BPAPF) group (sPAR-F-chr1), respectively. The obtained polymers were characterized and evaluated by UV-Vis, 1H NMR, DSC and TGA. All the polymers exhibited good electro-optic (EO) activity. The relationship between EO coefficients (r33) and the chromophore concentration of the three polymers were also characterized and discussed. There were no obvious differences found in EO activity between mPAR-chr1 and sPAR-chr1 polyarylates with the same chromophore. The fluorinated block polyarylate sPAR-F-chr1 has the largest r33 value in these three polyarylates which is 52 pm/V at the wavelength of 1310 nm (which is almost twice the r33 value of normal polymers contained the same chormophore at the same content), when the concentration of chromophore 1 is 18wt.%. 85% of the r33 value was retained in the sPAR-F-chr1 after being heated at 85oC for 600 hours. The polymer sPAR-F-chr1, with good solubility, high Tg (above 200 oC) and side functional group at the same time, may probably be a practical NLO material. These properties make the new polyarylates have potential applications in EO devices such as EO modulators and switches.

8983-63, Session PWed

Design of Mach-Zehnder interference modulators composed of enhanced electro-optic active polymers

Guangming Xu, Jialei Liu, Haohui Ren, Guofang Fan, Zhen Zhen, Xinhou Liu, Technical Institute of Physics and Chemistry (China)

Organic electro-optic polymer has relatively low dielectric constant and especially high electro-optic coefficient, which is one of the perfect materials for making modulators with low loss and high bandwidth. In this paper, we firstly synthesized a novel chromophore based on 4-(diethylamino) salicylaldehyde, which was used as an electron donor and had one reactive site to introduce rigid isolated benzyl group. Polymers doped with the innovative chormophore showed good thermal stability and high electro-optic activity, which were adopted as core materials and used to design Mach-Zehnder interference (MZI) modulator. In the second part of the paper, we combined cladding materials and core materials and designed a low loss MZI optical

waveguide. We used tapered waveguides at the input and output ports of MZI to reduce the coupling loss with fibers and tapered multimode Y-branches to equally split or combine optical signals. By simulating the transmission of optical modes in tapered structures, we calculated the optical loss of MZI waveguides and optimized the waveguides structures. Finally, we respectively designed the modulators with 50GHz 3dB bandwidth using the coplanar waveguide electrodes (CPWE) and the micro-strip electrodes (MSE), which are two typical traveling wave electrodes in microwave applications. We detailed analyzed the influence of electrodes structures on the microwave response and compared the CPWE and MSE when applied to polymer modulators. Fabrication of the modulators is under development. Modulators made of organic electro-optic polymers have great application prospects in the fields of information procession and communication needing high speed and high bandwidth.

8983-64, Session PWed

Reflection resonance switching in metamaterial twisted nematics liquid crystal cell

Yeon Ui Lee, E. Y. Choi, Jae-Heun Woo, E. S. Kim, Jeong-Weon Wu, Ewha Womans Univ. (Korea, Republic of)

No Abstract Available

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8984-1, Session 1

Ultrafast thermal nonlinear optics: it may not be an oxymoron! *(Invited Paper)*

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

Among all the optical nonlinearities the one of thermal origin are among the strongest, but, typically, they are also among the slowest ones, which precludes their application in optical communications and information processing. The paradigm, however, changes drastically when the dimensions are scaled down to nanometers, which causes thermal diffusion times to scale down to picoseconds and enable ultrafast thermal switching. In this talk we show how combination of thermal nonlinearity with nanoplasmonics can engender novel compact low power ultrafast all-optical devices.

8984-2, Session 1

Nonlinear optical properties of novel two-dimensional crystals *(Invited Paper)*

Nardeep Kumar, Qiannan Cui, Frank Ceballos, Rui Wang, Hui-Chun Chien, Hsin-Ying Chiu, The Univ. of Kansas (United States); Sina Najmaei, Pulickel M. Ajayan, Jun Lou, Rice Univ. (United States); Dawei He, Yongsheng Wang, Beijing Jiaotong Univ. (China); Hui Zhao, The Univ. of Kansas (United States)

Recently, there is a growing interest in exploring new types of novel two-dimensional crystals that composed of single atomic sheets of layered materials, such as transition metal dichalcogenides. Although significant progress has been made in understanding the mechanical, thermal, electrical, and linear optical properties of monolayer transition metal dichalcogenides, their nonlinear optical properties have been less studied. Here we discuss our recent investigations on nonlinear optical properties of transition metal dichalcogenide monolayers, including molybdenum disulfide, molybdenum diselenide, and tungsten diselenide. We found that the lack of inversion symmetry allows efficient second harmonic generation in transition metal dichalcogenide monolayers. The effect vanishes in even layers and bulk crystals that are inversion symmetric. We demonstrate that this second-order nonlinear optical effect can be used as a non-invasive tool to study quality of thin films grown by chemical vapor deposition, such as film uniformity, grain size, and stacking order of multilayers. Various third-order nonlinear optical effects are also studies, including third harmonic generation, saturable absorption, and two-photon absorption. Furthermore, we show that absorption saturation of a probe laser pulse caused by excitons injected by a pump pulse can be used for time-resolved and spatially resolved studies of excitonic dynamics in these atomic layers, including exciton-exciton annihilation, exciton recombination, and exciton diffusion. For comparison, similar measurements are also performed in bulk crystals of these transition metal dichalcogenides.

8984-3, Session 1

Hyper Rayleigh Scattering from Gold Nanorods : The Shape Effect for Centrosymmetric Nanoparticles

Isabelle Russier-Antoine, Univ. Claude Bernard Lyon 1 (France); Alison McLintock, Alastair W. Wark, University of Strathclyde (United Kingdom); Franck Bertorelle, Univ Claude Bernard Lyon 1 (France); Emmanuel Benichou, Univ. Claude Bernard Lyon 1 (France); Emeric Bergman, Aurélie Bruyère, Univ Claude Bernard Lyon 1 (France); Christian Jonin, Pierre-François Brevet, Univ. Claude Bernard Lyon 1 (France)

Nonlinear plasmonics is a domain in rapid expansion. The possibility to easily focus in time and space photons in metallic nanostructures exhibiting localized surface plasmon resonance has driven over the past years the field, especially towards applications like sensing and imaging. Fundamental studies to uncover the details of the nonlinear interaction between light and matter is however still of importance. Second Harmonic Generation (SHG), the process whereby two photons at the fundamental frequency are converted into one photon at the harmonic frequency, is the simplest of these nonlinear processes. Yet, due to symmetry cancellations, an in-depth understanding of the origin of the response requires to go beyond the standard electric dipole approximation. In order to provide an extensive description of this problem, metallic nanoparticles with different shapes and morphologies, for example nanospheres, nanorods, nanopyramids, nanocubes, as well as homogeneous or core-shell nanoparticles, have been investigated with hyper Rayleigh scattering. A particular emphasis has been given on the different contributions to the nonlinear polarization and the multipole fields components of the response.

8984-4, Session 1

Ultrafast nonlinear dynamics in gas-filled kagomé photonic crystal fiber

Silvia M. Rodrigues, Margarida Facão, Sofia C. Latas, Mário F. S. Ferreira, Univ. de Aveiro (Portugal)

There are two main types of hollow-core photonic crystal fibers (HC-PCFs). One of them confines light by means of a full two-dimensional photonic bandgap. They can provide very low transmission loss (< 1dB/km) at 1.55 nm, which makes these fibers useful for many applications. However, the limited transmission window and extreme dispersion slopes make them not suitable to ultrafast pulse experiments. The other type of HC-PCFs has a kagomé-lattice cladding and provides ultrabroad-band guidance at loss levels of ~1dB/m, which makes them ideal for ultrafast applications.

In this paper we investigate the dispersion and ultrafast nonlinear dynamics of a gas-filled kagomé HC-PCF. By varying the pressure, the normal group-velocity dispersion (GVD) of the filling gas can be balanced against the anomalous GVD of the kagomé PCF allowing the zero dispersion wavelength to be tuned across the ultraviolet (UV), visible and near-infrared spectral regions. Compared with solid-core PCFs, a kagomé PCF presents also a much smaller dispersion magnitude, which provides a much slowly broadening of ultrashort pulses.

A generalized Schrödinger equation is used to describe ultrashort pulse propagation in a gas-filled kagomé PCF. Different monoatomic noble gases are considered, in which Raman scattering is absent. As a consequence, soliton dynamics and pulse compression are not affected by the soliton self-frequency shift effect. Few-cycle pulse compression is achieved with energies covering at least the 0.1-30 ?J range. Self-compression can lead to a highly efficient deep-UV dispersive wave generation, which can be tuned in the range 150-350 nm. We show that pulse durations shorter than ~40fs are necessary for obtaining high-quality UV spectra at high conversion efficiencies.

8984-5, Session 1

Polarization dynamics of vector solitons in mode-locked fiber laser

Veronika Tsatourian, Sergey Sergeyev, Chengbo Mou, Aleksey G. Rozhin, Aston Univ. (United Kingdom); Vitaly Mikhailov, Paul S. Westbrook, Bryan Rabin, OFS Labs. (United States); Sergei K. Turitsyn, Aston Univ. (United Kingdom)

Mode-locked lasers (MLL) emitting a train of femtosecond pulses, called dissipative solitons, is an enabling technology for metrology, high-resolution spectroscopy, telecommunications, nano-optics and other fields of science and applications. With increased gain in an active medium, the fundamental soliton becomes unstable and more complex waveforms can appear, multi-pulsing, pulse bunching, harmonic mode locking, bound states and soliton rains. A particularly important issue for application of MLLs is the generation and control of different dynamic states of polarization (SOPs) at the output of MLL. In this paper, we address issues related to control of SOPs in MLLs using fast polarimetry on a nanosecond timescale.

We used a high-speed in-line polarimeter based on 4 tilted fiber Bragg gratings written in polarization maintaining fiber. The device has electrical and optical bandwidths of 550 MHz and 20 nm respectively, which allows monitoring of pulse-to-pulse SOP evolution of femtosecond pulses with spectral width of about 10 nm with DOP accuracy of 4%. We used a carbon nanotubes mode-locked Er:fiber laser with repetition rate of 24 MHz to generate vector solitons with controllable SOP. Different laser operations have been recorded (fundamental soliton, multipulse and harmonic mode locking) with resolution higher than one round trip time. We have found new types of vector solitons for two- and four-multipulse operation. The states of polarization for these vector solitons reveal either fast pulse-to-pulse polarization switching or slow cyclic evolution. To the best of our knowledge, our work is the first report of the pulse-to-pulse evolution of vector soliton SOP.

8984-6, Session 2

Ultra-compact plasmonic MOS-based electro-optic switches and modulators *(Invited Paper)*

Volker J. Sorger, Zhuoran Li, Chenran Ye, Chen Huang, The George Washington Univ. (United States); Richard Soref, Univ. of Massachusetts Boston (United States)

We report on two ultra-compact plasmonic Metal-Oxide-Semiconductor (MOS) –based, waveguide integrated electro-optic (EO) devices namely a switch and modulator. The former is a three-waveguide electro-optic switch for ultra-compact photonic integrated circuits and data routing. The device features a plasmonic MOS mode for enhanced light-matter-interactions. The switching mechanism originates from a capacitor-like design where the refractive index of the active medium, Indium-Tin-Oxide (ITO), is altered via shifting the plasma frequency due to carrier modulation inside this waveguide-based MOS design. This modulation controls the transmission direction of TM polarized light into either a CROSS or BAR waveguide port. For a tolerable insertion loss of 3 (8) dB, the switch provides a cross-to-bar state discrimination of 4 (10) times. Secondly we present on a plasmonic Silicon waveguide-based electro-absorption featuring an in-line cavity with extremely strong light-matter-interaction. By optimizing the Fabry-Perot cavity, this modulator features more than 10 dB/µm extinction ratios, while having a low insertion loss of less then 0.3 dB. The seamless integration of these EO converters into the standard SOI platform are promising candidates for low cost, high performance and short time-to-market solutions of future photonic-electronic hybrid integrated circuits.

8984-7, Session 2

Ultrafast two photon absorption generated free carrier modulation in a silicon nanoplasmonic resonator

Michael P. Nielsen, Abdulhakem Y. Elezzabi, Univ. of Alberta (Canada)

Ultrafast all-optical modulation in Ag/HfO2/Si/HfO2/Ag metal-insulator-semiconductor-insulator-metal (MISIM) nanoring resonators through two-photon absorption photogenerated free-carriers is studied using self-consistent 3-D finite difference time domain (FDTD) simulations. The self-consistent FDTD simulations incorporate the two-photon absorption, free carrier absorption, and plasma dispersion effects in silicon. The nanorings are aperture coupled to Ag/HfO2/Si(100nm)/HfO2/Ag MISIM waveguides by 300nm wide and 50nm deep apertures. The effects of pump pulse energy, HfO2 spacer thickness, and device footprint on the modulation characteristics are studied. Nanoring radius is varied between 540nm and 1µm, the HfO2 spacer thickness is varied between 10nm and 20nm, and the pump pulse energy explore up to 60pJ. Modulation amplitude, switching time, average generated carrier density, and wavelength resonant shift is studied for each of the device configurations. In a compact device footprint of only 1.4µm2, a 13.1dB modulation amplitude was obtained with a switching time of only 2ps using a modest pump pulse energy of 16.0pJ. The larger bandwidth associated with more compact nanorings and thinner spacer layers is shown to result in increased modulation amplitude.

8984-8, Session 2

Active plasmonics: merging metals with semiconductors *(Invited Paper)*

Parinda Vasa, Indian Institute of Technology Bombay (India); Wei Wang, Robert Pomraenke, Carl von Ossietzky Universitaet Oldenburg (Germany); M Maiuri, Cristian Manzoni, Giulio Cerullo, IFN-CNR, cDipartimento di Fisica, Politecnico di Milano, Milano, Italy (Italy); Christoph Lienau, Carl von Ossietzky Universitaet Oldenburg (Germany)

Future nano-plasmonic devices will most likely be based on active plasmonics, relying on the interplay between the strong intrinsic optical nonlinearities of excitonic nanostructures and the ability of metallic nano-objects to concentrate electromagnetic fields locally. Consequently, the optical properties of hybrid nanostructures comprising active materials, e.g., semiconductors or J-aggregated molecules, and metals are currently attracting considerable attention. In favorable geometries, their properties are governed by a new class of short-lived quasiparticles, exciton - surface plasmon polaritons with hitherto unexplored nonequilibrium dynamics. In this talk, the optical properties of prototypical hybrid nanostructures probed using ultrafast spectroscopy will be discussed. These hybrid structures are progressively becoming important for developing high efficiency optical devices.

8984-9, Session 2

Active plasmonics with surface acoustic waves

Claudia Ruppert, Frederike Förster, Technische Univ. Dortmund (Germany); Artur Zrenner, Univ. Paderborn (Germany); Jörg Kinzel, Achim Wixforth, Hubert J. Krenner, Univ. Augsburg (Germany); Markus Betz, Technische Univ. Dortmund (Germany)

We explore the impact of ~500 MHz surface acoustic waves traveling

across a commensurable plasmonic grating coupler. A stroboscopic technique involving surface acoustic waves synchronized to a modelocked optical source allows to time-resolve the dynamical impact of the electro-mechanically induced perturbation. The surface acoustic wave periodically enhances or decreases the surface ripple of the static grating. Most remarkably, the dynamic surface deformation deliberately modulates the coupler's efficiency by +/- 2% during the ~2ns acoustic cycle.

8984-10, Session 3

Feasibility of GaN-based room-temperature THz laser in a spoof plasmon waveguide *(Invited Paper)*

Greg Sun, Univ. of Massachusetts Boston (United States)

We propose and study the feasibility of a THz GaN/AlGaN quantum cascade laser (QCL) consisting of only five periods with confinement provided by a spoof surface plasmon (SSP) waveguide for room temperature operation. The QCL design takes advantages of the large optical phonon energy and the ultrafast phonon scattering in GaN that allow for engineering favorable laser state lifetimes, and the SSP waveguide provides the optical confinement for the ultrathin QCL. Our analysis has shown that the waveguide loss is sufficiently low for the QCL to reach its threshold at the injection current density around 6 kA/cm2 at room temperature.

8984-11, Session 3

THz acoustic spectroscopy based on GaN nanostructures *(Invited Paper)*

Kung-Hsuan Lin, Academia Sinica (Taiwan)

Due to the high attenuation in vitreous silica, acoustic attenuations in the THz regime are typically measured by incoherent techniques such as Raman, neutron, and X-ray scattering. Here, we utilized multiple-quantum-well structures to demonstrate acoustic spectroscopy of vitreous silica up to THz regime. The acoustic properties of silica thin films prepared by physical and chemical deposition methods were characterized in the sub-THz regime. This technique can be useful in resolving debated issues relating to Boson peak around 1 THz.

8984-12, Session 3

Modeling of ultrafast THz interactions in molecular crystals

Pernille Klarskov Pedersen, Technical Univ. of Denmark (Denmark); Stewart J. Clark, Durham Univ. (United Kingdom); Peter U. Jepsen, DTU Fotonik (Denmark)

With single cycle pulses of sub-picosecond duration, optical terahertz (THz) technology based on femtosecond lasers is ideal for investigating ultrafast phenomena on a molecular scale. In particular, the low-frequency range of the terahertz spectrum can be used for resonant excitation of phonons in many materials, including crystals of organic molecules. This opens up for nonlinear spectroscopy of the lowest vibrational modes in such systems, which offers the exciting possibility of extending studies of energy flow and dissipation in large organic and biological molecules from the mid-IR to the THz range.

The most accurate method for modeling the full low-frequency dynamics in crystalline materials is based on ab-initio modeling of the interaction between the charge distribution in the molecular unit cell and the electromagnetic field. In particular, Quantum Mechanical Molecular Dynamics (QMMD) based on Density Functional Theory (DFT) offers high precision simulations at quantum mechanical level of molecular dynamics at finite temperatures, including finite temperature effects and nonlinear couplings.

Here we have performed QMMD studies of the interaction of a molecular crystal with ultrafast, broadband THz pulses. Specifically, the technique is implemented in the form of an add-on module to the commercially available Density Functional Perturbation Theory-based code Castep, thus allowing simulations of linear and nonlinear spectroscopic experiments at THz frequencies. We investigate the linear and nonlinear dynamics of phonons in crystalline materials, such as sucrose, at finite temperature, and directly compare the simulations to experimental measurements with high field strengths (in the MV/cm range) on crystalline systems.

8984-13, Session 3

Ultrastrong light-matter coupling between superconducting complementary THz metasurfaces and Landau levels in semiconductors

Giacomo Scalari, Curdin Maissen, ETH Zurich (Switzerland); Sara Cibella, Istituto di Fotonica e Nanotecnologie (Italy); Pasquale Carelli, Univ. Degli Studi Dell Aquila (Italy); Roberto Leoni, Istituto di Fotonica e Nanotecnologie (Italy); Christophe Charpentier, Werner Wegscheider, Mattias Beck, Jérôme Faist, ETH Zurich (Switzerland)

Enhancement and tuning of the light-matter interaction represent key aspects for fundamental studies of cavity quantum electrodynamics and for applications both in classical and quantum devices. We recently demonstrated ultrastrong coupling regime in a system composed by an high-mobility two-dimensional electron gas (2DEG) coupled to terahertz (THz) metamaterial resonators with a light-matter coupling ratio of $\Omega/\omega=0.58$.

In order to observe with greater detail the spectroscopic features of the polaritonic branches, we now change the configuration of the metamaterial cavity and we employ a complementary cavity. The intriguing quantum optical predictions for an ultra-strongly coupled system rely on a non-adiabatic modulation of the system's parameters; in our case on timescale faster than the Rabi frequency of the system. The realization of a superconducting cavity offers an interesting opportunity, since the cavity characteristics depend strongly on the state (superconducting or normal) in which the material operates. On the other hand the presence of the superconductor will mitigate the ohmic losses eventually yielding a longer polariton coherence time. We realized complementary superconducting metamaterial with Nb on top of a single GaAs-based 2DEG. We observe the superconducting transition of the metasurface with a Tc=8.2 K and we perform light-matter coupling experiments measuring a coupling ratio $\Omega/\omega=0.3$ for a superconducting metasurface resonating at 430 GHz. In another series of experiments, we use a single InAs-based 2DEG with Au-based complementary metasurface measuring a record normalized coupling ratio $\Omega/\omega=0.75$ at 450 GHz.

8984-14, Session 3

Optical response of tightly-coupled THz metamaterials

Ji-Hun Kang, Q-Han Park, Korea Univ. (Korea, Republic of)

For metamaterials with periodically arranged unit resonators, their optical responses can be understood by taking into account the total electromagnetic field of each unit, which states a superposition of two kinds of interactions: scattering of incident waves by individual units which means incident-unit interaction, and interaction of each unit with waves scattered by other units. The later interaction is the inter-unit coupling mediated by those scattered waves. In tightly-coupled metamaterials, whose units are very close to neighboring ones, the importance of inter-unit coupling is pointed out from other experimental and numerical studies. However, despite successful describing of optical responses of weakly-coupled metamaterials, conventional methods fail to provide an explanation of the inter-unit coupling in tightly-coupled metamaterials so that a quantitative account of optical responses of those metamaterials are lacking. Because the inter-unit coupling is another degree of freedom for the metamaterials, it would pave the way in designing metamaterials with novel optical response.

Here, we present THz metamaterials composed of tightly-coupled sub-wavelength ring resonators. Based on the resonant optical responses highly dependent on the inter-unit coupling, we theoretically demonstrate that effective optical properties of the THz metamaterials can be controlled by nanometer-scaled gap between the resonators. In order to predict optical response and spectral behavior of effective indices of tightly-coupled metamaterial analytically, a model based on coupled-mode theory is established, and we show that our model provides a qualitative agreement with more rigorous finite-difference time-domain numerical calculations.

8984-16, Session 4

Optimizing adiabatic nanofocusing: k-vector imaging and control

Martin Esmann, Simon F. Becker, Jens H. Brauer, Ralf Vogelgesang, Petra Gross, Christoph Lienau, Carl von Ossietzky Univ. Oldenburg (Germany)

Adiabatic nanofocusing of ultra-short surface plasmon polariton (SPP) wavepackets launched on the surface of a conical gold taper by means of grating coupling leads to the formation of a 10 nm-sized light source at the taper apex with time-resolution in the fs regime [1]. Hence, this nanostructure bears great potential as a novel probe for optical imaging and spectroscopy applications in near-field scanning optical microscopy (NSOM) [2].

In order to identify factors which influence the formation of the optical near-field at the tip apex, we have incorporated such gold tapers in an AFM setup combined with a k-space imaging technique. This provides direct access to the near-field's symmetry and decay length. We experimentally demonstrate that only the lowest two eigenmodes of the taper with distinctly different rotational symmetry contribute to the fields in the vicinity of the taper end. While the lowest eigenmode is efficiently nanofocused, the first excited mode remains loosely bound. k-space imaging for the first time allowed us to clearly separate these different contributions to the fields around the apex.

We furthermore show that wave-front shaping using adaptive optics with a deformable mirror considerably enhances the coupling efficiency of far-field radiation to the lowest taper mode. To demonstrate this performance enhancement, we conduct line-scans across different test structures and investigate the influence of tip-sample coupling on the near-field distribution around the tip.

[1] Schmidt, S. et al. ACS Nano 6, 6040 (2012)

[2] Kravtsov, V. et al. Opt. Lett. 38, 1322 (2013)

8984-17, Session 4

Si-based nanoplasmonic resonant devices for all-optical integrated circuits

Michael P. Nielsen, Abdulhakem Y. Elezzabi, Univ. of Alberta (Canada)

Presented here are nanoplasmonic Bragg reflector and disk resonators based on Au/SiO2/Si metal-insulator-semiconductor (MIS) nanoplasmonic waveguide platform and integrated with conventional silicon-on-insulator waveguides. The underlying 200nm wide Au(50nm)/SiO2(50nm)/Si(340nm) MIS waveguides are found to have an impressive propagation length of 16.0μm, compared to 21.9μm predicted by 3-D finite difference time domain (FDTD) simulations, and a coupling efficiency of 59.4% per interface with conventional silicon-on-insulator waveguides at 1.55μm. Incorporating the experimental results for the MIS waveguides into the FDTD simulations enabled the design of the Bragg reflector resonators and disk resonators. A 1μm radius disk resonator evanescently coupled to the MIS bus waveguides by a 200 nm gap was shown to have a high plasmonic quality factor of 82.3, one of the highest reported for an integrated silicon based nanoplasmonic device with a compact device footprint of only 4μm2. Further optimization of the fabrication process to eliminate 'rabbit ears' from the liftoff process is required to increase device performance by reducing losses. Selective removal of the Au layer from the MIS waveguides formed tapered Bragg mirrors surrounding a central cavity. These devices had extremely compact footprints as low as 1.5μm2 and quality factors as high as 64.4, giving these resonators the highest quality factor over device footprint figure of merit yet demonstrated for a silicon nanoplasmonic device. A higher quality factor is shown to be achievable by using smaller gaps in the Bragg reflectors.

8984-18, Session 4

Coherent oscillations in plasmonic Ag atomic layer deposition films

Ryan E. Compton, Sharka M. Prokes, Orest J. Glembocki, Irina R. Pala, Helen K. Gerardi, Jeffrey C. Owrutsky, U.S. Naval Research Lab. (United States)

The plasmonic properties of Ag thin films produced by plasma enhanced atomic layer deposition (PEALD) were investigated with static and transient spectroscopy. Under appropriate conditions, PEALD produces films with cylindrical 2D nanostructures separated by very small (<10 nm) air gaps which exhibit plasmonic behavior. Films were deposited on transparent substrates over a range of thicknesses (10 - 45 nm) and lateral diameters (30 – 50 nm) as determined by SEM and AFM measurements. Surface plasmon resonances (SPRs) for the structured metal films, also known as spoof resonances, spanning from the visible to the near-IR (450 – 1000 nm) are revealed by ellipsometry and transmission studies. In contrast, e-beam deposited films are devoid of band structure. Transient absorption measurements reveal that the electron-phonon dynamics for the ALD films resemble those for the e-beam films, but the lattice dynamics observed at longer times (>1 ps) are different. Coherent acoustic oscillations are observed for the ALD films in the nanostructures. A transition from electron-phonon coupling dynamics to lattice dynamics is observed as the probe wavelength is tuned from short (400 nm) to longer wavelengths (<1300 nm) through the resonance. Oscillations are attributed to breathing of the cylindrical structures which modulates the gap thickness.

8984-50, Session 4

Plasmonic nanostructures by design *(Invited Paper)*

Xiaoqin Li, The Univ. of Texas at Austin (United States)

Plasmonics has emerged as a promising approach to shape and control light on length scales well below the optical diffraction limit. This small length scale, however, brings serious challenges in designing, assembling, and characterizing plasmonic devices. When a few nanoparticles are brought to close proximity to each other, strong near-field coupling leads to rich optical repsonse, which sensitively depends on the composition and geometry of the cluster. To reveal instrisic properties of plasmonic nanostructures, one has to establish structure-property correlation at the single particle level in well defined nanostructures. We will discuss a few examples of nanostructures assembled with Atomic Force Microscope (AFM) nanomanipulation method. In the first example, we discuss a three-dimensional (3D) spectroscopic nanosensor, called "plasmonic protractor", based on a low-symmetry plasmonic nanostructure formed between a plasmonic sphere and a nanorod placed in the vincinity. This plasmonic far-field, in-situ spatial arrangement sensor greatly expands the capability of existing spectroscopic rulers. In the second example, we discuss the assembly, characterization, and simulation of photonic circuits consisting of both dielectric and metallic nanoparticles. The clusters are shown to produce the designed spectral response, quantitatively predicted by simple circuit rules.

8984-19, Session 5

Ultrafast spectroscopy of carbon nanomaterials *(Invited Paper)*

Junichiro Kono, Rice Univ. (United States)

Carbon-based nanomaterials—single-wall carbon nanotubes (SWCNTs) and graphene, in particular—have emerged in the last decade as novel low-dimensional systems with extraordinary properties. Because they are direct-bandgap systems, SWCNTs are one of the leading candidates to unify electronic and optical functions in nanoscale circuitry; their diameter-dependent bandgaps can be utilized for multi-wavelength devices. Graphene's ultrahigh carrier mobilities are promising for high-frequency electronic devices, while, at the same time, it is predicted to have ideal properties for terahertz generation and detection due to its unique zero-gap, zero-mass band structure. There have been a large number of basic optical studies on these materials, but most of them were performed in the weak-excitation, quasi-equilibrium regime. This talk will give an overview on our recent work on their ultrafast and nonlinear optical properties as well as THz properties.

8984-20, Session 5

Carrier multiplication and optical gain in graphene *(Invited Paper)*

Ermin Malic, Florian Wendler, Technische Univ. Berlin (Germany)

We present microscopic time-resolved calculations of the ultrafast relaxation dynamics of photo-excited Dirac carriers in graphene. We take all relevant Coulomb- and phonon-induced relaxation channels into account focusing in particular on the importance of Auger-type processes.

In the presence of a strong magnetic field, graphene exhibits an unconventional Landau quantization including the existence of a zero Landau level. Due to optical selection rules, single Landau-level transitions can be selectively excited and probed with circularly polarized light. Here, we investigate the carrier dynamics in the energetically lowest Landau levels by modeling experimental differential transmission spectra. Our theory is based on the density matrix formalism, where we exploit the Peierls substitution to incorporate the magnetic field. The derived graphene Bloch equations describing the coupled dynamics of carrier and phonon occupations as well as optical coherences allow us to track the way of optically excited carriers toward equilibrium. The dynamics is determined by interplay of optical pumping, carrier-carrier, and carrier-phonon scattering.

We show that the expected symmetric behavior in differential transmission spectra for different relative pump and probe pulse polarizations is broken due to the presence of doping, which induces polarization-dependent Pauli blocking. Furthermore, our calculations clearly reveal that Auger processes dominate the inter-Landau level dynamics on a femtosecond timescale followed by much slower phonon-induced scattering processes.

8984-21, Session 5

Transient plasmons in graphene *(Invited Paper)*

Javier Garcia de Abajo, ICFO - Institut de Ciències Fotòniques (Spain)

We will review the plasmonic properties of graphene, including its electrical, magnetic, and thermal tunability. We will further discuss the ultrafast optical response of this material, including the existence of transient plasmons that evolve adiabatically over picosecond time scales.

8984-22, Session 6

Optical Three-Dimensional Coherent Spectroscopy *(Invited Paper)*

Hebin Li, Florida International Univ. (United States) and Univ. of Colorado (United States); Alan D. Bristow, West Virginia Univ. (United States) and Univ. of Colorado (United States); Mark E. Siemens, Univ. of Denver (United States) and Univ. of Colorado (United States); Galan Moody, Steven T. Cundiff, JILA (United States) and Univ. of Colorado (United States)

Optical two-dimensional coherent spectroscopy (2DCS) is a powerful tool for studying structure and dynamics in complex systems, such as semiconductors. An important advantage of 2DCS is the ability to discern quantum pathways by unfolding a one-dimensional spectrum onto a two-dimensional (2D) plane. For many systems, however, the quantum pathways are only partially separated in a 2D spectrum. In order to completely isolate the quantum pathways, we extend 2DCS into a third dimension to generate three-dimensional (3D) spectra in which the spectrum can be further unfolded. A 3D spectrum provides complete and well-isolated information of the third-order optical response of the sample. The information can be used to fully characterize the system's Hamiltonian.

Quantitative knowledge of the Hamiltonian enables prediction and coherent control of quantum processes. The primary principle for coherent control is the manipulation of constructive and destructive interference of quantum pathways between the initial and target states. Thus, a detailed understanding of the quantum pathways used to construct the Hamiltonian is essential for deterministic control and improved performance of coherent control schemes. By implementing three-dimensional coherent spectroscopy (3DCS) in an atomic vapor, we demonstrate that (i) the spectral contributions from different quantum pathways are unambiguously isolated and (ii) the parameters describing each quantum pathway, including the transition energies, dipole moments and relaxation rates, can be determined from a 3D spectrum. The system Hamiltonian can be constructed from these parameters. The results demonstrate the unique potential of 3DCS as a powerful technique for resolving the complex nature of quantum systems.

8984-23, Session 6

Quantum coherence controls the charge separation in a prototypical artificial light-harvesting system *(Invited Paper)*

Christoph Lienau, Carl von Ossietzky Univ. Oldenburg (Germany)

The efficient conversion of light into electricity or chemical fuels is a fundamental challenge.

In artificial photosynthetic and photovoltaic devices, this conversion is generally thought to happen on ultrafast, femto-to-picosecond timescales and to involve an incoherent electron transfer process. In some biological systems, however, there is growing evidence that the coherent motion of electronic wavepackets is an essential primary step, raising questions about the role of quantum coherence in artificial devices. Here we investigate the primary charge-transfer process in a supramolecular triad, a prototypical artificial reaction centre.

Combining high time-resolution femtosecond spectroscopy and time-dependent density functional theory, we provide compelling evidence that the driving mechanism of the photoinduced current generation cycle is a correlated wavelike motion of electrons and nuclei on a timescale of few tens of femtoseconds. We highlight the fundamental role of the interface between chromophore and charge acceptor in triggering the coherent wavelike electron-hole splitting.

8984-24, Session 7

The role of coherence for light-trapping in thin-film silicon solar cells *(Invited Paper)*

Martin Aeschlimann, Technische Univ. Kaiserslautern (Germany); Tobias Brixner, Julius-Maximilians-Univ. Würzburg (Germany); Dominik Differt, Matthias Hensen, Univ. Bielefeld (Germany); Christian Kramer, Julius-Maximilians-Univ. Würzburg (Germany); Florian Lükermann, Univ. Bielefeld (Germany); Pascal Melchior, Technische Univ. Kaiserslautern (Germany); Walter Pfeiffer, Univ. Bielefeld (Germany); Martin Piecuch, Christian Schneider, Technische Univ. Kaiserslautern (Germany); Helmut Stiebig, Christian Strüber, Univ. Bielefeld (Germany); Philip Thielen, Technische Univ. Kaiserslautern (Germany)

The absorption of thin-film solar cells can be enhanced by increasing the effective light path in the absorptive layer via light trapping. We investigate amorphous thin-film Si solar cells with nanotextured internal interfaces by means of optical spectral interferometry and coherent two-dimensional nanoscopy [1]. By probing the electric field of the ultrashort near-infrared laser pulses scattered in the investigated sample coherence lifetimes of local modes are examined. The latter technique combines coherent 2D spectroscopy with photoemission electron microscopy (PEEM) and enables a high spatial resolution below the optical diffraction limit. In our experiments we observe hot-spot photoemission confirming strongly localized electric field distributions in the absorptive Si layer. Both techniques reveal that these photonic modes feature long coherence lifetimes and a statistical distribution of resonance frequencies. Fitting the measured 2D nanospectra with a damped Lorentzian oscillator model we reconstruct the spatially-resolved information about lifetimes and spectral shifts of localized photonic modes with sub-diffraction resolution. We conclude that effective light trapping in amorphous thin film solar cells by nanotextured interfaces involves the generation of strongly localized photonic modes that arise via multiple scattering in the randomly nanotextured thin-film solar cell.

[1] M. Aeschlimann, T. Brixner, A. Fischer, C. Kramer, P. Melchior, W. Pfeiffer, C. Schneider, C. Strüber, P. Tuchscherer, D. V. Voronine, Science 333, 1723 (2011)

8984-25, Session 7

Two-color coherent control of XUV and THz radiation: experiment and theory

Aram Gragossian, The Univ. of New Mexico (United States); Denis V. Seletskiy, Univ. Konstanz (Germany); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

Extreme ultraviolet emission (XUV) from rare gases is possible by focusing intense ultrafast laser pulses onto a gas target. Within the well-known three-step model, tunnel ionized electrons generate high harmonics on the return trajectories, upon recombination with the parent ion. The driving pulses (3.5mJ, 800 nm, 35 fs, 1 kHz), produced by combination of fundamental and second harmonic, control electron trajectories via the asymmetry in the field [1], regulated by the relative phase difference of the two harmonics. XUV originates from the recombination of the return trajectories, while the THz is emitted via the macroscopic net current [2], resulting from the escaped electron trajectories. In this work we detect the emission of both XUV (XUV spectrometer) and THz radiation (ZnTe-based Electro-Optic sampling and/or pyroelectric detector) from the gas target. Furthermore, we show that by combining polarization-resolved detection and precise control of the mutual phase in the two-color field, we can verify anti-correlated nature of the concurrent XUV and THz emission, as expected from the classical three-step model. We also modify the three-step model to quantitatively explain our data in the regime of strong polar asymmetry. Ongoing work is exploring the generality of our results by further studies of the optical polarization and field-strength dependence.

[1] N. Dudovich et al., Nat. Physics 2, 781 (2006)

[2] K.-Y. Kim, A. J. Taylor, J. H. Glownia, and G. Rodriguez, Nat. Photonics 2, 605 (2008)

8984-26, Session 7

New aspects of coherently-controlled currents in GaAs

Elmar Sternemann, Thorben Jostmeier, Technische Univ. Dortmund (Germany); Huynh Thanh Duc, Torsten Meier, Univ. Paderborn (Germany); Markus Betz, Technische Univ. Dortmund (Germany)

Seizable current burst in GaAs can be induced with phase-stable superpositions of harmonically related near-infrared femtosecond pulses. Here we first explore the regime of elevated irradiances where absorption saturation and ultimately the onset of Rabi oscillations contribute to the optical response. In fair agreement with theoretical simulations we find marked departures from the perturbative third-order picture of current injection which are related to macroscopic state filling. We then move on to realize pulse characterization schemes which utilize the phase-dependence of coherent control schemes. In particular we demonstrate sensitive amplitude- and phase retrieval of ~50 fs near-infrared pulses via a novel Fourier transform approach based on two-color current injection.

8984-27, Session 7

Spectral and temporal characteristics of s transient Cherenkov radiation from a periodic resonant medium excited by an ultrashort laser pulse at superluminal velocity

Rostislav Arkhipov, Weierstrass-Institut für Angewandte Analysis und Stochastik (Germany); Ihar Babushkin, Humboldt-Univ. zu Berlin (Germany); Mikhail V. Arkhipov, St. Petersburg State Univ. (Russian Federation); Yurii A. Tolmachev, Saint-Petersburg State Univ. (Russian Federation)

The problem of the existence of superluminal motions in nature has attracted the attention of various researchers for a rather long time. It is well-known that spots of light can propagate at the superluminal velocity, as it was considered by I.M. Frank, and V.L. Ginzburg [1]. There are spots of light formed by the rotating searchlight at a fairly remote screen, or the illumination of a flat screen with plane wave, where intersection of the pulse and the screen moves along the screen at the superluminal velocity and an intersection point of two interfering laser beams. Using these spots of light it is possible to realize an optical excitation of a resonant medium at a velocity exceeding the velocity of light [2]. We consider a periodically modulated string of oscillators (two-level atoms, quantum dots, optical nanoantennas) excited by a laser pulse crossing the string in an oblique direction. It is shown that if the velocity of the propagating

excitation is greater (lower) than the velocity of light in vacuum c, a new frequency appears in the spectrum of the medium response. This frequency depends on the velocity of excitation and spatial period of oscillator density. Dependence of this frequency on string geometry is investigated. Possible applications of the effect are discussed.

References

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8984-28, Session 8

Overcoming the diffraction limit with the use of disordered nanostructures *(Invited Paper)*

Wonshik Choi, Eunsung Seo, Wonjun Choi, Korea Univ. (Korea, Republic of)

Multiple light scattering in a disordered medium is normally considered detrimental to optical imaging. For example, translucent biological tissues limit the depth at which microscopy can be performed. Therefore, main focus of the past studies such as adaptive optics and optical phase conjugation has been to mitigate the detrimental effects of multiple scattering. In this talk, I will describe the counterintuitive finding that a disordered medium, rather than being a hindrance to imaging, can in fact dramatically improve both the spatial resolution and the field of view of the target images. These improvements are based on our method of extracting the original image information from the image distorted by the multiple scattering, which we call turbid lens imaging (TLI). With the use of TLI, we achieved the resolution enhancement by more than five times over the diffraction limit and the extension of view field over the physical area of the camera. In addition, I will introduce our recent efforts on making use of the evanescent waves generated on the surface of disordered nanostructures by the use of TLI. Our technique will lead to great important applications in super-resolution imaging and deep-tissue biological imaging.

8984-29, Session 8

Ultrafast optical microscopy on single semiconductor nanowires *(Invited Paper)*

Minah Seo, Jinkyoung Yoo, Shadi A. Dayeh, Samuel T. Picraux, Antoinette J. Taylor, Rohit P. Prasankumar, Los Alamos National Lab. (United States)

Ultrafast optical microscopy (UOM) combines a typical optical microscope and femtosecond (fs) lasers that produce high intensity, ultrashort pulses at high repetition rates over a broad wavelength range. This enables us new types of imaging modalities, including scanning optical pump-probe microscopy, which varies the pump and probe positions relatively on the sample and ultrafast optical wide field microscopy, which is capable of rapidly acquiring wide field images at different time delays, that is measurable nearly any sample in a non-contact manner with high spatial and temporal resolution simultaneously. We directly tracked carriers in space and time throughout a NW by varying the focused position of a strong optical 'pump' pulse along the Si core-shell nanowires (NWs) axis while probing the resulting changes in carrier density with a weaker 'probe' pulse at one end of the NW. The resulting time-dependent dynamics reveals the influence of oxide layer encapsulation on surface state passivation in core-shell NWs, as well as the presence of strong acoustic phonon oscillations, observed here for the first time in single NWs. Time-resolved wide field images of the photoinduced changes in transmission for a patterned semiconductor thin film and a single silicon nanowire after optical excitation are also captured in real time using a two dimensional smart pixel array detector. Our experiments enable us to extract several fundamental parameters in these samples, including the diffusion current, surface recombination velocity, diffusion coefficients, and diffusion velocities, without the influence of contacts.

8984-30, Session 8

Principles of perfect and ultrathin anti-reflection with applications to transparent electrode *(Invited Paper)*

Q-Han Park, KyoungHo Kim, Korea Univ. (Korea, Republic of)

Perfect broad band anti-reflection (AR) through admittance matching has long been an important challenge in optics and electrical engineering. Beyond trial and error optimization, however, a systematic way to realize AR is still absent. Here, we report the discovery of an analytic solution to this long standing problem. We present a design rule for the ultra-thin AR coating which has been confirmed experimentally. This work opens a new design procedure for ultra-thin AR in optoelectronic devices, THz and microwave applications. Specifically, we explain applications of AR to transparent electrodes and present our recent achievement.

8984-31, Session 9

Phase space monitoring of Exciton-polariton multistability *(Invited Paper)*

Yoan Léger, Institut National des Sciences Appliquées de Rennes (France)

Nonlinear interactions in coherent Bose gases are the essential ingredients of amazing phenomena such as superfluidity and soliton formation. In cold atom physics, interactions can even be tailored through Feshbach resonances to control the nature of quantum fluids.[1] Beyond fundamental physics, interactions are also crucial in the development of novel photonic components. In particular, nonlinear effects in optical microresonators have been demonstrated to result in bistability and all-optical memory schemes.[2]

Recently, a new class of Bose gas appeared to be an extremely versatile system for the investigation of all these phenomena. So called exciton-polaritons are half-light half-matter quasi-particles forming in strongly-coupled semiconductor microcavities. From their dual nature, they inherit unique properties: a very low mass allowing condensation at high temperature, a full optical access to the gas properties through the light leaking out of the cavity, and above all, strong and anisotropic coulombian interactions provided by polaritons' excitonic component.

In this work we investigate the spin dynamics of a driven polariton gas by exploiting the multistable character of the system. We demonstrate ultrafast all-optical switching between three stable spin configurations of the polariton gas.[3] We observe large changes in the system transients, from a few ps to hundreds of ps, depending on the excitation conditions. We show that this behavior is due to the influence of nonlinear losses in the polariton gas and the subsequent formation of a non-radiative reservoir, still interacting with the polariton gas.

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8984-32, Session 9

Formation and Control of Transverse Patterns in a Quantum Fluid of Microcavity Polaritons

Przemyslaw Lewandowski, Univ. Paderborn (Germany); Vincenzo Ardizzone, Lab. Pierre Aigrain (France); Yuen Chi Tse, The Chinese Univ. of Hong Kong (Hong Kong, China); Nai-Hang Kwong, College of Optical Sciences, The Univ. of Arizona (United States) and The Chinese Univ. of Hong Kong (China); Ming Ho Luk, The Chinese Univ. of Hong Kong (Hong Kong, China); Andreas Lücke, Univ. Paderborn (Germany); Marco Abbarchi, Lab. Pierre Aigrain (France) and Lab. de Photonique et de Nanostructures (France); Jacqueline I. Bloch, Lab. de Photonique et de Nanostructures (France); Emmanuel Baudin, Lab. Pierre Aigrain (France); Elisabeth Galopin, Aristide Lemaître, Lab. de Photonique et de Nanostructures (France); Pui Tang Leung, The Chinese Univ. of Hong Kong (Hong Kong, China); Philippe Roussignol, Lab. Pierre Aigrain (France); Rolf Binder, College of Optical Sciences, The Univ. of Arizona (United States); Jérôme Tignon, Lab. Pierre Aigrain (France); Stefan Schumacher, Univ. Paderborn (Germany)

Transverse patterns in polariton fluids were recently studied as promising candidates for all-optical low-intensity switching [1,2]. Here we demonstrate these patterns in a specifically designed double-cavity system. We theoretically and experimentally analyze their formation and optical control [3]. Our detailed theoretical analysis of the coupled nonlinear dynamics of the optical fields inside the double-cavity and the excitonic excitations inside the embedded semiconductor quantum wells, is firmly based on a microscopic many-particle theory. Our calculations in the time domain enable us to study both the ultrafast transient dynamics of the patterns and their steady-state behavior under stationary excitation conditions.

The patterns we report and analyze go beyond what can be observed and understood in a simple scalar quantum field. We find that polarization-selective excitation of the polaritons leads to a complex interplay between longitudinal-transverse splitting of the cavity modes and the spin-dependent interactions of the polaritons' excitonic component. We also show that changes in the patterns' appearance and external control of the patterns can be understood in terms of phase transitions in the nonlinear system's complex phase structure.

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8984-33, Session 9

Coupled electron-hole-photon systems in two-dimensional semiconductors *(Invited Paper)*

Chih-Wei Lai, Michigan State Univ. (United States)

Optical microcavities have played an important role in areas as diverse as fundamental science of cavity QED and technological developments in photonics. The Fabry-Perot (FP) and photonic crystal resonators have over the past decade been demonstrated to hold light-matter quantum fluids beyond applications in optical communication, such as vertical cavity surface emitting lasers (VCSELs). The explorations of the spin-orbit coupling effects and polarization dynamics have added additional complexity and functionality to the solid-state microcavities. Polariton lasers or dynamics exciton-polariton condensates remain largely limited to operate at cryogenic temperatures (< 80 K) and have dissimilar polarization dynamics depending on structural anisotropies in material systems. Here we demonstrate room-temperature spin-polarized polariton lasing in the weak coupling regime in a gallium arsenide (GaAs) FP planar microcavity embedded with indium gallium arsenide (InGaAs)/GaAs quantum wells. The composition structure of our microcavity is similar to that of commercial VCSELs. Spin polarized carriers are optically injected by a non-resonant picosecond pulsed laser excitation with excessive energy more than 150 meV. We temporally modulate the pump laser intensity and spatially shape the pump beam to a top-hat profile with a lateral size less than 20 μm, generating negligible thermal heating and a highly circularly polarized single transverse laser oscillation mode. The lasing characteristics are analogous to those reported for 'exciton-polariton condensates'. We attribute the ultrafast picosecond energy relaxation and spin memory effect to a stimulated carrier-carrier scattering process mediated by the cavity light field. Such a device and pumping scheme allows for studies of quantum light fluids at room temperature and can enable practical spin lasers with a reduced threshold for laser action.

8984-34, Session 9

Ultrafast nonlocal control of spontaneous emission in photonic crystals

Chaoyuan Jin, Technische Univ. Eindhoven (Netherlands); Robert Johne, Max-Planck-Institut für Physik komplexer Systeme (Germany); Milo Y. Swinkels, Thang B. Hoang, Leonardo Midolo, René P. J. van Veldhoven, Andrea Fiore, Technische Univ. Eindhoven (Netherlands)

The ultrafast control of cavity quantum electrodynamics (CQED) at optical frequencies requires the GHz manipulation of the cavity-dipole interaction. As a significant step towards this target, we demonstrate the ultrafast nonlocal control of spontaneous emission (SE) rate by altering the coupling condition between two photonic crystal cavities which have very different Q-factors and mode volumes. We first show that, by thermo-optically bringing a Fabry-Perot (FP) cavity into resonance with a target cavity, the local density of states experienced by quantum dots (QDs) in the target cavity is modified nonlocally, leading to a change in the SE rate by as much as a factor of 2.7, where the control beam is positioned 30 μm away from the target cavity. By replacing the thermo-optic control with the free carrier injection by a ps laser, the SE in the target cavity is manipulated dynamically with a characteristic time of ~200 ps that is defined by the lifetime of free carriers in the FP cavity. A strong transient enhancement and reduction of the SE have both been observed in our experiments as a peak/dip appears in the time-resolved photoluminescence from the constantly pumped target cavity with a full width half maximum of 232/246 ps, respectively. Additionally, we show that the SE decay curve from the target cavity can be modified from the natural single-exponential by the application of a pump pulse in the FP cavity. These results open the way to the ultrafast control of CQED processes in the solid state.

8984-35, Session 10

THz detection in graphene nanotransistors *(Invited Paper)*

Alessandro Tredicucci, Lab. NEST (Italy)

Nanotransistors offer great prospect for the development of innovative THz detectors based on the non-linearity of transport characteristics. Semiconductor nanowires are appealing for their one-dimensional nature and intrinsically low capacitance of the devices, while graphene, with its record-high room-temperature mobility, has the potential to exploit plasma wave resonances in the transistor channel to achieve

high-responsivity and tuneable detection. First graphene detectors have been recently demonstrated at 300 GHz in both monolayer and bilayer field effect devices, with performances already suitable for imaging applications [1]. New generation devices now show improved responsivities in the V/W range and allow clearer interpretation of the operation mechanism. Research is then tackling configurations suitable for high-speed response, multi-pixel detection, and low-cost fabrication.

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8984-36, Session 10

Imaging ultrafast dynamics on the nanoscale with a THz-STM *(Invited Paper)*

Tyler L. Cocker, Univ. of Alberta (Canada) and Univ. Regensburg (Germany); Vedran Jelic, Manisha Gupta, James R. Hoffman, Sean J. Molesky, Jacob A. J. Burgess, Glenda B. De Los Reyes, Lyubov V. Titova, Ying Y. Tsui, Mark R. Freeman, Frank A. Hegmann, Univ. of Alberta (Canada)

No Abstract Available

8984-37, Session 10

Ultrafast THz-pulse-induced tunneling dynamics in an STM

Vedran Jelic, Univ. of Alberta (Canada); Tyler L. Cocker, Univ. of Alberta (Canada) and Univ. Regensburg (Germany); James R. Hoffman, Manisha Gupta, Reginald Miller, Sean J. Molesky, Jacob A. J. Burgess, Univ. of Alberta (Canada); Glenda B. De Los Reyes, University of Alberta (Canada); Lyubov V. Titova, Ying Y. Tsui, Mark R. Freeman, Frank A. Hegmann, Univ. of Alberta (Canada)

We have recently developed an ultrafast terahertz-pulse-coupled scanning tunneling microscope (THz-STM) that can image nanoscale dynamics with simultaneous 0.5 ps temporal resolution and 2 nm spatial resolution under ambient conditions. Broadband THz pulses that are focused onto the metallic tip of an STM induce sub-picosecond voltage transients across the STM junction, producing a rectified current signal due to the nonlinear tunnel junction current-voltage (I-V) relationship. We use the Simmons model to simulate a tunnel junction I-V curve whereby a THz pulse induces an ultrafast voltage transient, generating milliamp-level rectified currents over sub-picosecond timescales. The nature of the ultrafast field emission tunneling regime achieved in the THz-STM will be discussed, and progress towards realizing atomic resolution with the THz-STM in vacuum will be presented.

8984-38, Session 10

Broadband THz imaging in gas and multiple quantum-well media

Chia-Yeh Li, 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)

We discuss two schemes of ultrafast THz imaging, both constituting non-perturbative response of either gas or solid-state media to the THz bias fields and thus offering very sensitive detection of the applied quasi-stationary THz bias. In the first approach, we image the delay-dependent second harmonic emission from the air-breakdown plasma thus resulting in three dimensional mapping of the THz bias. Complementary to the recently demonstrated second harmonic imaging via FWM in diamond [1], our method offers a simple and robust imaging method with minimal perturbation to the standard 2-color gas-based THz setup. Moreover, we utilize a CMOS-based detector array operated in the lock-in mode, resulting in high signal-to-noise images, compared to conventional CCDs. As the second approach, we use THz-induced strong electro-absorption response in the solid-state samples, consisting of 90 alternating pairs of GaAs/AlGaAs coupled quantum wells. The overall thickness of the structure is much smaller than the internal THz wavelength, thus resulting in ultrabroadband phase-matching bandwidth. Transmission modulation exceeding 50% has already been observed under the external THz field strength < 1 MV/cm. In combination with the lock-in CMOS array, this method allows for ultrabroadband and fully three-dimensional mapping of the THz transients. Polarization dependent studies are currently underway to fully characterize the response of the two methods. Additionally, ongoing THz generation and propagation modeling is aimed at providing additional insight into the complexities of the air-based single-cycle THz photonics.

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8984-39, Session 10

Silicon wafer thickness measurement using terahertz time domain spectroscopy

Chih-Yu Jen, Christiaan Richter, Rochester Institute of Technology (United States)

This work studies the capability of transmission mode terahertz time domain spectroscopy (THz-TDS) to measure silicon wafer thickness. We describe optimal methods and compare the resolution of each method for industrial semiconductor and photovoltaic applications. In a typical THz-TDS measurement a pulse of far-infrared (THz) light is transmitted through the wafer. The waveform of the transmitted electric field is mapped out on a sub-picosecond time-scale in time. The Fourier transform of this pulse then provides both the power spectrum and phase delay for all frequencies in the pulse bandwidth. Wafer thickness can then be inferred from this data in several ways that can be divided into time domain and frequency domain methods. In the time domain the best resolution (+/-2.6 µm for ~ 500 µm wafers) is obtained by tracking the arrival time of the transmitted THz pulse (the thicker the wafer the later the pulse). In the frequency domain there are two approaches that give even better resolution. The silicon wafer acts as a natural Fabry-Pérot cavity for the transmitted THz radiation. The silicon wafer thickness can be inferred with at least +/-1.0 µm for ~ 500 µm wafers by tracking the resonant peak positions in the frequency domain. Finally, the phase delay across frequencies can also be used to infer wafer thickness with approximately the same resolution as the method based on resonant peak position.

8984-40, Session 11

Ultrafast spin precession and transport controlled and probed with terahertz radiation *(Invited Paper)*

Tobias Kampfrath, Fritz-Haber-Institut der Max-Planck-Gesellschaft (Germany); Marco Battiato, Uppsala Univ. (Sweden); Alexander Sell, Univ. Konstanz (Germany); Frank Freimuth, Forschungszentrum Jülich GmbH (Germany); Alfred Leitenstorfer, Univ. Konstanz (Germany); Martin Wolf, Fritz-Haber-Institut der Max-Planck-Gesellschaft (Germany); Rupert Huber, Univ. Regensburg (Germany); Peter M. Oppeneer, Uppsala Univ. (Sweden); Markus Münzenberg, Univ. Göttingen (Germany)

Terahertz (THz) electromagnetic radiation has a wavelength of the order

of 100µm and is located between the realms of electronics and optics. Besides its use in imaging and surveillance, THz radiation is capable of probing and even controlling many low-energy excitations such as phonons, excitons or Cooper pairs. Here, we consider two examples showing that THz spectroscopy is also a highly useful and versatile tool in the field of spin-based electronics (spintronics).

First, we use the magnetic-field component of an intense THz pulse to start and stop a spin wave in the antiferromagnet NiO for only few precession cycles (corresponding to only few picoseconds). Such resonant spin control based on Zeeman coupling may pave the way to an ultrafast switching of spin states in antiferromagnetically ordered solids [Nature Photon. 5, 31 (2011)].

Second, a femtosecond laser pulse is employed to inject spin-polarized electrons from a ferromagnetic into a nonmagnetic metal film. The resulting ultrafast spin current is detected through the inverse spin Hall effect that converts the spin flow into a measurable THz electromagnetic transient. Choosing nonmagnetic layers with different electron mobility allows one to manipulate the temporal shape of the spin current [Nature Nanotech. 8, 256 (2013)].

8984-41, Session 11

Terahertz radiation from magnetic excitations in diluted magnetic semiconductors *(Invited Paper)*

Rakchanok Rungsawang, Ecole Supérieure de Physique et de Chimie Industrielles (France); Florent Perez, Univ. Pierre et Marie Curie (France); Dimitri Oustinov, Ecole Normale Supérieure (France); Javier Gomez, Univ. Pierre et Marie Curie (France); Valery Kolkovsky, Grzegorz Karczewski, Tomasz Wojtowicz, Institute of Physics (Poland); Julien Madéo, Nathan Jukam, Sukhdeep S. Dhillon, Ecole Normale Supérieure (France); Jérôme Tignon, Ecole Normale Supérieure (France) and Univ. Pierre et Marie Curie (France)

Spin-based sources of THz electromagnetic radiation have recently attracted a great deal of attention, especially since spin waves were proposed to provide radiating sources to transmit or modify logical spin-based information [1]. In this context, direct light emission or absorption from the spin degrees of freedom is at the frontier of novel physics. Until now, however, optically [2] or magnetically [3] excited spin waves have been primarily investigated in antiferromagnets such as NiO. It is less obvious to expect similar THz emission from spin excitations in semiconductors, since typical semiconductors are paramagnetic and are limited by much lower concentrations of available spins (by about 4 orders of magnitude), which results in much weaker emitted fields. Here [4], we probed, in the time domain, the THz electromagnetic radiation originating from spins in CdMnTe diluted magnetic semiconductor quantum wells containing high-mobility electron gas. Taking advantage of the efficient Raman generation process, the spin precession was induced by low power near-infrared pulses. We provide a full theoretical first-principles description of spin-wave generation, spin precession, and of emission of THz radiation. Our results open new perspectives for improved control of the direct coupling between spin and an electromagnetic field, e.g., by using semiconductor technology to insert the THz sources in cavities or pillars.

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8984-42, Session 11

Quantum tricks with femtosecond light pulses teach magnetic devices to think ultrafast *(Invited Paper)*

Ilias E. Perakis, P. C. Lingos, Univ. of Crete (Greece); Jigang Wang, Iowa State University and Ames Lab (United States)

The technological demand to push the gigahertz switching speed limit of today's magnetic memory/logic devices into the terahertz regime underlies the entire field of spin–electronics and integrated multi-functional devices. This challenge is met by all–optical magnetic switching based on coherent spin manipulation. By analogy to femto–chemistry and photosynthetic dynamics where photo-products of chemical/biochemical reactions can be influenced by creating suitable superpositions of molecular states, femtosecond (fs) laser–excited coherence between spin/orbital/charge states can switch magnetic orders, by "suddenly" breaking the delicate balance between competing phases of correlated materials, e.g., the colossal magneto–resistive (CMR) manganites.

In the present work, we show fs photoinduced switching from antiferromagnetic to ferromagnetic ordering in manganites, by observing the establishment, within 120 fs, of a huge temperature–dependent magnetization with photoexcitation threshold behavior absent in the optical reflectivity. The development of ferromagnetic correlations during the fs laser pulse reveals an initial quantum coherent regime of magnetism, clearly distinguished from the picosecond lattice-heating regime characterized by phase separation without threshold behavior. Our simulations reproduce the fs local spin nonlinear dynamics and underpin fast quantum spin–flip fluctuations correlated with coherent superpositions of electronic states to initiate local ferromagnetic correlations via quantum kinetic processes beyond the statistical approach.

8984-43, Session 11

Optical tailoring of electron and hole spin polarization in bulk germanium

Jan Lohrenz, Timo Paschen, Christine Hautmann, Markus Betz, Technische Univ. Dortmund (Germany)

We analyze the wavelength dependence of optical spin orientation in bulk germanium via time-resolved Faraday rotation. Significant hole spin polarization is found only when addressing indirect optical transitions. In contrast, electron spins can be oriented via both direct and indirect optical transitions and even with excess energies up to ~1 eV. For photon energies very close to the indirect bandgap, the degree of electron spin polarization is significantly enhanced – a trend in line with theoretical predictions. Finally we use resonant spin amplification to demonstrate remarkably robust electron spin coherence with dephasing times of ~30 ns at cryogenic temperatures.

8984-44, Session 12

Laser near-field acceleration of strong-field few-cycle photo-emitted electrons from a sharp metal tip *(Invited Paper)*

Petra Gross, Jan Vogelsang, Bjoern Piglosiewicz, Slawa Schmidt, Doo-Jae Park, Christoph Lienau, Carl von Ossietzky Univ. Oldenburg (Germany)

Sharply etched metallic tips are emerging as a test bed for exploring strong-field phenomena such as high-harmonic generation and photoemission of electrons. When such tips are illuminated with few-

cycle laser pulses of sufficient laser field strength, the field enhancement at the tip apex results in tunneling of electrons out of the tip. The acceleration of these electrons in the local near field around the tip apex can be so strong that their typical quiver motion in the oscillating laser field is suppressed and they traverse the near field within less than one half oscillation cycle.

Under these conditions, we enter a whole new regime of electron emission, which is characterized by the motion of the electrons in the oscillating, fast decaying near-field with a decay length of only a few nm. We discuss this new regime, and demonstrate how the motion of the electrons can be controlled via the applied laser field. We follow the electron motion numerically using a modified Simpleman model. Experimentally we observe a steering effect of the fastest electrons, and we show how the carrier-envelope-phase admits a new control mechanism for electron motion.

8984-45, Session 12

Extreme nonlinear optical processes with beams carrying orbital angular momentum *(Invited Paper)*

Christian Spielmann, Michael Zürch, Christian Kern, Abbe School of Photonics (Germany); Peter Hansinger, Abbe School of Photonics (Germany); Alexander A. Dreischuh, Sofia Univ. "St. Kliment Ohridski" (Bulgaria)

Light beams carrying an isolated point singularity with a screw-type phase distribution are called an optical vortex (OV). The free space the Poynting vector of the beam gives the momentum flow leads to an orbital angular momentum (OAM) of the photons in such a singular beam, independent on the spin angular momentun. Many applications are only feasible when optical vortex beams in all spectral regions are available. For example, transitions forbidden by selection rules in dipole approximation appear allowed when using photons with the additional degree of freedom of optical OAM. However, the common techniques of producing new light frequencies by nonlinear optical processes seem problematic in conserving the optical vortex when the nonlinearity becomes large. We show that with the extremely nonlinear process of High Harmonic Generation (HHG) it is possible to transfer OVs from the near-infrared to the extreme ultraviolet (XUV) at wavelengths down to ~30 nm. The spatial profile showed the expected singular behavior, a dark region in the centre. A phase feature that showed a shift of π on opposing sides of the beam profile was found with a wave front splitting technique. A screw-like phase evolution around the profile was also verified by employing a Hartmann type measurement. The generated spectrum revealed that in all Harmonic orders an OV was present. The profile however looked the same in all orders, indicating identical topological charge, which runs counterintuitive to the assumption that the phase of $\exp(-il\varphi)$ is multiplied by the order of the nonlinearity.

8984-46, Session 12

Extending hhg spectroscopy to new molecular species

Felicity C. McGrath, Emma R. Simpson, Peter Hawkins, Thomas Siegel, Dane Austin, Zsolt Diveki, Amelle Zair, Imperial College London (United Kingdom); Marta Castillejo, Consejo Superior de Investigaciones Científicas (Spain); Jonathan P. Marangos, Imperial College London (United Kingdom)

We present developments made for performing HHG experiments with samples starting in the liquid phase. We demonstrate a sub 3% fluctuation in the harmonic signal generated from a vapour backed continuous gas jet using an organic liquid target (e.g. benzene, fluorobenzene, toluene). Low ionisation potentials and expected femtosecond timescale dynamics necessitate the use of longer wavelengths from a mid-IR source. The acquisition of stable reproducible harmonic spectra has been verified and the dependence of HHG upon ellipticity was measured for a number of molecules. We report, to our knowledge, the first impulsive molecular alignment of the Benzene molecule using an 800nm-800nm alignment - generation collinear configuration. This paper will also detail experiments planned using a sub 10fs 1800nm laser pulse to access femtosecond timescale dynamics in large polyatomic molecules and will pioneer an extension of well established HHG Spectroscopic techniques to these molecular systems.

8984-47, Session 13

Ultrafast strong-field plasmonics *(Invited Paper)*

Peter Dombi, Max-Planck-Institut für Quantenoptik (Germany) and Wigner Research Ctr. for Physics (Hungary)

Plasmonic phenomena involving femtosecond excitation pulses and strong laser fields have gained significance in recent years. Fundamental electron photoemission, acceleration and rescattering phenomena were observed in the nanoscale vicinity of plasmonic nanoparticles recently with applications including high harmonic generation or THz pulse production. I will review these developments focusing in fundamental electron phenomena in surface plasmon fields. I will point out what are the basic differences if these processes are taking place in electromagnetic fields that are changing on the nanoscale. Versatile control possibilities are offered by tailoring the nanoparticle shape and/or the interacting laser pulse (such as carrier-envelope phase control). This will be demonstrated by selected examples. Besides developing the applications in attosecond and THz science, these investigations can also help to answer the fundamental question, how collective electron oscillations in nanoparticles build up and evolve on ultrafast time-scales.

8984-48, Session 13

Terahertz-field-induced luminescence from structured metallic layers

Krzysztof Iwaszczuk, DTU Fotonik (Denmark); Maksim Zalkovskij, Technical Univ. of Denmark (Denmark); Andrew C. Strikwerda, Peter U. Jepsen, DTU Fotonik (Denmark)

Development of the high power table-top terahertz sources allowed for the terahertz nonlinear optics is become a rapidly growing field of optics. Various gases, liquids, and both semiconductors and insulators have shown broad range of nonlinear terahertz phenomena. But so far very little work on exploring terahertz nonlinear effects in metals has been done. In this work we present experimental demonstration of photoluminescence from structured metallic layers exposed to strong single-cycle terahertz transients with peak electric field over few hundreds of kV/cm. We investigate spectra of the generated light and we show that UV-Vis-NIR light is generated. We look at the nonlinear field scaling of this phenomena. We also look at the dynamics of the effect by use of two strong terahertz pulses with varied time delay between and show that subpicosecond UV-Vis-NIR optical pulses are generated. Finally we analyze possible mechanisms of the light generation.

8984-49, Session 13

Study of filamentation compression in the near infrared in the

1.6 um to 2 um region for HHG experiments

Steffen Driever, Damien Bigourd, Imperial College London (United Kingdom); Nikita Fedorov, Commissariat à l'Énergie Atomique

(France); Jean-Christophe Delagnes, 2 Université de Bordeaux, CEA, CNRS UMR 5107, CELIA (Centre Lasers Intenses et Applications) (France); Dominique Descamps, Univ. Bordeaux 1 (France); Eric Cormier, Eric Constant, Univ. Bordeaux 1 (France); Martin Arnold, Imperial College London (United Kingdom); Konstantin Holzner, Amelle Zair, Imperial College London (United Kingdom)

This investigation was conducted to study the tunability of the filamentation process using a near infrared laser source at wavelength ranging from 1.6 um to 2 um. A Krypton cell filled statically with 4 bar was employed as filamentation medium. A spectral broadening via filamentation was observed over the whole range of wavelengths employed and achieved broadening factor of ~2-3. In best experimental conditions about 300nm of bandwidth where generated. The accumulated group velocity dispersion in the filament was compensated by fused silica since the dispersion of fused silica is negative at these wavelengths. It was possible to compress the pulses down to the few-cycle regime with 2-3 cycles for 1.7 um, 1.8 um and 1.9 um. Theses pulses contained about 200 uJ pulse energy. Theoretical studies were conducted to underline our findings. These qualitatively reproduced the spectral broadening behaviour with the wavelengths employed. In order to understand the impact of the nonlinearity and ionisation, additionally to the B-integral we define a C-integral that quantifies the ionisation part. Understanding the phenomenon of filamentaion at theses wavelengths bares significant potential for strong field physics application such as attosecond science where longer wavelength and few-cycle pulses are of great advantage.

8984-51, Session 14

Electromagnetic near-fields: from optical response to microscopy *(Invited Paper)*

Nir Rotenberg, Boris le Feber, FOM Institute for Atomic and Molecular Physics (Netherlands); Javier Garcia de Abajo, ICFO - Institut de Ciències Fotòniques (Spain); Laurens K. Kuipers, FOM Institute for Atomic and Molecular Physics (Netherlands)

The near-field of nanoscopic structures, even those where the magnetic permeability is near unity, generally contains components of all six electromagnetic fields: 3 electric and 3 magnetic. We show that, in a similar fashion, nanostructures such as subwavelength air holes in opaque metallic films have both an electric and a magnetic optical response. This response can be understood in terms of the dipoles that are induced in the nanostructure, and can lead to structured radiation fields, both in spatially and temporally. In particular, we demonstrate that plasmonic scattering from such holes can be very directional due to the interference of the electric and magnetic contributions.

Near-field aperture probes, which are often likened to subwavelength holes in metallic films, also have a complete electromagnetic response, not just an electric one. Here we examine what, in fact, is detected by such a probe, and again unravel the electric and magnetic contributions. We show that these contributions can be understood in terms of a combination of the electromagnetic near-fields associated with both the probe and the sample being measured. In fact, it is this complex behavior of the nanoscopic probe that makes near-field microscopy such a powerful and promising technique, particularly in the emerging field of magnetically active structures.

8984-52, Session 14

Engineering plasmonic and dielectric directional nanoantennas

Andre Hildebrandt, Matthias Reichelt, Torsten Meier, Jens Förstner, Univ. Paderborn (Germany)

Optical and infrared antennas provide a promising way to couple photons in and out of nanoscale structures. As counterpart to conventional radio antennas, they are able to increase optical fields in sub-wavelength volumes [1], to enhance excitation and emission of quantum emitters or to direct light, radiated by quantum emitters [2]. The directed emission of these antennas has been mainly pursued by surface plasmon based devices, e.g. Yagi-Uda like antennas, which are rather complicated due to the coupling of several metallic particles. Also, like all metallic structures in optical or infrared regime, these devices are very sensitive to fabrication tolerances and are affected by strong losses. It has been shown recently, that such directed emission can be accomplished by dielectric materials as well [3].

In this paper we present an optimization of nanoscopic antennas in the near infrared regime starting from a metallic Yagi-Uda structure. The optimization is done via a particle-swarm algorithm, using full time domain finite integration simulations to obtain the characteristics of the investigated structure, also taking into account substrates. Furthermore we present a dielectric antenna, which performs even better, due to the lack of losses by an appropriate choice of the dielectric material. These antennas are robust concerning fabrication tolerances and can be realized with different materials for both the antenna and the substrate, without using high index materials.

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8984-53, Session 14

Polarization-modulated second-harmonic generation from sub-wavelength Archimedean nanospirals

Roderick B. Davidson, Ryan Rhoades, Jed I. Ziegler, Sergey M. Avanesyan, Richard F. Haglund Jr., Vanderbilt Univ. (United States)

Archimedean spirals of subwavelength overall dimensions have no spatial symmetry, but do exhibit spectroscopically distinct, resonant modes — designated as standing-wave, focusing and hourglass modes corresponding to their spatial patterns in the optical near field. Because of the total lack of symmetry in this spiral geometry, we hypothesized that these nanospirals might also be efficient generators of second-harmonic radiation. We have tested this hypothesis on gold nanospiral arrays fabricated by electron-beam lithography, and measured the second-harmonic generation (SHG) efficiency in the near-field focusing mode with linear, left-hand and right-hand circularly polarized light pulses from a mode-locked, cavity-dumped oscillator at 800 nm with a pulse duration of 12 fs as measured by autocorrelation.

SHG signals from the nanospiral arrays in the forward direction exhibit efficiencies on the order of 10-11 at 30mW incident power and polarization enhancement factors of over an order of magnitude. Circularly polarized light yields the strongest modulation due to the chiral nature of the nanospirals. Circular polarization in the direction counter to the handedness of the spiral enhances SHG, while circularly polarized light with matching handedness extinguishes the signal. The geometric characteristic of the enhancement reveals information about the near field structure of a complex plasmonic resonance. Enhanced angular emission of SHG signals have also been observed as a function of polarization modulation at those angles that correspond to the principal diffraction angles of the nanospiral arrays. The SHG intensity can also be affected by manipulating the spectral content of the pump laser laser using a spatial light modulator.

8984-54, Session 14

Universal control of femtosecond pulses beyond the diffraction limit for phase investigation on the nanoscale

Nicolò Accanto, Lukasz Piatkowski, Jana B. Nieder, Jan Renger, Marta Castro-Lopez, Francesco Pastorelli, Daan Brinks, Niek F. van Hulst, ICFO - Institut de Ciències Fotòniques (Spain)

Investigation of the ultrafast processes and the intrinsic phase response in single nano-objects requires a combination of phase controlled femtosecond pulses and nanometer spatial resolution. However, controlling femtosecond pulses in the phase and time domain with nanometer accuracy is very challenging, as the limitations imposed by dispersive optics to the time duration of a pulse and by the spatial diffraction limit to the focusing of light need to be overcome at the same time. Moreover, such control of laser pulses becomes the more challenging when high phase sensitivity is required as it is the case of resonant nano-structures where the investigated nano-object possesses intrinsic phase response that one desires to determine and control.
We provide a universal method that allows for full femtosecond pulse control on sub diffraction limited areas and enables amplitude and phase mapping of resonant nano-structures. We achieve this by exploiting the intrinsic coherence of the second harmonic (SH) emission from a single non-linear nano-particle of deep sub wavelength dimension. The method is tested on various nano-particles of different sizes, shapes and materials, both dielectric ($BaTiO_3$, $Fe(IO_3)$) and metallic (Ag, Au), demonstrating its robustness and versatility. The accuracy of phase control at the nano-scale that we achieve enables the study of the intrinsic amplitude and phase response of individual nano-antennas, which opens up new frontiers in the field of coherent control and active plasmonics. Our results will facilitate the investigation of light-matter interactions on the femtosecond-nanometer level.

8984-55, Session PWed

Ultrafast fluorescence polarization spectroscopy of near-infrared dye in picosecond dynamic range

Kenneth J. Zhou, Stony Brook Univ. (United States); Lin Wang, The Herbert Irving Comprehensive Cancer Ctr. (United States) and Kunming Medical College (China)

Molecules undergo vibrational and rotational motion in the relaxation of the excited electronic states. Near-infrared (NIR) dyes which absorb and emit light within the range from 700 to 900 nm have several benefits in biological studies. However, because of the less than ideal anisotropy behaviour of NIR dyes stemming from the fluorophores elon-gated structures and short fluorescence lifetime in picosecond range, no significant ef-forts have been made to recognize the theory of these dyes in time-resolved polarization dynamics. In this paper, the depolarization of the fluorescence due to emission from rota-tional deactivation in solution will be measured with the excitation of a linearly polarized femtosecond laser pulse, and detected using a streak camera. The theory, experiment and application of the ultrafast fluorescence polarization dynamics and anisotropy are illu-strated with examples of the most important medical dyes in NIR range, namely Indo-cyanine Green (ICG). A set of first-order linear differential equations was developed to model fluorescence polarization dynamics of NIR dye in picoseconds range. Using this model, the important parameters of ultrafast polarization spectroscopy were identified: risetime, initial time, fluorescence lifetime, fluorophore's rotation time. It is the first time to present the fundamental theory of NIR dye in picosencond dynamic range and verify it by the ultrafast spectra obtained by streak camera.

8984-56, Session PWed

Review of the negative-index materials

Dongshan Zhu, China Satellite Maritime Tracking & Control Dept. (China); Liheng Ma, National Univ. of Defense Technology (China)

With the rapid development of simulation and nanofabrication techniques, the artificially fabricated negative-index materials (NIMs) have attracted a lot of interest and a booming growth in publication for the recent decade. NIMs have simultaneously negative electrical permittivity ε and magnetic permeability μ which result in a negative refractive index and many counter-intuitive properties that are not observed in natural materials including a modified Snell Law, the inverse Doppler Effect, the inverse Goos-Hänchen shift and the inverse Cherenkov Effect.
Many composite structures and methods to NIMs are developed and researched including photonic crystals (PCs). The frequency range has been broadened and NIMs at optical frequency are also structured. Perfect lens with sub-wavelength resolution that breaks the diffraction limit arouses the passion and it will bring a revolution in optical devices. NIMs have the ability to control and change the electromagnetic fields and cloaking is possible. These features lead to many potential applications in optics, communications, medical facilities, etc. In this paper, the fundamental physical concepts and phenomena, history and advance, the inverse effects and applications of the NIMs will be reviewed. Finally, the trend of NIMs was introduced briefly and new NIMs would be created and adopted in applications in the near future.

8984-57, Session PWed

Funneling of millimeter waves through 5-nm gap

Young-Mi Bahk, Ji Yeah Rhie, Dai-Sik Kim, Seoul National Univ. (Korea, Republic of)

In this work, we fabricated an infinite single slit by photolithography and thin film technology. With this method, it is possible to make a few nanometer gap samples, with not only a few millimeter length but also high aspect ratio between metal thickness (h), and gap size (w). We made two kinds of infinite single slits with 10 and 5 nm gap filled with Al_2O_3 on sapphire substrate. The thickness of gold film is 200 nm.

We measured transmitted electric fields through the nanogap samples by using terahertz time domain spectroscopy. We observed that the transmitted electric field increases with decreasing frequency, describing a 1/f dependence. This implies a capacitor-like charging of the nano gap with high aspect ratio of thickness (h)/gap size (w). With this far field measurement, we can estimate near field enhancement by using Kirchhoff integral theorem. It was shown that the field enhancement goes up to 5,000 for 5 nm gap at the frequency of 0.1 THz (intensity enhancement of 25 million).

It is important to investigate the field enhancements for an infinite single slit with non-resonant behavior, where analytical calculations are available, in terms of gaining physical insight and achieving quantitative description of the interaction between millimeter waves with nano sized aperture. Furthermore, the strong electric field through a few nanometer gap can be applied in plasmonics, light focusing and strong light matter interaction.

Conference 8985: Terahertz, RF, Millimeter, and Sub-Millimeter-Wave Technology and Applications VII

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8985-1, Session 1

ErAs:GaAs extrinsic photoconductivity: a new alternative for 1550-nm-driven THz sources *(Invited Paper)*

Matthieu Martin, Elliott R. Brown, Wright State Univ. (United States)

Interest for terahertz (THz) waves has risen dramatically since the advent of ultrafast lasers and optoelectronic components in the 1980s. Today ultrafast photoconductive devices are the most widely used THz sources and are commonly made of low-temperature grown GaAs (LTG-GaAs). An alternative to this material is GaAs doped heavily with ErAs [1]; however, due to the band gap energy of GaAs, the usual optical drive wavelength is around 800 nm. At this wavelength, the only option is to use Ti:Sapphire lasers which are bulky and expensive, or GaAs-based single-frequency diode lasers which have marginal output power and modal quality. Therefore, research currently pushes toward ultrafast photoconductive sources the make use of fiber-optic telecom wavelengths. Indeed, around 1550 nm, femtosecond fiber lasers are powerful, reliable, affordable, and compact. In addition, fiber components for 1550 nm applications are already developed and are fully mature. This paper summarizes our recent progress on the discovery and THz performance of ErAs:GaAs photoconductive devices driven around 1550 nm [2]. We will present the impulse response of such device in a time-domain spectrometer where the detection is realized with a GaAs electro-optic crystal. The full width at half-maximum of the temporal pulse is 500 fs and the corresponding bandwidth is greater than 2.5 THz. We also present different 1550-nm properties of this material including carrier lifetime by pump-probe phototransmission, and carrier polarity and mobility by photo-Hall measurements. All evidence to date suggests that the 1550-nm ultrafast behavior in ErAs:GaAs occurs by extrinsic photoconductivity, not two-photon effect.

[1] J. E. Bjarnason, T. L. J. Chan, a. W. M. Lee, E. R. Brown, D. C. Driscoll, M. Hanson, a. C. Gossard, and R. E. Muller, "ErAs:GaAs photomixer with two-decade tunability and 12??W peak output power," Applied Physics Letters, vol. 85, no. 18, p. 3983, 2004.

[2] J. R. Middendorf and E. R. Brown, "THz generation using extrinsic photoconductivity at 1550 nm," Optics Express, vol. 20, no. 15, p. 16504, Jul. 2012.

8985-2, Session 1

Plasmonic photoconductive terahertz optoelectronics

Shang Hua Yang, University of Michigan (United States) and University of California Los Angeles (United States); Christopher W. Berry, Ning Wang, Mohammad R. Hashemi, Mona Jarrahi, Univ. of Michigan (United States)

Photoconductive sources and detectors are extensively used for generation and detection of terahertz radiation in time-domain and frequency-domain terahertz imaging and spectroscopy systems for various chemical sensing, product quality control, medical imaging, bio-sensing, pharmaceutical, and security screening applications. They consist of an ultrafast photoconductor connected to a terahertz antenna, which is pumped by a pulsed or heterodyning laser illumination for pulsed or continuous-wave terahertz generation/detection, respectively. In spite of their great promise, the inherent tradeoff between high quantum-efficiency and ultrafast operation of conventional photoconductors has significantly limited the output power of photoconductive terahertz sources and detection sensitivity of photoconductive terahertz detectors. Here, we present new designs of photoconductive terahertz sources and detectors that utilize plasmonic electrodes to offer significantly higher terahertz radiation powers and detection sensitivities compared to the state-of-the-art. The use of plasmonic contact electrodes in a photoconductive terahertz source and detector manipulates the spatial distribution of photocarriers and enhances the number of photocarriers in nanoscale distances from contact electrodes significantly, enabling efficient collection of the majority of carriers in a sub-picosecond time scale. It also allows increasing photoconductor active area without a considerable impact on device parasitics, boosting the maximum terahertz radiation power and detection sensitivity by preventing the carrier screening effect and thermal breakdown at high optical pump powers.

8985-3, Session 1

Narrowband continuous-wave terahertz generation and imaging

Brian D. Dolasinski, Peter E. Powers, Univ. of Dayton (United States)

The output of seeded, dual periodically poled lithium niobate (PPLN) optical parametric generators (OPG) are combined in the nonlinear crystal 4-dimthylamino-N-methyl-4-stilbazolium-tosylate (DAST) to produce a widely tunable narrowband THz source via difference frequency generation (DFG). We have demonstrated that by employing this type of configuration we are able to tune our system seamlessly, without mode-hops, from 1.2 THz to 26.3 THz with a minimum bandwidth of 3.1 GHz. The bandwidth of the source was measured by using the THz transmission spectrum of water vapor lines over a 3-meter path length. By selecting of the DFG pump wavelength to be at 1380 nm and the signal wavelength to tune over a range from 1380 nm to 1570 nm, we produced several maxima in the output THz spectrum that was dependent on the phase matching ability of the DAST crystal and the efficiency of our pyro-electric detector. Due to the effects of dispersive phase matching, filter absorption of the THz waves, and two-photon absorption multiple band gaps in the overall spectrum occur and are discussed. Employing the dual generator scheme, we have obtained THz images at several locations in the spectrum using an infrared camera that runs at a rate of 35 frames per second. We have demonstrated the ability to image 2 THz to 26 THz both in static and in real time conditions. We will present images of carbon fibers illuminated at different THz frequencies.

8985-4, Session 1

Nonlinear optical resonators for tunable THz emission

Raju Sinha, Mustafa Karabiyik, Chowdhury Al-Amin, Phani K. Vabbina, Nezih Pala, Florida International Univ. (United States)

We designed and theoretically investigated nonlinear optical micro-ring resonators by exploiting high value of second order optical nonlinearity χ2) in crystals or polymers for tunable terahertz (THz) emission in 1-10 THz range. The lack of tunable THz generator operating at room temperature is still one of the major challenges in the application of THz radiation. Our design is realized based on difference frequency generation (DFG) phenomenon where two narrowband pulses of slightly different frequencies incident upon a non-centrosymmetric crystal can produce an electromagnetic wave of frequency equal to the difference between two input frequencies.

The proposed device on SiO2 substrate in this study primarily consists of two Si optical waveguides coupled to a nonlinear micro-ring resonator for carrying and mixing two near-infrared input waves. For sustaining and guiding the THz field generated in the nonlinear ring, Si THz waveguides of optimized dimension were placed underneath the ring as well as the input waveguides. Phase matching condition is satisfied due to near coincidence of effective indices of fundamental mode at the generated THz and higher order modes of the two incident optical waves. A commercial FDTD simulation tool is employed to investigate the proposed device. The value of nonlinearity was set as 2.5x10^(-17) F/V in the top ring. A generated THz peak is observed in frequency spectrum of electric field in the ring that coincides exactly with the theoretical calculations involving DFG phenomenon. Our device has the potential to be a platform for various tunable compact THz devices.

8985-5, Session 2

Photonic devices for tunable continuous-wave terahertz generation and detection *(Invited Paper)*

Kyung Hyun Park, Namje Kim, Kiwon Moon, Hyunsung Ko, Jeong-Woo Park, Eui Su Lee, Il-Min Lee, Sang-Pil Han, Electronics and Telecommunications Research Institute (Korea, Republic of)

Recently developed semiconductor beating sources, including monolithically integrated dual-mode lasers and low-temperature-grown semiconductor photomixers loaded with broadband antenna show the possibility of the realization of cost-effective terahertz (THz) system. However, a compact continues-wave terahertz line-of-sight system is still demanded to examine terahertz finger prints of specimens without limitations.

In this study, various approaches including traveling-wave photomixers, Schottky barrier diodes, and nano-structured photomixers are investigated to realize high performance THz platforms as the main building blocks of a THz system. Compact and cost-effective photonics technologies for THz system will show the bright future prospects for the real industrial applications.

8985-6, Session 2

Silicon gradient index lens for THz pulse extraction

Sang-Gil Park, Ki-Hun Jeong, KAIST (Korea, Republic of)

For the past few decades, terahertz (THz) technology exploiting a frequency range 0.1-30 THz has attained great advances with development of reliable sources and detectors. However, a lack of diverse THz photonic devices hinder further advances in THz technology. Here, we reports a silicon gradient index (GRIN) lens as a solid immersion lens. A solid immersion lens has been widely used to extract THz pulse from a photo-conductive emitter, because a high-index of the photo-conductive substrate causes substantial loss in a collection efficiency due to total internal reflection. The silicon-GRIN lens consists of sub-wavelength honeycomb structures, whose effective refractive index is precisely controlled by the geometric parameters such as a diameter and a period. As controlling the diameters along a radial direction, parabolic gradient-index profile was achieved with a diameter of 2 mm, thickness of 600 ?m and a focal length of 1.4 mm. The silicon GRIN lens was monolithically fabricated on a silicon wafer by a deep reactive ion etching (DRIE) process. The silicon GRIN lens was mounted on the backside of a dipole-type photoconductive emitter to measure the collection efficiency. The collection efficiency increased in 2 times with mounting the silicon GRIN lens and the radiation angle was modified with the number of the piled lens. In this work, the silicon GRIN lens is simply integrated on the backside of the high-index THz emitter and can open up many opportunities for compact integration of THz imaging and spectroscopic systems.

8985-7, Session 2

A cost-effective terahertz continuous-wave system based on a compact dual-mode laser diode

Han-Cheol Ryu, Sahmyook Univ. (Korea, Republic of); Namje Kim, Kiwon Moon, Sang-Pil Han, Jeong-Woo Park, Hyunsung Ko, Eui Su Lee, Electronics and Telecommunications Research Institute (Korea, Republic of); Min Yong Jeon, Chungnam National Univ. (Korea, Republic of); Kyung Hyun Park, Electronics and Telecommunications Research Institute (Korea, Republic of)

We demonstrate a cost-effective terahertz (THz) continuous-wave (CW) system based on a compact semiconductor dual-mode laser diode (DML). The DML is used for an optical beat source to generate a THz CW. It is composed of two distributed-feedback lasers and one phase section. Two micro-heaters are integrated on the top of each DFB laser to independently tune the two lasing modes from the DML. One phase section is reversely biased to effectively suppress the compound cavity mode within the DML. The characteristics of the generated THz CW are determined by the spectral purity of the optical beat source. The lased spectra from the DML show clear four-wave mixing signals, which means two lasing modes are well correlated and they can generate a high-purity THz photomixing CW. The developed cost-effective THz CW system is composed of one DML, two THz photomixers and an all-fiber optical path to make a simple coherent homodyne THz system. The photomixer was fabricated on the 1.2 μm InGaAs layer grown on SI-InP using a molecular beam epitaxy system. The THz CW system was applied to measure the thickness of a sample; it doesn't need to precisely control the wavelengths of two lasing modes from the DML; it doesn't suffer from the ambiguity of a modulo 2π, which can be a problem in conventional THz thickness measurement system. And its minimum measurable thickness was enhanced by a signal processing technique and the maximum measurable thickness was controlled by changing the wavelengths of the two modes.

8985-8, Session 2

Non-contact thickness and conductivity measurement using a continuous-wave terahertz spectrometer based on a 1.3 ?m dual-mode laser

Kiwon Moon, Namje Kim, Jeong-Woo Park, Sang-Pil Han, Hyunsung Ko, Eui Su Lee, Il-Min Lee, Kyung Hyun Park, Electronics and Telecommunications Research Institute (Korea, Republic of)

We demonstrate a frequency-tunable continuous-wave (CW) terahertz (THz) system based on a 1.3 μm dual-mode laser diode (DML). The DML consists of two distributed feed-back lasers monolithically integrated in a single-cavity with a phase section placed in between for electrical and optical isolation. Two micro-heaters are monolithically integrated on each of the DFB section to thermally control the frequency offset between each DFB laser, which lies in the THz frequency region. By using a photomixer, the optical beating signal from the DML is converted to CW THz radiation. The CW THz radiation is tuned between 230 to 1485 GHz with tuning speed of 30 ms/THz.

In this work, we implemented a fiber-coupled compact homodyne terahertz system using the DML, measured a commercial indium-tin-oxide (ITO) coated glass for a PDP display. In a conventional homodyne CW THz system, the phase difference between the THz beam and

probing optical signal is scanned by a mechanical delay line to obtain a time-domain signal at fixed THz frequency. In contrast, we fixed the mechanical delay line and scanned the THz frequency to measure the broadband conductivity of the ITO layer. Moreover, we developed a noble phase analysis method for thickness measurement of the glass substrate. Utilizing the fast frequency tuning speed, broadband conductivity of the ITO layer and the thickness of the glass substrate was successfully measured in a short measurement time, without using a mechanical delay line. Our work provides prospects for a cost-effective compact THz system for broad industrial application.

8985-9, Session 2

Intense THz supercontinuum generation from metallic thin films with nano-pore-structures

Cunlin Zhang, LiangLiang Zhang, Capital Normal Univ. (China)

Terahertz (THz) spectroscopic sensing and imaging has identified its potentials in a number of areas such as standoff security screening at portals, explosive detection at battle fields, bio-medical research, and so on. With these needs, the development of an intense and broadband THz source has been a focus of THz research. The available methods include optical-rectification process in non-linear crystals, transient current in photo-conductive antennas, strong THz field enhancement in laser induced air plasmas, and THz radiations from metals. In this work, we identified a strong THz emission from metallic thin films with nano-scale surface structures. The metallic film was deposited on an anodic-aluminium-oxide (AAO) membrane with nano-scale pores. The metallic surface therefore also acquired a nano-scale surface roughness. With the optimized design of the metal deposition parameters, we identified that the THz signal generated from this sample is strong (energy conversion rate is ~10^-2) and the frequency spectrum is ultra-broadband (>150 THz). In addition, the measured THz beam bears a Gaussian wavefront. These properties enable a number of possible future applications in remote spectroscopic sensing and imaging.

8985-10, Session 3

Non-contact probes for THz-integrated devices based on fiber-coupled photomixers

Matthieu Martin, Elliott R. Brown, Wright State Univ. (United States)

Full characterization of new THz semiconductor devices and integrated circuits is required for their successful development. However, there is currently a lack of instrumentation capable of characterizing such devices above ~750 GHz. Presently, the most promising approach is either dc-coupled contact probes combined with vector network analysis [1], [2], or electro-optic sampling combined with time-domain spectrometry [3]. Here, we investigate through numerical simulation and analytic design the electromagnetic coupling properties of a novel, contact-free optoelectronic probe that should operate up to 1 THz and beyond. The probes are based on cw photomixing and are designed to transmit and receive THz waves propagating along a coplanar waveguide (CPW) containing a device-under-test (DUT). The coupling to and from the DUT CPW occurs through near-field, polarization-current coupling utilizing the high dielectric constant and low absorption in the semi-insulating semiconductor substrate of the probe. In the receiver the polarization current is converted to conduction current by a modal transformation from dielectric waveguide to quasi-TEM CPW. The signal in the CPW is then down-converted to baseband by a monolithically integrated, fiber-coupled, unbiased THz photomixer connected to a transimpedance amplifier and driven by a pair of frequency-offset single-frequency diode lasers. The transmitter operates in a reciprocal fashion, but must be dc-biased. Two kinds of designs have been investigated: a broadband design that performs up to 1300 GHz with coupling exceeding -27 dB over 1 THz, and a narrow band design showing a coupling better than -20 dB over a range of 100 GHz.

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8985-11, Session 3

Terahertz emission in organic crystals pumped by conventional laser wavelength

Carlo Vicario, Balazs Monoszlai, Paul Scherrer Institut (Switzerland); Blanca Ruiz, Mojca Jazbinsek, Carolina C. Medrano, Rainbow Photonics AG (Switzerland); Christoph P. Hauri, Paul Scherrer Institut (Switzerland)

The optical rectification in organic salt materials permits the realization of extremely intense and broadband terahertz electro-magnetic fields. These nonlinear materials combine in fact low absorption at terahertz frequency and among the highest nonlinearity for optical rectification.

Efficient velocity matching between high intensity terahertz pulses and ultrashort laser is typically achieved using mid-infrared pump wavelengths between 1.3 and 1.5 microns.

In this near infrared spectral range intense femtosecond pump sources are hardly available. Here we present results on powerful terahertz generation by using DAST, DSTMS, OH1 and other organic crystals combined with the widely used and well established Ti:sapphire laser technology, emitting at 0.8 microns. This approach enables straightforward terahertz generation by optical rectification and opens new opportunities in the femtosecond laser community. We present systematic studies on terahertz conversion efficiency, spectral and temporal terahertz characteristics, crystal damage threshold and maximum achievable field strengths.

8985-12, Session 3

Generation of broadband THz pulses (1-14 THz) with organic crystal DSTMS pumped by compact fs fiber lasers

Mojca Jazbinsek, Blanca Ruiz, Carolina C. Medrano, Peter Günter, Rainbow Photonics AG (Switzerland)

THz generation using nonlinear optical effects in organic crystals has unique advantages compared to inorganic alternatives: high figures of merit for THz generation using various fs–ns pump laser sources in the infrared, as well as a very broad THz frequency range, which is because of the possibility for phase matching between pump optical and the generated THz waves in the region between 0.1–20 THz. We investigate THz interactions using recently developed materials, stilbazolium salt DSTMS* and phenolic polyene OH1*, which have advantageous properties for THz-wave generation compared to the more commonly used DAST* crystals.

Using THz time-domain spectroscopy we have measured the optical properties of DSTMS, OH1 and DAST in the extended THz range up to 12 THz. Best phase-matching parameters of these materials for pump optical wavelengths in the range of 700–1700 nm and for THz frequencies in the range of 0.1–12 THz have been determined based on these data. The results allow for the prediction of the optimal crystal configuration and thickness for broadband THz generation and detection using either optical rectification (OR) or difference-frequency generation (DFG) nonlinear optical processes. We demonstrate efficient generation and coherent detection of very broadband THz pulses (1–14 THz) using DSTMS, pumped by fs fiber lasers at telecommunication wavelengths, and show their use for THz time-domain spectroscopy, imaging and material testing in a compact system with a very broad THz frequency range up to 14 THz.

*DSTMS (4-N,N-dimethylamino-4'-N'-methyl-stilbazolium 2,4,6-trimethylbenzenesulfonate);

DAST (4-N,N-dimethylamino-4'-N'-methyl-stilbazolium tosylate);

OH1 (2-(3-(4-hydroxystyryl)-5,5-dimethylcyclohex-2-enylidene) malononitrile).

8985-13, Session 3

Direct observation of terahertz photoluminescence from multi-layer epitaxial graphene on SiC under excitation by a mid-IR quantum cascade laser

Peter Q. Liu, Giacomo Scalari, Federico Valmorra, Curdin Maissen, Sabine S. Riedi, ETH Zurich (Switzerland); Alfredo Bismuto, ETH Zurich (Switzerland) and Alpes Lasers SA (Switzerland); Jérôme Faist, ETH Zurich (Switzerland)

Direct photoluminescence (PL) measurements on multi-layer epitaxial graphene on SiC are conducted using a quantum cascade laser (QCL) emitting at ~10.4 µm as the excitation source which corresponds to an excitation energy of ~120 meV, significantly below the graphene optical phonon energy (~196 meV) in order to suppress the fast carrier relaxation induced by optical phonon scattering. The QCL is operated in pulsed mode with 500 kHz repetition rate and 130 ns pulse length which is much larger than the timescale of any photo-excited carrier dynamics. Several graphene samples with numbers of layers varying from 20 to 70 are characterized and show similar results. Relatively strong PL signal in terahertz (THz) spectral range is observed from 7 K (lowest measurement temperature) up to room-temperature. The peak of THz PL spectrum at 7 K is around 6 meV (~1.5 THz) and shifts to higher energy with increasing temperature. The THz PL intensity changes almost linearly with the pump power and decreases considerably with increasing temperature. At 7 K and peak pump power of ~1 W, ~0.5 nW THz PL is observed, corresponding to an external quantum efficiency of ~2x10-7 when taking into account the collection efficiency. When placing a neodymium magnet behind the graphene samples (not in direct contact) to introduce a perpendicular magnetic field of ~0.35 T, the THz PL intensity is enhanced by ~30% with slight spectral blueshift. For comparison purpose, same measurements are conducted on SiC substrate and Kish graphite samples, but no such THz PL is observed.

8985-14, Session 3

Confinement loss scaling law analysis in tube lattice fibers for terahertz applications

Masruri Masruri, Univ. degli Studi di Parma (Italy); Luca Vincetti, Univ. degli Studi di Modena e Reggio Emilia (Italy); Carlo Molardi, Univ. degli Studi di Parma (Italy); Enrico Coscelli, Annamaria Cucinotta, Stefano Selleri, University of Parma (Italy)

The development of low loss, small size and flexible waveguides is one of the most challenging issues of THz research due to the poor characteristics of both metal and dielectrics in this frequency range. Hollow core tube lattice fibers (HC-TLFs) have been recently proposed and experimentally demonstrated to overcome this problem. They are composed of a hollow core surrounded by an array of dielectric tubes. The first prototypes made of polymethylmethacrylate tubes have shown that propagation loss can be significantly reduced with respect to the bulk material one. However, the performance of this kind of fibers requires further optimization. In particular the detrimental effect of the material absorption requires very big hollow core radius leading to big and hardly flexible fibers. Scaling law analysis plays an important role in determining the best trade-off between low loss and small size. The scaling law of the propagation loss in terms of frequency, core radius and tube size are here both theoretically and numerically investigated. The general expression of the loss dependence on core size and frequency is obtained. Results show that propagation loss exhibits a stronger dependence of core size and frequency with respect to other hollow core fibers proposed for THz waveguiding such as, Bragg, Tube, and Kagome fibers. Solutions to reduce the fibers size without affecting propagation loss are also proposed.

8985-15, Session 4

Epitaxial graphene devices: improving performance through materials and design optimization *(Invited Paper)*

Joshua A. Robinson, The Pennsylvania State Univ. (United States)

Graphene exhibits high charge carrier mobility and saturation velocity, making it a promising candidate for radio frequency (rf) applications. However, one of the key limitations to the realization of graphene's full potential comes from its interaction with dielectric over layers and metal contacts, which act to limit the excellent charge transport properties of graphene. I will discuss the importance of buffer elimination at the graphene/SiC(0001) interface, developed of a robust method for forming high quality ohmic contacts, and methods for ultra-thin gate oxides. Each of these developments have provided a means to achieve graphene transistors with current saturation values >1.5 A/mm, transconductance > 400mS, impressive extrinsic current gain response of epitaxial graphene transistors (>30 GHz). Additionally, I will discuss the impact of nanoribbon fabrication on the performance of graphene FETs, and show significant improvement in performance as devices are scaled. Finally, the performance of a graphene mixer will be discussed and evidence is provided that matched graphene mixers can outperform current state-of-the-art technologies.

8985-16, Session 4

Optical design for translation of THz medical imaging technology *(Invited Paper)*

Zachary D. Taylor, Univ. of California, Los Angeles (United States)

This talk presents novel THz optical designs intended to overcome numerous practical problems face when imaging animal models and patient volunteers. Current THz medical imaging research typically employs and fixed source detector architecture where the sample of interest is flattened by a window and scanned beneath a fixed THz beam. The window flattens the tissue an provides a specular target to the system thus reducing the contribution of rough surface scattering and curved surface reflection to the observed image contrast. While data acquired with target scanning and field flattening windows have generated significant interest from the medical community, these system methodologies have proven difficult to translate to large animals and preliminary trials where translation and window contact is either impractical or impossible. In this talk we discuss optical designs that mitigate the effects of non-specular reflection and enable high speed, efficient beam scanning. Imaging results in characterization targets and animal models are presented.

8985-17, Session 4

High-speed and broadband RF spectrum analyzer based on spectral hole burning in rare-earth-ion doped crystal

Perrine Berger, Loïc Morvan, Daniel Dolfi, Thales Research & Technology (France); Héloise Linget, Anne Louchet-Chauvet, Thierry Chanelière, Lab. Aimé Cotton (France) and Univ. Paris-Sud 11 (France); Jean-Louis Le Gouet, Univ. Paris-Sud 11 (France) and Lab. Aimé Cotton (France)

We investigate a large bandwidth / high resolution RF spectrum analyzer, based on spectral hole burning in rare-earth-ion doped crystal. In order to be compatible with electronic warfare applications, our demonstrator is designed to reach a large instantaneous bandwidth (20GHz), and the captured signals should be processed within a few microseconds.

For this purpose, we chose the rainbow architecture with a Tm^{3+}:YAG crystal, operating at 793nm: two beams engrave spectrally multiplexed Bragg gratings in the crystal, whose spectral selectivity is determined by the width of one rare-earth-ion. These gratings convert spectral content to spatial angle information and are used to filter one of the sidebands of optically carried microwave signals.

We previously demonstrated a 100-channel spectrum analyzer with a 3.3GHz bandwidth. The crystal was inserted into a 5K helium bath cryostat.

In order to increase the bandwidth and the resolution of the analyzer, we accomplish the fast and high repeatability frequency and angular scans of the engraving beams by using fast scanning DFB lasers and stable mechanical beam scanners. We also worked towards an easier future implementation into naval systems, in particular by using a closed-cycle cryostat.

Experimentally, fast and high repeatability 20GHz-wide frequency scan have been synchronized with a 200mrad-broad angular scan. This set-up is able to discriminate more than 400 angular channels, and each single channel offers less than 20MHz spectral width.

We will present at the conference a RF spectrum analyzer with 400 channels distributed over a 20GHz bandwidth with a temporal resolution in the microseconds range.

8985-18, Session 4

10,000-fold field-enhancement for millimeter-wave transmission through one-nanometer gaps

Sanghoon Han, Young-Mi Bahk, Namkyoo Park, Dai-Sik Kim, Seoul National Univ. (Korea, Republic of)

Electromagnetic field enhancement of metal slit structure is investigated at THz frequency. Dependencies of field enhancement on slit width and thickness are calculated by modal expansion method for perfect electric conductor (PEC) approximation and numerical finite difference time domain (FDTD) method for real Au parameter. The width and thickness range from 1 nm to 1000 nm. We restrict our discussion to the classical regime. Field enhancement increases as slit width and thickness decrease, and converges into a specific value. It is also found that slit thickness as well as width has a large influence on field enhancement when the width becomes small. Field enhancement factors of 10,000 can be achievable with 1 nm gap. The difference between field enhancement of PEC slit and that of Au slit occurs only when the thickness is less than 5 nm. This difference comes from reduction of induced current by direct transmission through very thin Au film to which the field enhancement is attributed.

A model based on charge and capacitor concept is also proposed to explain the dependencies. In this model, it is assumed that all charges exist at metal surfaces and charge distributions have the form of Ax^(-p), where p is the only fitting parameter. According the model field enhancement of metal slit structure is due to current-induced charge accumulation and its saturation tendency is related to charge distribution on the slit surfaces. It can be thought that small width and thickness make the charge density on the side end of the slit large but dense charges also experience repulsive forces which disperse the charges. The results from each method and the model are in good agreement.

8985-19, Session 4

Terahertz polarization imaging for colorectal cancer detection

Pallavi Doradla, Univ. of Massachusetts Lowell (United States); Karim Alavi, Univ. of Massachusetts Medical School (United States); Cecil S. Joseph, Robert H. Giles, Univ. of Massachusetts Lowell (United States)

Colorectal cancer is the third most commonly diagnosed cancer in the world. The current standard of care for colorectal cancer is the conventional colonoscopy which relies exclusively on a physician's experience. The terahertz (THz) frequency range, located midway between the microwave and infrared region, is non-ionizing and has high sensitivity to water content. In this study, we show that continuous wave terahertz imaging has the ability to offer a safe, noninvasive medical imaging modality for delineating colorectal cancers and shows promise as an additional tool to aid in colorectal cancer screening.

The terahertz reflection measurements of fresh 3 ? 5 mm thick human colonic excisions were acquired using a continuous-wave polarization imaging technique. A CO_2 pumped Far-Infrared molecular gas laser operating at 584 GHz was used for illuminating the tissue, while the reflected signals were detected using a liquid Helium cooled silicon bolometer. Using polarizers in the experiment both co-polarized and cross-polarized remittance form the samples were collected. Consequently, obtained cross- (co-) polarized terahertz images showed intrinsic contrast between cancerous and normal regions based on increased reflection from the tumor 0.65 % (19.28 %) instead of 0.55 % (17.13 %). Also, our results demonstrate that the cross-polarized terahertz images not only correlates better with the histology, but also provides consistent relative reflectance difference values between normal and cancerous regions for all the measured specimens. The data and results will be presented and discussed during SPIE conference.

8985-20, Session 5

Terahertz plasmonic waveguide sensing based on metal rod array structures

Borwen You, National Taiwan Univ. (Taiwan) and National Cheng-Kung Univ. (Taiwan); Chien-Chun Peng, Ja-Yu Lu, National Cheng Kung Univ. (Taiwan); Hungh-Hsuan Chen, Jia-Shing Jhang, Chin-Ping Yu, National Sun Yat-Sen Univ. (Taiwan); Tze-An Liu, Jin-Long Peng, Industrial Technology Research Institute (Taiwan); Chi-Kuang Sun, National Taiwan Univ. (Taiwan) and Academia Sinica (Taiwan)

Transmission properties of metal rod arrays are successfully characterized in terahertz spectroscopy using the parallel-plate-metal-waveguide configuration. The spectral loss of the guided waves is distinct for different polarizations according to the rod axis. For transverse-electric polarized waves, there is obvious cut-off frequency with high-pass spectral features and strongly dependent on the lattice constants of the metal-rod-array. The measured modification of cut-off frequency is able to approximate 100GHz per 100um-variation of lattice constant, but the transmittance of the passed waves is restricted in two-row structure. Based on the integration of the metal-rod-array with a fluidic channel in the parallel-plate-metal waveguide, liquid drops can be spread on the

metal-rod-array surface as liquid layers to change the transmittance of the high-frequency-passed terahertz waves. Different volatile liquids are recognized from the evaporated layers in dynamic detection in which the minimum detectable molecule quantity can be decreased about 140 ?mole. For transverse-magnetic polarized waves, there are rejection bands in the transmission spectrum following Bragg-diffraction principle owning the best distinction ratio of 23dB, also depending on the lattice constants of the metal rod array. For the transmitted transverse-magnetic waves, 30-row structure can be used as a dielectric slab waveguide without parallel-metal-plate to bind electromagnetic field along the metal-rod-array. Tailoring the lattice constant not only determines the deliverable terahertz frequencies but also the field confinement at the interface of air-metal rod array. Using the bound terahertz waves is able to detect nano-thin film around ?/1923-thickness via the observation of phase retardation for the guided terahertz waves.

8985-21, Session 5

Doping profile recognition in silicon using terahertz time-domain spectroscopy

Chih-Yu Jen, Christiaan Richter, Rochester Institute of Technology (United States)

This work studies the prospect of utilizing transmission mode terahertz time domain spectroscopy (THz-TDS) to distinguish doping profile discrepancies in silicon for semiconductor and photovoltaic industry applications. Non-destructive and fast measurements are major advantages of this approach. Several boron and phosphorus doping profiles with junction depth comparable to PV junctions were fabricated on p-type wafers. THz radiation, which have a strong interaction with free carriers, gets more attenuated under higher implant dosages and longer diffusion drive-in time corresponding to higher surface concentrations and deeper junction depths. The terahertz interaction with both electrons and holes are strong enough so that doping profile differences in both N and P type junctions could be identified. Differences between boron and phosphor drive-in time and doping profiles will be discussed. The ability to distinguish between junction depths, and the accuracy thereof, was studied by repeated measurement. The ability to do measurements on commercial mc-Si wafers for solar cells at various stages of production including after surface texturing was also investigated.

8985-22, Session 5

Widening the span of GHz spacing optical frequency comb by increasing the pulse-shortening rate in RHML fiber lasers

Tianxin Yang, Yuchen Zhang, Tianhe Wang, Tianjin Univ. (China); Guifang Li, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Optical frequency combs (OFCs) with high frequency spacing (e.g., 10 to 1000 GHz) are desirable for a number of applications, however generating these signals is challenging with conventional passive mode-locked laser-based OFCs due to the necessity of a short cavity length. Recently there have been many efforts on the development of integrated photonic microchip devices for OFC sources which can deliver large optical frequency component spacing, narrow optical line width, and excellent RF phase noise and stability with small footprints, high electrical efficiency, and ease of use[1-2]. However these devices have not been used in practical systems due to their low output power and delicate fabrication techniques. It is not difficult to realize a moderately high output power at a high pulse repetition rate (PRR) of tens of GHz in an active mode-locked laser without any specific confinement on the cavity length. In general, the span of a GHz-spacing OFC coming from a purely active mode-locked fiber laser is only about 0.2 ~ 0.4 nm at 1550 nm which is not wide enough to cover more than a few (e.g., 3 to 5) comb frequency components. For a 10 GHz-spacing frequency comb, the wavelength difference between the contiguous comb teeth is about 0.08 nm at the center of 1550 nm. It has been demonstrated that the span can be increased by nearly 10 times by introducing a so-called soliton pulse-shortening mechanism into an active harmonic mode-locked (HML) fiber lasers [3]. In this paper we report on the improvements to widen the span further by driving an electro-optic modulator in a cavity of an active rational harmonic mode-locked (RHML) fiber laser with a square waveform instead of conventional sinusoidal RF signals. Our simulation results show that the curvature of the transmission of the modulator is crucial to increase the pulse-shortening rate for each pulse passing through the modulator. Finally, it can be demonstrated experimentally that the additional pulse-shortening mechanism can result in the span of GHz frequency comb being wider and more stable.

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8985-23, Session 5

Innovative evaluation methods for terahertz-spectra by combining different chemometric tools

Frank Ellrich, Daniel Molter, Joachim Jonuscheit, Georg von Freymann, René Beigang, Fraunhofer-Institut für Physikalische Messtechnik (Germany); Frank Platte, Konstantinos Nalpantidis, IANUS Simulation GmbH (Germany); Thorsten Sprenger, Daniel Hübsch, HÜBNER GmbH (Germany)

Many crystalline substances like explosives, drugs or chemicals can be identified using terahertz time-domain spectroscopy. In most publications the samples have been measured in optimal conditions in order to obtain undistorted spectra. However, in real-world applications the spectra are additionally influenced by several effects. Especially, when used for the identification of hidden objects the substances may be covered by barriers like paper or cardboards. Therefore, a reliable method for the automatic identification of those real-world spectra has to be developed.

Here, we combine different chemometric methods for the extraction of information from terahertz measurements. These chemometric methods are known from the evaluation of infrared spectra, but have to be adapted to the specific features of terahertz spectra. It is very important to apply appropriate mathematical algorithms to pre-process the raw data. Using raw data only would lead to unacceptably large values of „false positives" and „false negatives".

We demonstrate that the data pre-processing and the combination of different chemometric methods are essential for the discrimination of the measurements in several multidimensional so-called "feature rooms". Based on such a reliable mathematical model, methods of pattern recognition can be used for automatic identification of substances. We have successfully implemented this technique in our terahertz spectrometer to achieve the powerful postal mail inspection system T-Cognition. A reliable operation demands not only high values of true positives but also for low values of false positives. Therefore we have intensively tested our classification and detection algorithms with samples that have not been in the databases.

8985-24, Session 6

Design and engineering of organic molecules for customizable terahertz tags

Bala Pesala, CSIR - Central Electronics Engineering Research Institute (India); Shaumik Ray, Central Electronics Engineering Research Institute (India); Jyotirmayee Dash, Kathirvel Nallappan, CSIR - Central Electronics Engineering Research Institute (India); Vaibhav Kaware, Nitin Basutkar, Ashootosh Ambade, Kavita Joshi, CSIR - National Chemical Lab. (India)

Terahertz (THz) frequency band lies between the microwave and infrared region of the electromagnetic spectrum. Molecules having strong resonances in this frequency range are ideal for realizing Terahertz tags which can be easily incorporated into various materials. These THz tags find novel use in various counterfeiting applications such as detection of fake currency notes, security documents and counterfeit pharmaceutical drugs.

THz spectroscopy of molecules, especially at frequencies below 5 THz, provides valuable information on the low frequency vibrational modes, viz. intermolecular vibrational modes, hydrogen-bond stretching, torsional vibrations in several chemical and biological compounds. So far there have been very few attempts to engineer molecules which can demonstrate customizable resonances in the THz frequency region.

In this paper, we present significant results towards the design and engineering of organic molecules with resonances in the THz region. First, we have characterized more than 50 candidate molecules which show several strong THz resonances. Density Functional Theory (DFT) simulations have been carried out to understand the origin of these THz resonances. Further, several isomers have also been studied to understand the potential of fine-tuning the THz resonances by rearranging the relative position of atoms in a molecule. Based on this detailed study, two generic principles arise for the design of THz molecules:

i. Molecules having hydrogen bonds or molecules with low frequency intra-molecular/inter-molecular bending/torsional modes.

ii. Molecules with large mass.

Similar to spring-mass resonance system analogy, the design principles listed above implies requirement of relatively weak resonances i.e. resonances with low spring constant and molecules with large mass, both contributing to low frequency THz resonances. Using these principles, we have designed and fabricated several diamidopyridine (DAP) based binary molecular complexes with varying mass and hydrogen bond strengths, demonstrating several resonances below 3 THz. The design approach presented here can be easily extended to engineer various organic molecules suitable for THz tags application.

8985-25, Session 6

Terahertz spectroscopy of concrete for evaluating the critical hydration level

Bala Pesala, Jyotirmayee Dash, CSIR - Central Electronics Engineering Research Institute (India); Shaumik Ray, Central Electronics Engineering Research Institute (India); Kathirvel Nallappan, CSIR - Central Electronics Engineering Research Institute (India); Saptarshi Sasmal, CSIR - Structural Engineering Research Ctr. (India)

Concrete, a mixture of cement, rock aggregate, sand and other filler materials, is widely used in the construction industry. Cement is a complex mixture of the clinkers such as Tricalcium Silicate (C3S), Dicalcium Silicate (C2S), Tricalcium Aluminate (C3A), Tetracalcium Aluminoferrite (C4AF) and Gypsum. During hydration, Cement reacts with water to form hardened cement paste which is mainly composed of Calcium Silicate Hydrate (C-S-H), Calcium hydroxide, unreacted cement and pores. C-S-H is the primary composite which determines the strength of the concrete structure.

Degree of hydration of cement in concrete structures needs to be carefully optimized since due to inadequate hydration, either unreacted cement will be present in the hydrated paste which is unwanted, or excessive water will still remain which would cause pores inside the concrete structure. To quantify the critical degree of hydration, a non-intrusive technique is highly desired. However, conventional techniques such as Near-Infrared (NIR) imaging have low penetration depth and hence cannot easily determine the hydration level of thicker concrete samples. This paper describes a promising approach using Terahertz spectroscopy to quantify and optimize the level of hydration of cement paste which would ensure the production of maximum amount of C-S-H.

Terahertz spectroscopy is a promising technique for evaluating the water content as THz rays can pass through concrete structures and water has strong absorption in this frequency region. In this paper, we have used terahertz spectroscopy to evaluate the hydration levels of cement and concrete structures using lower frequency THz waves (< 500 GHz) and demonstrate how the hydration level changes with time. Further, the chemical constituents of the hardened cement are detected using higher frequency THz waves (> 2 THz). This study will help in developing methodologies for estimating the degree of hydration and formation of C-S-H which will lead to better and effective usage of cement in the construction industry.

8985-26, Session 6

Compact and reconfigurable fiber-based terahertz spectrometer at 1550 nm

Alireza Zandieh, Daniel M. Hailu, David Biesty, TeTechS Inc. (Canada); Armaghan Eshaghi, Ehsan Fathi, TeTechS Inc (Canada); Daryoosh Saeedkia, TeTechS Inc. (Canada)

In this paper, we present a new compact and versatile spectrometer system operating at 1.55 µm for research and industrial application. The system is capable of testing solid, powder, thin film, gas, and liquid samples for material sensing and characterization applications. A high efficient system with bandwidth up to 3THz is realized by using recently developed high resistive ultra-fast epitaxially grown multi-quantum well InGaAs-InAlAs substrates which is packaged in terahertz chip enclosure module.

The key components are the fiber-coupled THz transmitter and receiver modules, where the laser beam is directly coupled to the THz chip using optical fibers to provide stable and movable transmitter and receiver heads. The antennas are excited by 100fs optical pulses at 1550nm and average power of 10mW. As femtosecond pulses are required on the antenna, the linear dispersion and nonlinear effect resulting from the propagation of the high power optical pulse along the fiber are taken into account and compensated using dispersion compensation fiber.

A fast scan optical delay module is employed to realize real-time THz signal and spectrum measurement. It uses a fast moving retro-reflector mirror to scan THz pulses. The optical delay module also has a long delay scan unit to allow the user to adjust the distance between the transmitter and receiver heads by up to 1m to use the system for characterization of materials in different industrial applications. For small pellet samples of D-Tartaric acid, the THz spectrometer is used to obtain the spectral signature through a transmission mode measurement module.

8985-27, Session 6

Terahertz selective and reversible volatile vapor detection using micro-porous polymer structure

Ja-Yu Lu, National Cheng Kung Univ. (Taiwan); Borwen You, National Taiwan Univ. (Taiwan); Cheng-Han Ho, National Cheng Kung Univ. (Taiwan)

Vapor sensors become essential in industry, medical science, and environmental protection for toxicity of volatile gas in biology and achieving better quality life. For decades various methods for sensing volatile gas with high sensitivity and selectivity have been developed. One method is based on precisely measuring spectral fingerprints of analytes using optical systems, such as the long path THz time-domain spectroscopy. The method is limited on its bulky and complex system, and extremely long interaction length (>5m) is necessary for a high sensitivity. The other gas sensing method is based on various active or passive devices with resonant structures such as photonic crystals and pipe waveguides. The method enables to detect extremely low refractive index change of minute gas molecules, but it is difficult in room-temperature operation. An alternative means to realize a compact and highly sensitive gas sensor is based on different optical porous structures. The porous device has sponge-like structure with a large internal surface-to-volume ratio enables to adsorb large amounts of chemical or biological substances into the pores to modify the electrical and optical properties of device for sensitive detection. In this presentation, a simple multilayer micro-porous structure has been experimentally demonstrated in THz frequency range for identifying different types and concentrations of vapor molecules. The measured minimum concentration is achieved 9 ppm, corresponding to molecular density variation of 0.16 nano-mole/mm^3, which is highest compared with other resonant type devices in THz frequency range.

8985-29, Session 7

Broadband monopole optical nano-antennas

Rongguo Zhou, Jun Ding, Bayaner Arigong, Univ. of North Texas (United States); Shihua Cao, Hangzhou Normal University (China); Yuankun Lin, Hualiang Zhang, Univ. of North Texas (United States)

At optical frequencies, optical waves are usually re-directed using components such as mirrors and lens for signal receiving and transmitting. However, this type of wave manipulation method cannot be used to control fields on sub-wavelength scale because of wave diffraction. Recent progress in nanotechnology and plasmonics technology has generated considerable interest in optical antenna concept, which can efficiently overcome the diffraction limit and make it possible to manipulate optical fields in nanometer scale. The optical nano-antennas can increase the efficiency of light-matter interacting leading to a wide range of applications, such as improving nanoscale imaging and spectroscopy resolution, increasing photodetecting speed, and enhancing LED (light-emitting devices) energy efficiency, etc. Given their wide applications, the investigations in optical antennas are still in the infancy phase. Only a few nano-antenna configurations are demonstrated, such as dipoles, bow-ties and Yagi-Uda. In this paper, we propose a novel monopole optical antenna with broad operating bandwidth. It features a planar configuration with corrugated elliptical patch inside an elliptical aperture. Various parametric studies of the antenna are performed to reveal the impacts of different parameters on the performance properties of these antennas. The optimized optical antenna demonstrates a broad bandwidth and significant field enhancement of more than 4000. It can effectively confine the incident radiation within a region on sub-wavelength scale. The proposed broadband optical antenna could be attractive for applications such as plasmonic solar units, biomedical sensing, and wideband photodetecting.

8985-30, Session 7

Ultrabroadband phased-array electronic warfare (EW) receivers based on optical techniques

Brock M. Overmiller, Christopher A. Schuetz, Garrett J. Schneider, Janusz A. Murakowski, Dennis W. Prather, Univ. of Delaware (United States)

The modern electronic battlefield is becoming an ever more crowded place resulting in rapidly increasing demands on modern electronic warfare (EW) receivers. Military operations require the ability to locate and identify electronic emissions in the battlefield environment. However, recent developments in RADAR (radio detection and ranging) and communications technology are making it harder to effectively identify such emissions. Using phased array systems aid in discriminating emitters in the scene by virtue of their relatively high-gain beam steering and nulling capabilities. To this end, we present an approach to realizing a broadband receiver for the location and identification of microwave and millimeter-wave emitters based on optical processing of low SWaP (size, weight, and power) distributed conformal antenna arrays. This approach utilizes photonic techniques that enable us to capture, route, and process the incoming signals. Optical modulators convert the incoming signals up to and exceeding 110 GHz with appreciable conversion efficiency and fiber optics route these signals to a central processing location. This central processing location consists of a closed loop phase control system which compensates for phase fluctuations induced in the fibers due to thermal or acoustic vibrations and enables spatial separation and imaging of emissions within the sensor field of regard. Additionally, an optical heterodyne approach is used to directly downconvert received signals in the optical domain enabling broadband electronic and signals intelligence to be performed. Preliminary testing of electronic emissions has been performed demonstrating the geolocation and frequency identification capabilities of our EW receiver.

8985-31, Session 7

Nb5N6 microbolometer array for a compact THz imaging system

Xuecou Tu, Qingkai Mao, Cao Wan, Nanjing Univ. (China); Lei Xu, Nanjing University (China); Lin Kang, Jian Chen, Peiheng Wu, Nanjing Univ. (China)

A novel Nb5N6 microbolometer integrated with micro diffractive lens array (MDLA) for terahertz wave detecting is described in this paper. Each detector in the array consists of an Nb5N6 thin film microbolometer, a dipole planar antenna and a five staircases micro diffractive lens made by Si material. The Si MDLA greatly improved the coupling efficiency of the incident power into the Nb5N6 microbolometers. We compared the voltage responsivity of the Nb5N6 microbolometer with or without micro diffractive lens. A more than 30 times larger voltage response was observed in the Nb5N6 microbolometer with micro diffractive lens. In order to demonstrate the excellent performance, Nb5N6 microbolometer with MDLA was applied to a large-area fast imaging system. The image shows a very good spatial resolution. These results show that Nb5N6 microbolometer array with MDLA are good candidates for room temperature focal plane arrays for THz detection and imaging.

8985-32, Session 7

High-performance room-temperature THz nanodetectors with a split ring antenna

Leonardo Viti, Scuola Normale Superiore (Italy); Daniele Ercolani, Scuola Normale Superiore (Italy); Dominique Coquillat, Univ.

Montpellier 2 (France) and Ctr. National de la Recherche Scientifique (France); Wojciech Knap, Univ. Montpellier 2 (France) and Ctr. National de la Recherche Scientifique (France); Lucia Sorba, Miriam S. Vitiello, Scuola Normale Superiore (Italy)

The fast and reliable detection of radiation at THz frequencies represents an important issue for a full exploitation of THz technology. Very recently, THz detection in InAs nanowires (Nw) field-effect transistors (FET) has been reported [1,2]. Due to their reduced size, these systems offer a very large cut-off frequency together with the possibility to be arranged in matrix arrays for imaging application across the far-infrared.

The extreme flexibility with which InAs nanowires can be grown allowed us to select a set of high electron mobility nanowires (2000 cm2/Vsec) which have shown good detection performances up to 2.8 THz.

We report on the development of a novel class of nanowire-based THz detectors in which the field effect transistor is integrated in a split-ring narrow-band antenna. When the THz field is applied between the gate and the source terminals of the FET, a constant source-to-drain photovoltage appears as a result of the non-linear transfer characteristic of the transistor. In order to achieve attoFarad-order capacitance we fabricate lateral gate FET with gate widths smaller than 100 nm.

Our devices show a maximum responsivity of 110 V/W without amplification, with impressive noise equivalent power levels ≤ 0.1 nW/√Hz at room temperature. The frequency noise spectral density shows a flattening to the white noise level at frequency of about 10 kHz.

The detection scheme provided by the split-ring resonant antenna opens a path to novel applications of our technology to metrology, spectroscopy and homeland security. Moreover the possibility to extend this approach to relatively large multi-pixel arrays coupled with THz sources makes it highly appealing for a future generation of THz detectors.

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8985-33, Session 7

Extraction and accuracy control of optical parameters for materials by terahertz time-domain spectroscopy signal

Dongxiong Ling, Dongguan Univ. of Technology (China)

Material optical parameters are extracted by use of terahertz time-domain spectroscopy signal and extraction accuracies are controlled and validated. It is shown from the research results that terahertz time-domain spectroscopy better response of the optical parameters of materials, as long as the use of appropriate methods, and good control of calculation accuracy, material optical parameters can be obtained more accurately than the other test methods to meet the actual requirements for material analysis.

8985-34, Session 7

Possibilities to make the panoramic receiver-frequencymeter in terahertz band at the base of Josephson junctions

Alexander Denisov, State Research Ctr. of Superconductive Radioelectronics - Iceberg (Ukraine); Jing hui Qiu, Harbin Institute of Technology (China)

At the base of previous theoretical and experimental investigation there proposed and described the idea about examined possibility to do the super wide panoramic receiver–frequencymeter (PRF) on the Josephson junctions (JJ). It can be especially convenient for the experimental purposes with new generation structures when radiative power is small and frequency are unknown correctly. This proved by two devices based on the JJ. First one is the receiver based in self-pump mode regime of JJ and second one is the using JJ as the way for the frequency measurement by the super wide frequencymeter.

1.INTRODUCTION

The self-pump mode regime on JJ as the variety of heterodyne detection methods. This regime was proved before by the published experimental and theoretical results and it were realized some patented (priorities of USSR) ideas during former world boom and “rushing” to come first in the realization and commercialization HTSC. At the base of the former experience after stock-jobbing HTSC boom, but new springing up boom concerning TERA as new field of the critical technologies, including Josephson media (JM) the thought occurred to propose our technical idea as possible decision for creation Panoramic Receiver - Frequencymeter (PRF) on JJ.

2. BACKGROUND

Strictly speaking it is necessary to use for the job two devices combined in one instrument (PRF): the first one - the sensitive receiver based on the JJ working in self-pumping regime and second one - frequency meter based on the same JJ working as the measuring instrument (criterion) according to 2eV= h?. Both devices were produced separately many years ago, so just know in accordance with the arisen thought it is reasonable to repeat briefly the main and principal parts of both their technical descriptions which concern the essence of the suggested complicated task.

8985-55, Session PWed

Continuous wave terahertz radiation using frequency-swept optical beat source

Yong Seok Kwon, Byeong Kwon Choi, Myeong Ock Ko, Chungnam National Univ. (Korea, Republic of); Sang-Pil Han, Namje Kim, Electronics and Telecommunications Research Institute (Korea, Republic of); Han-Cheol Ryu, Sahmyook Univ. (Korea, Republic of); Kyung Hyun Park, Electronics and Telecommunications Research Institute (Korea, Republic of); Min Yong Jeon, Chungnam National Univ. (Korea, Republic of)

We have been successfully demonstrated a continuous wave terahertz (THz) radiation based on a frequency-swept optical beat source and a fiber-coupled THz measurement system with low-temperature grown (LTG) InGaAs photomixing emitter and receiver modules. The fiber-coupled THz measurement system is constructed with LTG-InGaAs photomixers and a frequency-swept optical beat source. The frequency-swept optical beat source is composed of a wavelength-swept laser and a wavelength fixed DFB laser diode through the 3 dB fiber coupler. The side mode suppression ratio for both lasers is more than 40 dB. The center wavelength of the fixed DFB laser diode is 1556 nm. And the sweeping bandwidth of the wavelength-swept laser is about 15 nm from 1542 nm to 1557 nm. Therefore, the CW THz radiation could be tuned up to 1.87 THz. The CW THz radiations are achieved with frequency-swept optical beat source at a few mHz sweeping speed. The sweeping frequency of the frequency-swept optical beat source is limited below a few mHz due to the integration time of the lock-in amplifier. The sweeping speed in the THz measurement system should be improved in the future. We measure the THz power which falls down to the noise level of the InGaAs photomixer beyond 0.6 THz. It is due to the polarization dependence from the frequency-swept optical beat source.

8985-56, Session PWed

Strong absorption of molecules inside terahertz nano-slot antenna

Jiyeah Rhie, Hyeong-Ryeol Park, Young-Mi Bahk, Dai-Sik Kim, Seoul National Univ. (Korea, Republic of)

Optical antennas have been applied to material sensing. Previous studies have verified the occurrence of a large field enhancement through the nano-slot antenna in the THz frequency range, when the wavelength of the incident light matches the antenna resonance wavelength for the rectangular hole. For a quantitative analysis, two negative nano-slot antennas were fabricated by focused ion beam (FIB) milling, after depositing gold film with e-beam evaporator. We dropped a diluted solution (α-lactose monohydrate or RDX in methanol) on the sample and dried in air. The resonance of the two antennas matches each of the inter-molecule vibrational modes of the molecules, respectively. THz spectroscopy enables the detection and identification of molecules or materials with strong absorption in the THz region.

We experimentally obtained the normalized intensity spectra of each material, lactose and RDX, on bare quartz and in the nano-slot antenna. Using these data, we obtained the absorption coefficient by following the Beer's law,-(1/t)ln(T/T0), where T and T0 are the transmissions with and without the molecules, respectively, with the material thickness (t). When the molecules feel the field enhancement of nano-slot antenna, the absorption coefficient and the cross section increase 3 orders of magnitudes. Around thousand-fold of Poynting vector enhancement forces the molecular cross section to be enhanced and leads to the molecular absorption enhancement to be more than 1,000,000. Due to its sensitivity, nano-slot antenna enables terahertz sensing chemical and biological molecules with ultrasmall quantities.

8985-57, Session PWed

Dispersion flattened terahertz photonic crystal fiber with high birefringence and low confinement loss

Soeun Kim, Young Soo Lee, Chul-Sik Kee, Gwangju Institute of Science and Technology (Korea, Republic of); Chung Ghiu Lee, Chosun Univ. (Korea, Republic of)

Recently polymer based PCF has also been demonstrated to guide terahertz waves (THz). In this research, using readily and commercially available material, highly flexible PCFs are assembled with novel manufacturing method.

A solid Teflon rod, hollow tube amd Teflon sheet are used to make the proposed fiber. On the Teflon sheet, well arranged Teflon rod and tuves are rolled up tightly. The PCFs are made of without any heating in furnace. Therefore, we make it easy manually.

The key advantage is that the dispersion of the proposed fiber is ultra flattened over wide band. The small air space between air holes and sheets in the cladding is due to the manual method withou heating. As a result, the small air spaces induce the flattened dispersion properties.

Using full-vectorial finite element method (FEM), the modal properties of a rolling up Teflon PCF are numerically investigated.

8985-58, Session PWed

Subharmonic mixing at 0.6 THz in an AlGaAs/InGaAs/AlGaAs field effect transistor

Valeria Giliberti, Alessandra Di Gaspare, Istituto di Fotonica e Nanotecnologie (Italy); Ennio Giovine, Institute for Photonics and Nanotechnologies (Italy); Sebastian Boppel, Alvydas Lisauskas, Hartmut G. Roskos, Johann Wolfgang Goethe-Univ. Frankfurt am Main (Germany); Michele Ortolani, Univ. degli Studi di Roma La Sapienza (Italy) and Istituto di Fotonica e Nanotecnologie (Italy)

Field-effect-transistors (FETs) are a family of room temperature THz detectors attracting much attention for their possible use in heterodyne mode. In the search for breakthrough technologies in THz detection, in fact, particular interest goes to fast receivers which have the potential for heterodyne spectroscopic imaging. In this work, we studied the nonlinear response, both in heterodyne and subharmonic mixing mode, at frequencies up to 0.6 THz of a pseudomorphic AlGaAs/InGaAs channel FET with high electron mobility of 7800 cm2/Vs at room temperature. The FET was fabricated in-house with on-chip bow-tie antenna integrated to the source and drain terminals, for controlling THz potentials at the ends of the transistor channel. The heterodyne, 2nd- and 3rd- subharmonic mixing signals were measured by employing a quasi-optical setup for heterodyne detection with IF frequency of 36 kHz, RF source at 0.592 THz and LO drive at 0.296 THz for 2nd and at 0.197 THz for 3rd subharmonic mixing. The corresponding IF currents versus the gate voltage Vg were collected at the maximum RF and LO power available. The experimental sub-harmonic IF currents are in good agreement with the theoretical curves calculated by differentiating the heterodyne IF current, as predicted by the subharmonic mixing theory. In conclusion, we have studied frequency mixing beyond-cutoff in a high mobility 2D channel of an AlGaAs/InGaAs heterostructure field effect transistor.

8985-59, Session PWed

Coded and compressive THz imaging with metamaterials

Claire M Watts, David Shrekenhamer, Department of Physics, Boston College (United States); John Montoya, Department of ECE, Center for High Technology Materials, University of New Mexico (United States); Guy Lipworth, John Hunt, Center for Metamaterials and Integrated Plasmonics, Department of ECE, Duke University (United States); Timothy Sleasman, Department of Physics, Boston College (United States); Sanjay Krishna, Department of ECE, Center for High Technology Materials, University of New Mexico (United States); David R Smith, Center for Metamaterials and Integrated Plasmonics, Department of ECE, Duke University (United States); Willie J Padilla, Department of Physics, Boston College (United States)

Imaging in long wavelength regimes holds huge potential in many fields, from security to skin cancer detection. However, it is often difficult to image at these frequencies – the so called 'THz gap[1]' is no exception. Current techniques generally involve mechanically raster scanning a single detector to gain spatial information[2], or utilization of a THz focal plane array (FPA) [3]. However, raster scanning results in slow image acquisition times and FPAs are relatively insensitive to THz radiation, requiring the use of high powered sources. In a different approach, a single pixel detector can be used in which radiation from an object is spatially modulated with a coded aperture to gain spatial information. This multiplexing technique has not fully taken off in the THz regime due to the lack of efficient coded apertures, or spatial light modulators (SLMs), that operate in this regime.

Here we present the implementation of a single pixel THz camera using an active SLM. We use metamaterials to create an electronically controllable SLM, permitting the acquisition of high-fidelity THz images. We gain a signal-to-noise advantage over raster scanning schemes through a multiplexing technique [4]. We also use a source that is orders of magnitude lower in power than most THz FPA implementations [5]. We are able to utilize compressive sensing algorithms to reduce the number of measurements needed to reconstruct an image, and hence increase our frame rate to 1 Hz. This 1st generation device represents a significant step towards the realization of a single pixel THz camera.

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8985-35, Session 8

Active metasurfaces

Ada-Simona Popescu, Igor Bendoym, Andrii B. Golovin, The City College of New York (United States); Alain Bergeron, Linda Marchese, Marc Terroux, INO (Canada); David T. Crouse, The City College of New York (United States)

An innovative method to create and examine metasurfaces is presented, including a theoretical analysis, modeling and experiment. A pump-probe beams technique is used to create the metasurface, having a Ti:Sa tuned at 800nm as source. The pump beam has its wavefront shaped by an SLM and then projected onto a high purity FZ silicon. The SLM is programmed to modify the wavefront into any desired pattern, in this case a metasurface composed of v-shaped antenna resonators. The Gerchberg-Saxton algorithm is used to retrieve the correct phase of the wavefront which is to be reshaped by the SLM. Given that the beam power is strong enough, this will create electron-hole pairs in the silicon in the areas of the beam front where light is shined upon. This will result in a metal-like behaving pattern on a silicon substrate for a timeframe of several microseconds. The probe beam, after passing through a nonlinear ZnTe crystal which downshifts the wavelength of the laser beam to a terahertz frequency of 800µm, is used to probe the metasurface inscribed in the silicon wafer, during the lifetime of the metasurface. The probe beam will be steered in a preferred direction, according to design. The detection of the steered terahertz beam is achieved with a terahertz imagining camera. This experiment is meant as an illustration for the more general method of writing a metasurface on a silicon substrate in order to quickly and efficiently assess its scattering properties.

8985-36, Session 8

Nonreciprocity and gyromagnetically-induced transparency of metasurfaces

Alexander B. Khanikaev, The Univ. of Texas at Austin (United States) and Queens College (United States); S. Hossein Mousavi, The Univ. of Texas at Austin (United States); Jeffery W. Allen, Monica S. Allen, Air Force Research Lab. (United States); Gennady B. Shvets, The Univ. of Texas at Austin (United States)

We demonstrate that a metallic meta-surface on top of a gyromagnetic substrate exhibits analog of electromagnetically induced transparency. Earlier work in metamaterials utilized the natural magnetic response of ferrites to achieve and control negative refractive index [1, 2, 3] and nonreciprocity [4]. The focus of this work is on demonstrating how the gyromagnetic activity induces Fano interferences in spatially symmetric metamaterials. As an example we consider a meta-surface comprised of an array of resonant antenna pairs placed on a slab of yttrium iron garnet (YIG) substrate and illuminated by a normally incident electromagnetic wave. Gyromagnetic activity of the substrate introduced by the external dc magnetic field makes meta-molecules bi-anisotropic and causes spectrally-sharp Fano interference between the otherwise uncoupled electric and magnetic dipolar resonances of the meta-molecules. This results in a sharp transmission peak through the otherwise reflective meta-surface. It is shown that for oblique wave incidence, one-way gyromagnetically induced transparency can be achieved by the combination of spatial dispersion and TR symmetry breaking. These phenomena hold significant promise for practical applications such as the dynamic control of resonant EM interactions using magnetic fields produced by the external currents, mitigation of co-site interference and improving isolation. Spectral positions, radiative lifetimes and quality factors of Fano resonances can be controlled by the magnitude direction of the external magnetic field. While similar tunability may be achieved with other methods, the approach based on gyromagnetically induced coupling to sub-radiant resonances proposed in this work is unique because of its non-reciprocal nature. One-way absorbers, one-way sensors, and one-way cloaking elements are just a few examples of such applications.

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8985-37, Session 8

RF-photonic wideband measurements of energetic pulses on NIF enhanced by compressive sensing algorithms

Jason T. Chou, Lawrence Livermore National Lab. (United States); George C. Valley, The Aerospace Corp. (United States); Vincent J. Hernandez, Corey V. Bennett, Lawrence Pelz, John E. Heebner, Jean-Michel G. Di Nicola, Mark Bowers, Lawrence Livermore National Lab. (United States)

At the National Ignition Facility (NIF), home of the world's largest laser, a critical pulse screening process is used to ensure safe operating conditions for amplifiers and target optics. To achieve this, high-speed recording instrumentation up to 34 GHz measures pulse shape characteristics throughout a facility the size of three football fields--which can be a time consuming procedure. As NIF transitions to higher power handling and increased wavelength flexibility, this lengthy and extensive process will need to be performed far more frequently. We have developed an accelerated high-throughput pulse screener that can identify nonconforming pulses across 48 locations using a single, real-time 34-GHz oscilloscope.

Energetic pulse shapes from anywhere in the facility are imprinted onto telecom wavelengths, multiplexed, and transported over fiber without distortion. The critical pulse-screening process at high-energy laser facilities can be reduced from several hours just seconds--allowing greater operational efficiency, agility to system modifications, higher power handling, and reduced costs. Typically, the sampling noise from the oscilloscope places a limit on the achievable signal-to-noise ratio of the measurement, particularly when highly shaped and/or short duration pulses are required by target physicists. We have developed a sophisticated signal processing algorithm for this application that is based on orthogonal matching pursuit (OMP) combined with solution of a nonlinear least squares problem at each iteration of the OMP. This algorithm, developed for recovering signals in a compressive sensing system, enables high fidelity single shot screening even for low signal-to-noise ratio measurements.

8985-38, Session 8

Terahertz applications: trends and challenges

Thierry Robin, Clementine Bouye, Jacques Cochard, TEMATYS (France)

The objective of the present work is to determine the opportunities and challenges for Terahertz application development for the next five years with a focus on systems: for homeland security, for industrial quality control and NDT (Non Destructive Testing).

Terahertz radiation has unique abilities and has been the subject of extensive research for many years. Proven concepts have emerged for numerous applications including Quality Analysis & Control, Security, Health, Telecommunications… Nevertheless, there has been no widely deployed application and Businesses based on THz technologies are still in their infancy. Some technological, market and industrial barriers are still to be broken.

We present the final data and recommendations: Analysis of the technology trends and major bottlenecks per application segment, Main challenges to be addressed both on technology side and application side in the next years, Key opportunities for THz technologies based on market needs and requirements.

8985-39, Session 8

RF-wave generation using external-cavity laser diodes frequency-stabilized to a single optical cavity by using orthogonally-polarized modes

Tomoyuki Uehara, Hagiwara Kohei, Toshihide Tanigaki, Kenichiro Tsuji, Noriaki Onodera, National Defense Academy of Japan (Japan)

Recently, the generation of electrical signals using photonic techniques has attracted great interest. Photonic approaches are suitable for high frequency electrical signal generation owing to their simple photomixing principle. Additionally, there are high speed phase shifters and various optical devices widely used in optical fiber communications, thus the photonic approaches can take full advantages of those devices. The easiest and cost-effective way to generate phase-coded GHz- to THz waves would be the beat-note signal generation using two lasers and a phase shifter. However, there exists frequency fluctuation in generated RF-signal due to the frequency fluctuations of those two lasers. Recently, we successfully generate stable microwave signals using orthogonally polarized two lasers. Both lasers are stabilized to the resonant frequency of a single optical cavity simultaneously. In this paper, we describe a series of experiments using a 1550 nm external cavity laser diode, a Fabry-Perot optical cavity, and additional electronic control circuits. The experiments involve: (1) the servo-locking two lasers to a single optical cavity with orthogonally polarized two lasers using the FM sideband technique; (2) the microwave generation by the optical beat-note generation between two frequency stabilized lasers. We obtained short-term stability of ten to the minus eleventh order at an averaging time of 1 ms, which is calculated from the square root of the Allan variance of the error signal. Actual frequency stabilities of each laser are limited by frequency fluctuation of resonance frequency of reference cavity. But the frequency fluctuation of a beat-note between the two lasers is comparable to the free spectral range (FSR) fluctuations. The frequency fluctuation in the FSR is smaller than that of a cavity resonance by three orders of magnitude. From above mentioned results, the generated microwave signals are well stabilized and applicable to the phase-coded RF signal generation. Photonic generation of frequency-stabilized signals in the region of GHz- to THz-frequency is demonstrated using a simultaneous locking technique with one reference cavity. The proposed technique will be the attractive candidate for GHz- to THz-frequency carrier signal generation.

8985-40, Session 8

Vertical Transitions between Transmission Lines and Waveguides in Multilayer Liquid Crystal Polymer (LCP) Substrates

Yifei Zhang, Shouyuan Shi, Richard D. Martin, Dennis W. Prather, Univ. of Delaware (United States)

Passive millimeter wave (mmW) imager with low size, weight, and power (SWap) has been developed with milliKelvin sensitivities enabling the discrimination of passive emissions of millimeter wave energy of objects at room temperature at University of Delaware. The mmW signal is captured by a sparse array of rectangular horn antennas, amplified by cascaded LNAs on ceramic substrate, then modulated and processed using optical techniques. To further reduce the SWaP, we propose multilayer monolithic millimeter wave integrated circuits (MMMICs) with antennas of high gain and narrow beamwidth on flexible LCP substrates as promising substitutions of the horns and ceramic circuits in our system. Multilayer flexible circuits provide great circuit density, high-connection density, and conformation possibility. The most appealing material for this application at mmW frequency is LCP. It has low dielectric constant, loss, and water absorption. Moreover, it is light, thin, inexpensive, and flexible. Multilayer circuits could be achieved vertically with two types of LCP materials with different melting temperature. Our proposed MMMIC consists of high-gain antennas, CBCPWs, SIWs, strip lines, LNAs, and the transitions between different components on 3-layer LCP substrates with 4-layer metal claddings at W-band. To minimize the internal loss, we designed CBCPW-to-strip line transition and CBCPW-to-SIW transition. The insertion losses are as low as <1 dB at 77 GHz. These transitions could efficiently connect antennas and LNAs in our mmW imaging systems.

8985-41, Session 9

Comparison analysis of microwave photonic filter using SOI microring and microdisk resonators

Li Liu, Jianji Dong, Ting Yang, Xinliang Zhang, Dingshan Gao, Huazhong Univ. of Science and Technology (China)

Among the methods to implement microwave photonic filter (MPF), silicon-based waveguides can offer distinct advantages of increased stability and reliability, compactness, capability of integration with electronics. In this paper, a compact notch MPF with central frequency continuous tunability using microdisk and cascaded microring resonator on a single silicon-on-insulator (SOI) chip is proposed and experimentally demonstrated. Assisted by the optical single side-band modulation, the optical frequency responses of microring and microdisk resonators are mapping to the microwave frequency responses to form an MPF whose central frequency is continuously tunable. Different SOI resonators, including two microdisk chips whose Q factors are 1.07x1e5 and 1.5x1e4 respectively, and a cascaded microring chip with a Q factor of 2.9x1e4, are used to implement the MPFs. The performances of these MPFs are compared in terms of bandwidth, tuning range and rejection ratio. The narrower 3dB-bandwidth is about 2GHz, the tuning range of central frequency is from 6 GHz to 18GHz, and the best rejection ratio is nearly 40dB. This approach will allow the implementation of very compact, low-cost, low-consumption and integrated notch MPFs in a silicon chip.

8985-42, Session 9

Techniques for the modelling of QUBIC: a next-generation quasi-optical bolometric interferometer for cosmology

Stephen P. Scully, Donnacha Gayer, David Bennet, Créidhe O'Sullivan, Marcin Gradziel, National Univ. of Ireland, Maynooth (Ireland)

The expansion of the universe has red-shifted remnant radiation, called the Cosmic Microwave Background (CMB) radiation, to the terahertz band, one of the last areas of the electromagnetic spectrum to be explored. The CMB has imprinted upon it extremely faint temperature and polarisation features that were present in the early universe. The next ambitious goal in CMB astronomy is to map the polarisation characteristics but their detection will require a telescope with unprecedented levels of sensitivity and systematic error control. The QUBIC (Q&U Bolometric Interferometer for Cosmology) instrument has been specifically designed for this task, combining the sensitivity of a large array of wide-band bolometers with the accuracy of interferometry. QUBIC will observe the sky through an array of horns whose signals will be added using a quasi-optical beam combiner (an off-axis Gregorian dual reflector designed to have low aberrations). Fringes will be formed on two focal planes separated by a polarising grid.

MODAL (our in house simulation package) has been used to great effect in achieving a detailed level of understanding of the QUBIC combiner. Using a combination of scalar (GBM) and vector (PO) analysis, MODAL is capable of high speed and accuracy in the simulation of quasi-optical systems. There are several technical challenges to overcome but the development of MODAL and simulation techniques have gone a long way to solving these in the design and analysis phase.

In this presentation I outline the quasi-optical modelling of the QUBIC beam combiner and work envisaged for the future.

8985-43, Session 9

Dual-frequency laser harmonic phase locking: Ultra-narrow line width of an optically carried signal at 300 GHz

Joachim Börner, Thales Research & Technology (France); Katarzyna Balakier, Univ. College London (United Kingdom); Gregoire Pillet, Loïc Morvan, Thales Research & Technology (France); Cyril C. Renaud, Univ. College London (United Kingdom); Daniel Dolfi, Thales Research & Technology (France)

The high spectral purity and widely tunable sources in the millimeter-wave and THz range are of great interest for high resolution spectroscopy and wireless communications. Among different techniques, the beatnote provided by a solid-state dual-frequency laser is suitable for low-noise THz signals generation. However, for stringent applications, it is necessary to further improve both the long-term frequency stability and spectral purity.

We present a dual-frequency laser at 1.5 µm, in which two intra-cavity etalons allow a tuning of the beatnote frequency from 2 GHz to 1.7 THz by few GHz steps. In this proposed setup, the stability of the beatnote is ensured by the oscillation of the two modes in a single laser cavity. In free running operation, we previously demonstrated the generation of 300 to 700 GHz signals with phase noise as low as -20 dBc/Hz at 1 kHz and -100 dBc/Hz at 100 kHz offset of the carrier. A relative frequency fluctuation of 10^-5 over 10 s is observed at 500 GHz.

To improve these performances, we set up an optical phase-locked loop. We first implemented a harmonic photonic phase demodulator to compare the millimeter-wave beatnote to a low frequency reference (below 20 GHz). We then inserted an electro-optic element inside the cavity that allows a continuous tuning of the beatnote. We have then been able to phase-lock a beatnote at 300 GHz, demonstrating a long-term stability equivalent to the reference (typ. 10^-9 per day). We also compared the performances of various resonant and non-resonant harmonic demodulation schemes.

8985-44, Session 9

Dual-frequency characterization of bending loss in hollow flexible terahertz waveguides

Pallavi Doradla, Robert H. Giles, Univ. of Massachusetts Lowell (United States)

The Terahertz (THz) frequency range, located midway between the microwave and infrared region, is a rapidly developing area for source and receiver technologies with a wide range of applications in imaging and spectroscopy. A flexible cylindrical waveguide with good mode selectivity is essential to guide the THz radiation in the field of interior in vivo medical imaging. In this study, we demonstrate silver coated hollow flexible waveguides that provides minimal propagation loss at different THz frequencies and supports mode preservation.

Low-loss, hollow, flexible silver (Ag) and gold (Au) coated waveguides have been designed and fabricated for the maximal transmission of terahertz radiation. Attenuation characteristics of 1µm thick Ag and Au coated waveguides with bore diameters 4.1mm, 3.2mm, and 2mm (in the order of 10 ? 20γ) were studied at 215µm wavelength. Since recent terahertz skin, colon, and breast cancer studies showed a contrast between normal and diseased tissues between 500 – 600GHz frequencies, these Ag coated waveguides with bore diameters of the order of 3 ? 8γ were studied at 584GHz (513µm). A propagation loss of 1.6dB/m was achieved with a 4mm diameter silver coated waveguide at both 215µm and 513µm wavelengths. In contrast, these metal coated waveguides exhibit different bending and modal characteristics at 513µm, as compared with 215µm wavelength, due to their diameter sizes comparable to the wavelength. However, our investigation shows the feasibility of using the same 1µm thick silver coated waveguides for both the frequencies, to obtain low transmission losses in addition to the Gaussian mode preservation.

8985-45, Session 10

A widely-tunable narrow linewidth RF source utilizing an integrated heterogeneous photonic module

David W. Grund Jr., Garrett J. Schneider, Janusz A. Murakowski, Dennis W. Prather, Univ. of Delaware (United States)

Generating RF signals over the entire spectrum, from hundreds of MHz into the hundreds of GHz, has previously required the use of special oscillators designed only for specific bands of operation within that spectrum. By mixing two lasers together it is possible to generate RF signals over that entire band. Through the use of a narrow linewidth low frequency oscillator, optical modulator, and injection locking, much higher frequency outputs can be produced that still retain the narrow linewidth of the low frequency oscillator. Here we present the results of our efforts to develop an integrated version of this system, based on a silicon-photonic integrated circuit coupled to III-V semiconductor gain chips. Towards that effort we have successfully demonstrated an integrated module and shown tunable RF generation with a 1 Hz linewidth.

8985-46, Session 10

A wide bandwidth analog front-end circuit for 60-GHz wireless communication receiver

Masanori Furuta, H. Okuni, M. Hosoya, A. Sai, J. Matsuno, S. Saigusa, T. Itakura, Toshiba Corp. (Japan)

The function of 360 degree camera angle has been required for security and sports camcorders. In such applications, wireless signal readout is a key building block of the camcorder system. Because high-speed and high-resolution CMOS image sensors are used in recent camcorders, the demand for readout speed is rapidly increased. For example, when 1-2Mpix and 60-120frame/sec CMOS image sensor is used in the camcorder, the maximum data rete becomes 1-4Gbps. For achieving high-speed data readout, a wireless communication system using millimeter wave (mm-Wave) band is proposed.

The receiver is divided into three components, RF, analog frontend (AFE) and digital baseband, and the bandwidth of AFE determines the communication speed of the system. This paper presents AFE circuit for mm-Wave receiver. The feature of the proposed analog front-end circuit is a bandwidth more than 1-GHz wide. To expand the bandwidth of a low-pass filter and a voltage gain amplifier, a technique to reduce the parasitic capacitance of a transconductance amplifier is proposed. Since the bandwidth is also limited by on-resistance of the ADC sampling switch, a switch separation technique for reduction of the on-resistance is also proposed. In a high-speed ADC, the SNDR is limited by the sampling jitter. The developed high resolution VCO auto tuning effectively reduces the jitter of PLL. The prototype is fabricated in 65nm CMOS. The AFE achieves over 1-GHz bandwidth and 27.2-dB SNDR and this is the best specification compared with the previous reported works.

8985-47, Session 10

Photonic generation of continuously-tunable microwave signals exploiting two tunable external-cavity lasers based on a polymer Bragg grating

Seung Bin K. Ahn, Sunduck Kim, Young-Geun Han, Hanyang Univ. (Korea, Republic of)

The optical generation of the microwaves signal has attracted interests in the last few decades for various applications, such as radio over fiber systems, antenna remote systems, radars, and broadband wireless access networks because of their many advantages like high speed, low loss, and immunity to electromagnetic interference. High frequency signal can be readily generated by using a beating technique which is basically to combine two coherence optical signals at a high frequency photodetector (PD). To generate microwave signals, fiber-based dual wavelength lasers with wide tunability of wavelength spacing and stability of output power have been proposed. However, the fiber-based dual lasers should exploit an unpumped erbium-doped fiber (EDF) or a sub-ring cavity to obtain the single longitude mode (SLM) operation, which causes additional loss and configuration complexity. We demonstrate a photonic generation of tunable microwave signals exploiting two tunable external cavity lasers (T-ECL) based on a polymer Bragg grating. The T-ECL consists of a superluminescent diode (SLD), and polymer Bragg grating. The central wavelength of the T-ECL is tuned by applying a current on the heater of the polymer device. The T-ECLs operate in single longitudinal mode (SLM) without saturable absorbers, sub-ring cavities due to its shorter cavity. By combining two outputs of the T-ECLs through an optical coupler, we generate and continuously control the microwave signals.

8985-48, Session 10

Continuously-tunable microwave photonic filter based on a multiwavelength fiber laser incorporating polarization-differential time delay and nonlinear polarization rotation

Young Bo Shim, Sunduck Kim, Young-Geun Han, Hanyang Univ. (Korea, Republic of)

Photonic microwave techniques are widely investigated in the field of high-performance signal processing of radio frequency due to the low electro-magnetic interference, broad bandwidth, and low signal loss. Among the various signal processing techniques for the radio frequency, microwave filter techniques are essential for wireless communication systems and radar systems. Versatile microwave filters using chirped Bragg gratings with many laser sources or a multiwavelength laser with a Sagnac interferometer are investigated. These techniques, however, have a limitation on continuous tuning of filtering frequency because the spacing of lasing wavelengths is discretely tunable.

In this study, we propose a continuously tunable microwave photonic filter based on polarization-differential time delay incorporating nonlinear polarization rotation. The multiwavelength filter with continuously tunable wavelength spacing was realized by using a Sagnac interferometer based on a polarization-differential delay line. The nonlinear polarization rotation structure is utilized for the stable operation of the multiwavelength laser. The modulated multiwavelength output of the proposed fiber laser with an electro-optic modulator was propagated through a single mode fiber with a length of 50 km to induce different time delay among multiple lasing wavelengths. As a result, each modulated lasing wavelength with different time delay should be superimposed resulting in the power variation of the output microwave signal according to the modulation frequency. Periodic transmission frequencies of the microwave signal corresponding to the wavelength spacing of the multiwavelength laser should be obtained. As the wavelength spacing of the multiwavelength erbium-doped fiber laser is tuned from 0.2 nm to 3.0 nm, the free spectral range of the proposed microwave filter is continuously controlled from 5.56 GHz to 0.37 GHz.

8985-49, Session 10

On the metrological performances of optoelectronic oscillators based on whispering gallery mode resonators

Khaldoun Saleh, Aurélien Coillet, Rémi Henriet, Patrice Salzenstein, Laurent Larger, Yanne K. Chembo, FEMTO-ST (France)

Optoelectronic oscillators (OEOs) are usually based on optical delay lines in order to generate high spectral purity signals above 10 GHz. However, despite the remarkable low phase noise results obtained, these systems remain bulky, their thermal stabilization is difficult and they produce spurious modes that need complex configurations to be reduced. Because of all these detrimental factors, an alternative solution is the use of optical resonators featuring ultra-high optical quality factors (Qs).

The OEO we are studying is based on a whispering gallery mode optical resonator (WGMR). In this OEO the laser lightwave is efficiently coupled into and out of the resonator through two tapered optical fibers in an add-drop configuration. This WGMR is fabricated with crystalline material to achieve extremely high Q above 10^9. On the other hand, the noise performance of this OEO has been found to be not only dependent on the resonator's Q. Indeed, many optical and microwave elements in the OEO setup have to be thoroughly studied and optimized in order to fully benefit from the resonator's high Q: the laser lightwave optimal coupling into the WGMR and its stabilization onto an optical resonance, the resonator's nonlinearity and its thermal stability, the photodiode's noise and nonlinearity and finally the noise in the active and passive

components in the microwave part of the oscillator. All these matters are currently under study and will be addressed in the final paper, followed by phase noise results that will be compared to the other types and state-of-the-art OEOs.

8985-50, Session 11

Graphene-based optical modulator realized in metamaterial split-ring resonators operating in the THz frequency range

Riccardo Degl'Innocenti, David Jessop, Yash D. Shah, Juraj Sibik, Axel Zeitler, Piran R. Kidambi, Stephan Hoffman, Harvey E. Beere, David A. Ritchie, Univ. of Cambridge (United Kingdom)

Active optical modulators working in the THz region represent a key element for the many applications continuously developing in this frequency range such as: Sensing, optical communications, and security scanning. Moreover, the integration of Quantum Cascade Lasers with devices capable of efficiently manipulating THz light, constitutes a fundamental step in many research fields. Split ring resonators, subwavelength metamaterial elements, exhibiting broad resonances that are easily tuned lithographically, have already been employed to control the electromagnetic properties of different materials. We realized a design based on the interplay between arrays of metallic split ring resonances and the electronic properties of a monolayer graphene sheet grown by chemical vapor deposition separated by a SiO_2 buffer layer. By acting on the doping level of the graphene along the Dirac cone, we could actively control the optical intensity of the incident light, by depleting the charges below the resonant elements. We tested our devices with a commercially available THz pulsed imaging system Imaga 2000 from Teraview, based on biased photoconductive antennas. We monitored the reflected and transmitted light from the split ring arrays while the sample was illuminated by a focused spot size of about 200 micrometers. The different arrays exhibited broad resonances varying from 2.2 THz to 3.5 THz, corresponding to the LC resonances, depending on the size of the split rings. By biasing the split rings, thus acting as top gate, with respect to the graphene, we achieved, in our non optimized device, a modulation depth of about 15%

8985-51, Session 11

Polymeric waveguide components for THz quantum cascade laser outcoupling

Fabrizio Castellano, Miriam S. Vitiello, Consiglio Nazionale delle Ricerche (Italy); Harvey E. Beere, David A. Ritchie, Univ. of Cambridge (United Kingdom)

The ability to control the beam shape and to efficiently couple light from and into THz quantum cascade lasers is crucial for applications but is complicated by the large impedance mismatch between the laser waveguide and free space.

We propose to employ polymeric materials for the realization of intermediate impedance-matching components to achieve the goal. We employ cyclic-olefin-copolymer (COC, refractive index 1.52 at 3THz) to realize optical fibers with a diameter of 400-600um. Our transmission measurments at 3 THz on fiber lengths up to 30mm yeld an absorption coefficient of 4.4 dB/cm for the bare fiber, and 4.9 dB/cm for an Au coated fiber. These values are low enough for the realization of few-millimiter-long components, and the thermoplastic properties of the material allow to directly mold the polymer onto processed lasers. As a proof of concept we attached a 2mm-long uncoated fiber to a THz QCL processed in a single-plasmon waveguide by hot-molding one of the fiber ends around the cleaved laser facet. We observe a circular single-lobed emission with a 10° divergence, compared to the 20° divergence of the bare laser. Our FEM simulations show that it is also possible to efficiently couple the COC fiber to a double-metal waveguide QCL. By appropriate patterning of apertures in the metallic wall between the laser waveguide and the optical fiber we can design forward and backward directional couplers with return loss below -20dB over a bandwidth of up to 500 GHz at 3THz.

Efforts are underway to realize the devices we have designed.

8985-52, Session 11

Enhanced transmission and beam confinement using bullseye plasmonic lenses at THz frequencies

Tanner J. Heggie, David A. Naylor, Brad G. Gom, Univ. of Lethbridge (Canada); Evgueni V. Bordatchev, National Research Council Canada (Canada)

A major limitation of terahertz (THz) imaging is the relatively poor diffraction limited spatial resolution. A common approach to achieve subwavelength resolution is near-field imaging using a subwavelength aperture, but the low transmission efficiency through the aperture limits the sensitivity and spatial resolution of this method. Bullseye structures, consisting of a single subwavelength circular aperture surrounded by concentric periodic corrugations, have been shown to enhance transmission through subwavelength apertures. This effect is due to the excitation of surface modes known as surface plasmon polaritons that are generated by periodic structures on metallic surfaces. We report on the design and simulation of bullseye lenses of different configurations for optimal transmission and tight angular confinement using a commercial-grade simulator based on the finite-difference time-domain (FDTD) method. Design variations include periodic input corrugations and Bragg reflectors, chosen for peak transmission of a circularly polarized Gaussian beam at 325 GHz, and output corrugations with depth-tuned grooves for optimal beam confinement over several wavelengths. Since the scale of plasmonic structures depends on the incident wavelength, THz plasmonic lenses can be fabricated using precision micromachining techniques instead of the lithographic or chemical processes normally employed at shorter wavelengths. We compare and contrast the theoretical transmission enhancement and transmitted beam profiles from simulated systems with their experimentally measured performance. High efficiency THz lenses based on bullseye plasmonic structures show promise in many applications requiring near-field THz imaging with subwavelength resolution.

8985-53, Session 11

An optically-controlled microwave phase stabilizer based on polarization interference technique using semiconductor optical amplifier

Han Chen, Mingming Sun, Xiaohan Sun, Southeast Univ. (China)

We introduce an optically controlled microwave phase stabilizer based on polarization interference technique using single semiconductor optical amplifier (SOA). A prototype with a frequency of 10 GHz is experimentally demonstrated. It provides a stable phase drift that can be linearly compensated over 10 km single-mode fiber by controlling the SOA injection current.

The processing of radiofrequency (RF) signals in the optical domain is of particular interest for applications such as optically controlled phased array antennas and radio-over-fiber (RoF) systems, since the RF signals can be processed directly in the optical domain without the need of extra optical-electrical and electrical-optical conversions. However, pressure and temperature variation along the fiber link results in the accumulative phase fluctuation, degrading the frequency phase stability at the remote end. Therefore, a real-time remote phase detection and stabilizer are required.

The key component in an optically controlled microwave phase stabilizer is the photonic RF phase shifter. Recently, the use of photonic elements to control the phase shift has raised attention due to the advantages of flexible tunability, high bandwidth, and light weight offered by optical systems. Some techniques for realizing photonic RF phase shifters have been reported, including wavelength conversion in a distributed feedback laser (DFB), stimulated Brillouin scattering (SBS) signal processing, homodyne mixing, and vector sum methods. In particular, the interests in applying the physical effects called coherent population oscillations (CPO) in SOA to photonic RF phase shifters are increasing. Semiconductor based structures provide these features and also allow on-chip integration with other devices while lowering the size and complexity of the conventional phase-shifting schemes.

We introduce an optically controlled microwave phase stabilizer based on birefringence effects in a SOA. The proposed method utilizes dynamic birefringence in the SOA and produces different phase shifting efficiency in two orthogonal polarization directions by controlling the operating state of SOA. The birefringence effects in SOA are composed of the intrinsic and dynamic birefringence. The former is produced by the waveguide structure and material, and the latter is determined by the operating state of SOA.

8985-54, Session 11

Analysis for multi-tone signal transmission using phase modulation in microwave photonic systems

Sandeep K. Arya, Guru Jambheshwar Univ. of Science and Technology (India)

Abstract – Multi-tone transmission using optical phase modulation in microwave photonic link through optical fiber which acts as a dispersive device is proposed. An optical phase modulated signal cannot be directly detected by a photo detector. We convert this phase modulated signal into intensity modulated signal by using a dispersive device such as optical fiber. In this paper, we present an analysis to characterize the PM based MWP system for multi-tone transmission by using PM to IM conversion in a dispersive link. Mathematical expression in closed form of generated harmonics at the output of RoF link is also derived.

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8986-1, Session 1

Large-area bow-free n+ GaN templates by HVPE for LEDs *(Invited Paper)*

Jacob H. Leach, Yevgeniy Shishkin, Kevin Udwary, Edward A. Preble, Keith R. Evans, Kyma Technologies, Inc. (United States)

The economic and energy efficiency promise of solid state lighting drive a continuous need to reduce the cost and improve the efficiency of visible LEDs. Current III-N LED manufacturing is dominated by non-native substrate approaches which result in strained epitaxial films, high dislocation density in the buffer and device active regions, and large epiwafer bow, which together present major limitations in terms of LED device yield, performance, and cost. Large area sapphire substrates (6", 8", and beyond) are becoming available and present cost reduction potential yet they are even more vulnerable to strain and bow related issues. We present a novel approach to realizing a zero-bow relatively-thick GaN on sapphire template that can be made at essentially any diameter and which bodes well for improved device yield, performance, and cost. The elimination of bow is achieved through a simple cost-effective stress balancing technique involving backside deposition. The result is a large area GaN template which is flat at all temperatures and which has 10x lower dislocation density than current GaN buffers. We report on the properties of these templates and provide device data for LED structures grown thereon.

8986-2, Session 1

Growth of bulk GaN crystal by Na flux method *(Invited Paper)*

Yusuke Mori, Osaka Univ. (Japan)

Growth of GaN crystals from small GaN seeds

Point Seed (PS) technique can be realized by putting a sapphire plate with a small hole (0.5~1.5 mm in diameter) on a GaN plate seed. Centimeter-sized bulk GaN single crystals with large dislocation-free areas could be fabricated by this technique. Cathodoluminescence measurement at the interface between the seed and the grown crystal has revealed that almost all dislocations propagated from the GaN seed were bent and terminated at the initial growth stage.

Coalescence growth of GaN crystals by Na flux method

We have developed coalescence growth of multi-GaN crystals in order to fabricate a large diameter single GaN crystal within a short period. As a first step, we grew two GaN point seeds and coalesced them. Two GaN point seeds were established by mounting a sapphire plate with two small holes. The coalescence direction was a-direction. Other experimental conditions were same as above. We have found the two GaN crystals grown from two separate seed area coalesced without generating dislocations at a coalescence boundary. The grown GaN crystal can remove from substrate easily during the growth. This phenomenon is effective to reduce the stress in the grown GaN crystal. 2-inch GaN crystals by the coalescence technique. Some of the crystals have very large curvature radius (~100 m), which exceed the detection limit of a Rigaku SmartLab X-ray diffractometer.

8986-3, Session 1

Examination of growth rate during hydride vapor phase epitaxy of GaN on ammonothermal GaN seeds

Boleslaw Lucznik, Michal Bockowski, Institute of High Pressure Physics (Poland); Robert Kucharski, Ammono Sp. z o.o. (Poland); Izabella Grzegory, Institute of High Pressure Physics (Poland)

Crystallization of GaN by Hydride Vapor Phase Epitaxy (HVPE) on ammonothermally grown GaN seed crystals (Am-GaN) will be presented. 1 in. Am-GaN crystals, with misorientation ~0.3 degree to the m direction and (0001) surfaces will be used as seeds. All seeds will be of high structural quality with FWHM of X-ray rocking curve for (002) reflexion of about 50 arcsec and bowing radii of the (0001) crystallographic planes of about 20 m. A free carrier concentration of the Am-GaN seeds will always be lower than 5x1018 cm-3. Various growth rates in the c-direction will be examined. The growth rate can be changed in two ways. First, the HCl flow can be changed (increased or decreased) at all other parameters constant during the process. Second, the HCl can be changed at constant III/V ratio. Thus, any increasing in HCl flow entails an increase in ammonia flow, and contrary, any decreasing in HCl flow entails a decrease in ammonia flow. The examination of the growth rate, changed by two presented above ways, will be described in details. An influence of the fastest and the slowest rate on a structural quality, purity and a morphology of the growing crystal's surface will be analyzed. The maximum rate for stable growth will be determined. This optimal growth rate and the way to its achieving will be discussed. Smooth HVPE-GaN layers up to a few millimeters thick and of excellent crystalline quality, without cracks and with extremely low oxygen concentration (< 1016 cm-3) will be presented.

8986-4, Session 1

Free-standing HVPE-GaN crystals obtained from ammonothermally grown GaN substrates as seeds for the HVPE and high nitrogen pressure solution growth

Michal Bockowski, Institute of High Pressure Physics (Poland); Robert Kucharski, Ammono Sp. z o.o. (Poland); Izabella Grzegory, Institute of High Pressure Physics (Poland)

Ammonothermally grown GaN crystals can be successfully used as seeds for the HVPE growth. Smooth GaN layers up to 2.5 mm thick (crystallized with a stable growth rate of 250 μm/h) and of excellent crystalline quality, without cracks, and with low dislocation density (5x104 cm-2) have been obtained. The free-standing (F-S) HVPE-GaN crystals have been sliced from the seeds. The structural properties of the F-S HVPE-GaN have not differed from the structural properties of the ammonothermal GaN seeds. Therefore, the F-S HVPE-GaN has been used as seed for further HVPE growth and also for the High Nitrogen Pressure Solution (HNPS) growth. (0001) and (000-1) surfaces of 1 in. F-S HVPE-GaN seeds have been prepared by mechano-chemical polishing and then cleaning to the epi-ready state. For the HVPE technique only (0001) surfaces of the seeds have been used in order to crystallize a new, 2.5 mm thick, GaN. For the HNPS growth method, in a multi-feed-seed (MFS) configuration, a polarity of the seed surface is always determined and controlled by the Ga solution and its impurities. Therefore, two surfaces of the F-S HVPE-GaN: (0001) and (000-1) have been used. Strongly n-type and absolutely semi-insulating crystals have been grown on (0001) and (000-1) surfaces, respectively. Structural, electrical and optical properties of the new grown GaN will be determined and presented. They will be compared with the properties of the GaN grown

by the HVPE and also by the HNPS-MFS on the HVPE-GaN seeds obtained by the HVPE growth on MOCVD-GaN/sapphire templates.

8986-5, Session 1

Recent developments on highly-resistive GaN substrates obtained by ammonothermal method

Marcin Zajac, Roman Doradzinski, Robert Dwilinski, Malgorzata Iwinska, Robert Kucharski, Ammono Sp. z o.o. (Poland); Jerzy Krupka, Warsaw Univ. of Technology (Poland); Romuald Stankiewicz, Ammono Sp. z o.o. (Poland)

At present commercially available GaN-based electronic devices are manufactured mainly by heteroepitaxy of quantum structures on non-native substrate (sapphire, SiC), leading to generation of large threading dislocation density, limiting power, efficiency and lifetime of the devices. High dislocation density (at the level of 10^6-10^9 cm^-2) is the reason of narrowing the range of operation parameters. The ideal solution of this problem would be use of bulk GaN substrates for homoepitaxy. Recently, large interest has been devoted to ammonothermal method, which is at present regarded as one of the key technologies of bulk GaN substrates manufacturing. It uses supercritical ammonia to dissolution of feedstock material and crystallization of GaN on native seeds due to convection-driven transport and supersaturation of the solution. It enables growth of large diameter crystals (now surpassing 2 inches) of high crystalline quality, large curvature radius (hundreds of meters) and low dislocation density (about 10^4 cm^-2). It is well controlled, reproducible and scalable process performed at relatively low temperature.

Recently, we presented a new type of n-type ammonothermal substrate of low absorption level and high transparency, especially dedicated for high brightness LED production [1]. These substrates are characterized by much lower impurity concentration, especially oxygen (below 10^18 cm^ -3) and transition metals (about 10^16 cm^-3) and low electron concentration (of the order of 10^17 cm^-3). This progress enabled further development of another type of ammonothermal material – highly resistive GaN substrates, suitable for high-power and high-frequency electronics. We recall, that in our previous semi-insulating substrates homogeneous resistivity up to 10^12 ?cm was observed [2]. Such resistivity was obtained by compensation of non-intentional donors (of very high concentration of 10^19 cm-3) by shallow acceptors. In this communication we show, that we reduced largely degree of compensation by conducting cleaner ammonothermal processes, decreasing by at least one order of magnitude the concentration of both donors and compensating acceptors. Such substrates were extensively studied by measuring their absorption, resistivity by a.c. contactless techniques, such as microwave resonance and various capacitance methods, both in frequency and time domain [3]. The results show resistivity of up to 10^10 ?cm at room temperature. Moreover, lower concentration of impurities leads to substantial reduction of absorption coefficient in visible spectral range (as compared to highly resistive substrates with high oxygen content) to few cm^-1 at 450 nm. It should be stressed that dislocation density (<5 x 10^4 cm^-2), crystalline properties and resitivity remains at the same level. First results on transistors grown on such ammonothermal material will also be shown.

To conclude, we present a new type of highly resistive ammonothermal substrate of lower absorption level, dedicated for high-power and/or high frequency electronics. The authors believe that measured resistivity enables good electrical isolation of horizontal transport of two dimensional electron gas (2DEG) in HEMT transistors grown on such a substrate, while cleaner and more transparent substrates will minimize the diffusion of impurities into the quantum structures.

[1] M. Zaj?c, R. Doradzi?ski, R. Dwili?ski, R. Stankiewicz, R. Kucharski, P. Wili?ski, A. Je?owski, presented at Photonics West 2013.

[2] R. Dwili?ski, R. Doradzi?ski, L. Sierzputowski, R. Kucharski, M. Zaj?c, Elektronika 7, 11 (2012).

[3] J. Krupka et al., Meas. Sci. Technol. 24 062001 (2013).

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8986-6, Session 1

Homoepitaxial growth of AlN films on freestanding AlN (0001) substrates by metalorganic vapor phase epitaxy

Tomohiro Morishita, Asahi Kasei Corp. (Japan); Motoaki Iwaya, Tetsuya Takeuchi, Satoshi Kamiyama, Isamu Akasaki, Meijo Univ. (Japan)

Recently, a AlN substrate with a much higher crystalline quality has been successfully grown by sublimation method. So far, there are many reports the crystal growth of AlN homoepitaxial and AlGaN heteroepitaxial growth and fabrication of DUV/UV-LEDs on freestanding AlN substrates. However, understanding about correlation of the crystallinity of the homoepitaxial AlN film and crystal growth conditions is insufficient.

In this study, we have investigated the homoepitaxial AlN films on on freestanding AlN substrate with just sliced at c-plane (off angle: 0° ± 0.5) by MOVPE. Crystallinity, such as surface morphology, full width at half maximum from X-ray rocking curves, of the homoepitaxial growth AlN film was strongly dependent on the growth conditions. When AlN films are grown on AlN substrate using relatively low V/III ratio of 80, high density hillocks appeared at the AlN surface. In addition, the polarity of the AlN had mixed in this growth condition. By optimizing the V/III ratio and growth temperature, homoepitaxial AlN films with good surface flatness and high crystallinity were able to realize. Moreover, the concentrations of oxygen and carbon in homoepitaxial AlN film were detected as approximately 2 x 1017 cm-3 and 1 x 1017 cm-3 by SIMS characteristic. Therefore, when using a low off AlN substrate, optimization of the growth conditions is essential for high quality homoepitaxial AlN films. Moreover, we have fabricated the AlGaN/AlN multi quantum well (MQW) on these underlying layers. The quality of these MQW was also strongly dependent by the underlying layer.

8986-7, Session 2

The growth optimization for high-quality crack-free GaN on pre-strained Si (111)

(Invited Paper)

Wang Nang Wang, C. Liu, Univ. of Bath (United Kingdom); Hao-Chung Kuo, C. Y. Chen, Taiwan Semiconductor Manufacturing Co. Ltd. (Taiwan) and National Chiao Tung Univ. (Taiwan); C. J. Sun, G. T. Chen, M. S. Hu, Veeco Taiwan, Inc. (Taiwan); A. Paranjpe, George Papasouliotis, Veeco Instruments Inc. (United States)

The pre-strained Si(111) wafers with different convex and concave bowing are used to study the effect of the various stress on the thickness and wavelength uniformity, crystal quality, PL, and EL performance of the LED on Si device. A 10-20 % improvement of the quality of the GaN on Si(111) was observed for IR laser treated wafers with convex bowing. Raman, PL, and EL all indicated a device with a more relaxed state. The systematic growth optimization in the growth methods for insertion layers and GaN growth was conducted. The effect of the temperature and thickness of the insertion layers upon compressive stress were studied systematically. There is a clear maximum compressive built up growing insertion layer of 10-15 nm around 850oC. There observed a linear trend on the quality of the GaN using 850 to 1030oC to grow the insertion layer. The XRC (002) shows the best with the 850oC insertion layer and the worst with the 1020oC insertion layer. The XRC (102) is just the opposite with the best result from the highest insertion growth temperature. These results indicate that the AlGaN insertion layer using lower temperature induces higher compressive strain and better reduction in screw dislocations shown by the narrower XRC (002) FWHM. Higher temperature AlGaN insertion layer seems to induce smaller compressive strain but more effective in reducing the overall defects density shown in the narrower XRC (102). The Silane doping can increase the tensile stress build up very significantly. This report shows that critical doping level of Silane up to 6x 1018/cm3 can still maintain a reasonable compressive stress even with a single layers thickness over 4 um. The systematic optimisation on the growth of GaN after the insertion layer allows us to grow a continuous 4 um GaN with total GaN thickness over 5 um. The GaN achieved the XRC (002) and (102) of 336" and 419" respectively using a three step GaN growth after the insertion layer.

8986-8, Session 2

GaN on Si: a promising route for integrated photonics *(Invited Paper)*

Fabrice Semond, Mohammad J. Rashid, Guillaume Gommé, Sylvain Sergent, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France); Bruno Gayral, Diane Sam-Giao, Commissariat à l'Énergie Atomique (France); Philippe Boucaud, Delphine Néel, Xavier Checoury, Institut d'Électronique Fondamentale (France) and Univ. Paris Sud (France); Thierry Guillet, Christelle Brimont, Meletios Mexis, Lab. Charles Coulomb (France); François Réveret, Joel Leymarie, Institut Pascal (France); Sophie Bouchoule, Lab. de Photonique et de Nanostructures (France)

Gallium nitride (GaN) materials are already playing an important role in the fabrication of practical optoelectronic devices such as light emitting diodes and laser diodes. So far, most of GaN-based epilayers used for the fabrication of such devices are epitaxially grown on sapphire and silicon carbide substrates. However, many players in the field are also looking for a cheapest route using GaN-based epilayers grown on silicon substrates. In this paper, we show that growing nitrides on silicon is not only a question of price but it also opens many interesting opportunities for the fabrication of photonic devices. For instance, AlN-based microdisks containing GaN quantum dots have been fabricated exhibiting quality factors up to 7000 at 400 nm. On the other hand, photonic crystal cavities with quality factors up to 4400 at 395 nm and 2300 at 358 nm are achieved. Growth issues as well as the fabrication process and characterization of such optical resonators will be discussed. Planar microcavities are also very interesting photonic devices to achieve strong light-matter coupling and lasing but growth of crack-free high-reflectivity nitride-based distributed Bragg reflectors (DBRs) is still very challenging. In this paper we show that using patterned silicon substrates high-reflectivity crack-free DBRs could be grown and then strong light-matter coupling and lasing could be achieved on silicon substrates. We believe that these results represent important breakthroughs for the development of GaN-based optoelectronic devices integrated on silicon.

8986-9, Session 2

Crystal quality improvement of semipolar (20-21) GaN on patterned sapphire substrates by in-situ deposited SiN mask

Tobias Meisch, Maryam Alimoradi-Jazi, Univ. Ulm (Germany); Benjamin Neuschl, Martin Klein, Ingo Tischer, Klaus Thonke, University of Ulm (Germany); Ferdinand Scholz, Univ. Ulm (Germany)

In order to avoid or to reduce the strong internal piezoelectric fields in GaN based heterostructures used for optoelectronic devices, the growth in non-c-directions seems to be a promising way. In particular, the (20-21) orientation has been found to be most appropriate for such devices. However, typically small GaN substrates cut from thick HVPE-grown c-plane wafers have to be used, limited in size of a few square mm. This size limitation can be overcome by growing such layers on foreign substrates like sapphire with unusual orientation. We present our results of (20-21) GaN growth on (22-43) patterned sapphire substrates. The substrates get patterned in such a way, that trenches with c-plane-like facets are formed. On these facets, the GaN growth starts in c-direction and forms triangularly shaped stripes coalescing to a fairly smooth (20-21) surface after a suitable growth time. Fairly high growth temperatures of about 1130 °C lead to improved selectivity of the initial GaN growth. Subsequently, a reduced temperature of about 1040 °C pushes the growth in c-direction and helps to suppress the development of parasitic facets. X-ray rocking curves (RC) measured parallel to the stripes of the symmetric (20-21) reflection show a FWHM of 675 arcsec. RC measurements of the (0002) reflection show a FWHM of just 70 arcsec indicating very good crystalline quality. We currently work on the overgrowth of such layers by HVPE in order to get thicker (20-21) GaN layers where the surface can be eventually improved by polishing.

8986-10, Session 2

Low extended defect density non-polar a-plane GaN films grown on nanowire templates

Hsun Chih Kuo, Tae Su Oh, S. J. Kim, Xiaoqing Pan, Pei-Cheng Ku, Univ. of Michigan (United States)

Low cost and high quality non-polar GaN substrates are strongly demanded for high-efficiency blue-green LEDs and lasers. It has been extensively reported that light emitters fabricated on non-polar or semi-polar substrates possess many advantages compared to c-plane devices. Several growth techniques have been developed to decrease the extended defect densities in nonpolar GaN films. Recently, we analyzed defect structures of a-plane GaN films grown on nanowire templates on r-plane sapphires. It was shown that small-angle tilts and twists of the nanowires were the main cause of defects in the GaN films. In this report, we propose to reduce the small-angle tilted and twisted nanowires by using a two-stage growth process. Once the first GaN thin film is coalesced from the nanowire template, we grow the nanowires again. The second nanowire template can exhibit a much smaller number of tilted and twisted nanowires. As a result, the extended defect density of the resulting GaN film can be greatly reduced.

8986-11, Session 3

New directions in GaN material research: thinner and smaller *(Invited Paper)*

Jung Han, Yale Univ. (United States)

The past two decades have witnessed phenomenal progress in optoelectronic display and illumination devices enabled by AlGaInN (III-N). As the technology of conventional devices enters commercial maturity, innovation is called for continual advances in device applications.

In this talk we will discuss the possibility of extending III-N devices in the directions of flexible and large-area applications. Our recent work in using electrochemical etching to achieve layer slicing will be presented with preliminary device demonstrations. We envision new possibilities in the manufacture of ultrathin and flexible GaN devices for photonic, electronic, and piezotronic applications.

To circumvent the difficulty in the growth of GaN on silicon, we investigated the concept of evolutionary growth combining modern fabrication techniques with epitaxy to provide new freedoms in tackling

this grand challenge. The result of preparing high quality, low dislocation GaN on amorphous SiO2 will be reported.

8986-12, Session 3

Application of BN for GaN devices *(Invited Paper)*

Yasuyuki Kobayashi, Hirosaki Univ. (Japan); Kazuhide Kumakura, Tetsuya Akasaka, Hideki Yamamoto, NTT Basic Research Labs. (Japan); Toshiki Makimoto, Waseda Univ. (Japan)

Nitride semiconductors are the preferential choice in various devices applications, such as optoelectronics and high-power electronics. These GaN-based device structures can be grown on sapphire, silicon carbide, and silicon substrates, but not on large, flexible, and affordable substrates, such as polycrystalline or amorphous substrates. Several techniques, including laser lift-off and chemical lift-off, have been studied for transferring the GaN-based structures from the sapphire substrates to other substrates, but those methods still have several disadvantages. Here we demonstrate that hexagonal boron nitride (h-BN) can form a release layer that enables the mechanical transfer of GaN-based device structure onto foreign substrates [1]. A flat single-crystal wurtzite GaN layer can be grown on AlN or AlGaN layer on h-BN grown on a sapphire substrate. AlGaN/GaN heterostructures and InGaN/GaN multiple-quantum-well (MQW) structures grown on h-BN-buffered sapphire substrates, ranging in area from five millimeters square to two centimeters square, are mechanically released from the host substrates and successfully transferred onto other substrates. X-ray diffraction and photoluminescence of the MQW before and after the transfer demonstrate that the MQW structure retains original crystal quality even after the transfer processes. In electroluminescence (EL) spectra of transferred light-emitting diode (LED) and conventional LED, the EL intensities from the transferred LED were comparable to or higher than the intensities from the conventional LED on low-temperature AlN buffer layer, indicating again that the MQW preserves its original quality after the transfer.

[1] Y. Kobayashi et al., Nature, Vol. 484, pp.223-227, 2012.

8986-13, Session 3

RF-MBE growth of GaN on alpha-Ga2O3 and mist CVD growth of Ga2O3 on GaN

Tohru Honda, Tomohiro Yamaguchi, Takumi Hatakeyama, Daiki Tajimi, Yohei Sugiura, Kogakuin Univ. (Japan)

GaN and related alloys are one of the promising materials for applications in optoelectronic devices. These materials are typically grown on sapphire substrates. Recently, the growth of high-quality alpha-Ga2O3 on a sapphire substrate was reported by mist chemical vapor deposition (CVD) [1]. In this study, radio-frequency plasma-assisted molecular beam epitaxy (RF-MBE) growth of GaN on alpha-Ga2O3, which was deposited on a sapphire substrate by mist CVD, was reported. The growth of Ga2O3 on GaN was also attempted by mist CVD.

For the growth of GaN on alpha-Ga2O3, the alpha-Ga2O3 layers were grown on (0001) sapphire substrates by mist CVD. Typical full-width at half maximum (FWHM) value of (0006) alpha-Ga2O3 rocking curve measured by X-ray diffraction (XRD) was approximately 100 arcsec. When alpha-Ga2O3 was annealed in a vacuum, the RHEED diffraction pattern intensity of alpha-Ga2O3 started to weaken at 620 C. From the result of XRD theta-2theta scan measurement, the new diffraction peaks different from the peaks of alpha-Ga2O3 were observed in the sample annealed at over 660 C. This suggests that the transformation of alpha-Ga2O3 to other structures occurred at over 620 C in a vacuum. Therefore, the GaN films were grown below 620 C. The epitaxial relationship was [0001]GaN//[0001]alpha-Ga2O3//[0001]sapphire and <10-10>GaN//<11-20>alpha-Ga2O3//<11-20>alpha-Al2O3. The growth of Ga2O3 by mist CVD on GaN will also be reported.

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8986-14, Session 3

The growth of hexagonal GaN-on-Si(100) using pulsed laser deposition

Kun-Ching Shen, Ming-Chien Jiang, Hsu-Hung Hsueh, Yu-Cheng Kao, Ray-Hua Horng, National Chung Hsing Univ. (Taiwan); Dong-Sing Wuu, National Chung Hsing Univ. (Taiwan) and Da-Yeh Univ. (Taiwan)

The fabrication of hexagonal GaN-on-Si(100) template using pulsed laser deposition (PLD) was employed in the development of GaN-on-Si technology. In contrast to common GaN-on-sapphire and GaN-on-Si(111) technologies, the use of PLD on the GaN-on-Si(100) development provides a low-cost and large-area single crystalline GaN template for the GaN device applications, via a single growth process without any interlayer or interruption layer. The evolution of GaN growth mechanism on Si(100) substrate with various growth times is established by the SEM and TEM data, which clearly indicated that the contribution of growth principle of PLD and N2 plasma nitridation induced a hexagonal GaN nucleation and facilitated further the hexagonal GaN film growth. The growth mode of GaN films gradually changes from island growth to layer growth when the growth time increases up to 2hrs. Moreover, no significant GaN meltback was found on the GaN template surface due to the high-temperature operation of PLD. The GaN template was subjected to MOCVD treatment to regrow a GaN layer. The results of X-ray diffraction analysis and photoluminescence measurement show the reliability of the GaN-on-Si(100) template and are promising for the development of the GaN-on-Si technology using PLD technique.

8986-15, Session 3

Defect-assisted exfoliation of GaN/InGaN flexible nanomembranes for optoelectronic applications

Rami T. ElAfandy, Abdul Majid Mohammed, Ahmed B. Slimane, Ahmed A. Al-Jabr, Tien Khee Ng, Boon S. Ooi, King Abdullah Univ. of Science and Technology (Saudi Arabia)

We report on the defect assisted exfoliation of gallium nitride (GaN) or indium gallium nitride (InGaN) nanomembranes using ultraviolet assisted electroless wet etching in hydrofluoric acid based solutions. Surface defects are induced through physical bombardment with different ions including argon (Ar+) or protons (H+) in inductively coupled plasma (ICP) system. Through masking certain features or using different ICP powers, the group III nitrides nanomembranes can be exfoliated with different shapes (ribbons, rings, pads) or different thicknesses (tens of nanometers), respectively. Once successfully exfoliated, several techniques including rapid thermal annealing (RTA) are applied to heal the bombarded surfacet and improve the nanomembranes crystal quality. High resolution transmission electron microscopy (HRTEM) is employed to image the crystalline quality and micro-photoluminescence (PL) measurements are used to monitor the nanomembrane optical emission characteristics through the bombardment, exfoliation and annealing processes. The GaN nanomembranes can be transferred to a handler substrates for overgrowth using NH3 source MBE, HVPE or MOCVD for subsequent overgrowth. The unstrained epitaxy grown onto these nanomembranes may resolve the strain problem caused by the lattice mismatch of gallium nitride with other common pseudo-substrate. The exfoliated nanomembranes with thicknesses less than 50 nm are highly flexible and thus are successfully transferred to flexible substrates such

as Polydimethylsiloxane (PDMS) without any induced fracture. Since varying the indium composition can span the whole visible range, the transferred InGaN nanomembranes open a new way of fabricating flexible photonics based devices.

8986-16, Session 4

Defects in nitride semiconductors *(Invited Paper)*

Anna Cavallini, Univ. degli Studi di Bologna (Italy)

Piezo-electric III-nitride semiconductors raise an ever increasing interest since they are very well suited for heterostructures for applications in solid state lighting in the spectral range from visible to ultraviolet as well as in power electronics, in spite of some critical weaknesses due to their high dislocation density. In addition, surface defects such as V-shaped defects and trench defects are also present. Alloying of GaN with In or Al leads to even a more complex scenario, as In atoms easily segregate at dislocations, changing their properties. While the microstructures of defects in nitrides are well known, their electronic properties are still under debate.

Following a brief overview of the current to-date knowledge of the defects in nitrides, this contribution focuses on the electrical and optical properties of GaN structures and Al/In GaN ternary alloys to evidence the role of the strain and the composition on the electrical properties of dislocations in III-nitrides. Going deeper into a specific topic, the present work reports on the characterization of InGaN/GaN based LED structures as a function of their dislocation density. Surface morphology and surface defect structures have been studied by Atomic Force Microscopy (AFM), while the electrical properties of defects have been investigated by Electron Beam Induced Current (EBIC) and Deep Level transient Spectroscopy (DLTS). These achievements are related to the luminescence properties of these LEDs, examined by electroluminescence.

8986-17, Session 4

Strain and charge density mapping of piezoelectric semiconductor heterostructures by sub-nanometer resolution inline electron holography *(Invited Paper)*

Sang Ho Oh, Pohang Univ. of Science and Technology (Korea, Republic of)

Typical GaN-based light emitting diodes (LEDs) suffer from efficiency droop, a decrease of their efficiency as the injection current increases. In conventional InGaN/GaN multi-quantum wells (MQWs) grown along the [0001] polar direction, internal electric fields are developed across the MQWs largely due to the piezoelectric polarization induced by the lattice misfit strain. We show that strain as well as associated charge distributions can be mapped quantitatively across all the functional layers constituting a LED, from n-type GaN, InGaN/GaN MQWs, to p-type GaN with sub-nm spatial resolution using recently developed inline electron holography technique. The obtained strain maps were verified by finite element simulations and confirmed that not only InGaN but also GaN in the MQW structure are strained in a complementary manner. By comparative analysis of the total charge density map with the polarization charge map we were able to detect an asymmetric screening of the polarization charges. We also investigated an InGaN/GaN double quantum well structure grown along the [11-20] nonpolar direction. Unexpectedly, the obtained electrostatic potential showed a non-flat band profile across the InGaN and GaN layers, indicating an asymmetric charge distribution across their interfaces. These charges appeared to be localized at the interfaces with opposite signs at the respective interfaces, very similar to polarization-induced sheet charges typically bound to interfaces. The origin of this charge distribution is still unclear but can be understood in consideration of the strong strain gradient resulting from the alternating strain with opposite signs in InGaN (compressive strain) and GaN (tensile strain) layers.

8986-18, Session 4

Suppression of thermal conductivity in InxGa1-xN alloys by nanometer-scale disorder *(Invited Paper)*

Trong V. Tong, Univ. of Illinois at Urbana-Champaign (United States)

We have systematically measured the room-temperature thermal conductivity of epitaxial layers of InxGa1-xN alloys with 15 different Indium compositions ranging from 0.08 to 0.98 by time-domain thermoreflectance method. The data are compared to the estimates of the strength of phonon scattering by cation disorder. The thermal conductivity is in good agreement with the theoretical modeling results based on the mass difference for In rich ($x > 0.9$) and Ga-rich ($x < 0.2$) compositions. At intermediate compositions ($0.2 < x < 0.9$), the thermal conductivity is strongly suppressed below the values expected for homogeneous alloys. We attribute this suppression of thermal conductivity to phonon scattering by nanometer-scale compositional inhomogeneities in alloys.

8986-19, Session 4

Measurement of the indium concentration in high-indium content InGaN layers by scanning transmission electron microscopy and atom probe tomography *(Invited Paper)*

Andreas Rosenauer, Knut Müller, Thorsten Mehrtens, Marco Schowalter, Timo Aschenbrenner, Carsten Kruse, Detlef Hommel, Univ. Bremen (Germany); Lars Hoffmann, Andreas Hangleiter, Technische Univ. Braunschweig (Germany); Pyuck-Pa Choi, Dierk Raabe, Max-Planck-Institut für Eisenforschung GmbH (Germany)

In this contribution we demonstrate a method for measurement of indium concentration in InGaN by scanning transmission electron microscopy using a high angle annular dark field detector. The intensity of high-angle scattered electrons is dominated by thermal diffuse scattering and depends on many parameters including specimen thickness, crystal orientation, as well as characteristics of illumination and detector. The quantification of composition is based on comparison of experimental images with image simulation, for which we use the frozen lattice approximation and take the non-uniform detector sensitivity into account. Local strain fields occur in InGaN as In and Ga atoms have different covalent radii. These static atomic displacements are computed with empirical potentials and included in the simulation. To provide a reference, the simulations are conducted as a function of composition and specimen thickness. The experimental image intensity is normalized with respect to the incident electron beam, and the image is decomposed into Voronoi cells in which the intensity is averaged. Image areas with known composition are used to evaluate the specimen thickness. Interpolating these values in regions with unknown composition, elemental concentrations are obtained by a comparison with the simulated reference data set. The composition evaluation is compared with atom probe tomography using InGaN layers with high In concentration of approximately 30 % as applied in green semiconductor laser diodes. The results of the STEM measurement are in excellent agreement with composition profiles obtained by atom probe tomography. As example of application we demonstrate existence of quantum dots in InGaN layers.

8986-20, Session 4

Polarized time-resolved photoluminescence measurements of m-plane AlGaN/GaN MQWs

Daniel Rosales, Bernard Gil, Thierry Bretagnon, Univ. Montpellier 2 (France); Fan Zhang, Serdal Okur, Morteza Monavarian, Virginia Commonwealth Univ. (United States); Natalia Izioumskaia, Virginia Commonwealth University (United States); Vitaliy Avrutin, Ümit Özgür, Hadis Morkoç, Virginia Commonwealth Univ. (United States); Jacob Leach, Kyma technologies (United States)

We report polarized time resolved photoluminescence (PL) measurements of nonpolar m-plane (1-100)GaN-AlGaN multiple quantum wells (MQWs) performed in the temperature range from 10 K to 300 K. The MQWs structures were grown homoepitaxially on bulk m-plane GaN substrate. Owing to the orientation of the growth template, strain field experienced by the ternary alloy layer exhibits in-plane anisotropy which strongly modifies the valence band splitting from the common situation. The x (r) valence band state is split from the y(r), and thanks to the breaking of translational symmetry along the growth direction, the GaN-AlGaN MQW structures behave like an orthorhombic crystal with discriminative selection rules for the three polarizations. The (10-10)-oriented m-plane (10-10) orientation permits polarization measurements and PL of Gamma 1 confined excitons (z(r) valence band) can be observed at higher energy than the PL of Gamma 2 (y (r) valence band). - won't it be better to say transitions rather than PL? - The energies of these two PL lines are followed up to room temperature. We also determine the excitonic recombination dynamics for both excitons. The decay times of Gamma 1 confined excitons are shorter than those of Gamma 2 ones up to about 150 K. Then both recombination times merge to a single value. The exciton binding energies are variationaly computed to about 50 meV. This indicates that the obtained values are quite robust with temperature in these non-polar QWs for which quantum confined Stark effect is canceled by invoking symmetry arguments. We attribute this onset of thermalization to the temperature-induced increase of the density of the phonon bath, which produces a substantial reduction of coherence time of the excitons.

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8986-21, Session 4

Optical and structural nanocharacterization of extended defects in GaN nanocolumns by low-temperature scanning transmission electron microscopy cathodoluminescence

Jürgen Christen, Otto-von-Guericke-Univ. Magdeburg (Germany); Marcus Müller, Otto-von-Guericke Univ. Magdeburg (Germany); Gordon Schmidt, Christopher Karbaum, Peter Veit, Frank Bertram, Otto-von-Guericke-Univ. Magdeburg (Germany); Arne Urban, Joerg Malindretos, Angela Rizzi, Georg-August-Univ. Göttingen (Germany)

The controlled growth of GaN nanocolumns (NC) offers a potential benefit for achieving higher efficiencies of III-Nitride based optoelectronic devices due to a high surface to volume ratio. Additionally, the low defect density in NC allows the characterization of single extended defects which is of high interest for a clear understanding of the formation of these defects.

In this study we present a direct nano-scale correlation of the optical properties with the actual real crystalline structure of single GaN NCs using low temperature CL spectroscopy in a scanning transmission electron microscope (STEM).

The sample was grown by molecular-beam epitaxy on pre-patterned GaN(0001) templates leading to a homogeneous formation of hexagonal Ga-polar NCs with semi-polar facetted tips. Cross-sectional TEM and STEM investigations reveal the formation of basal plane stacking faults within several NCs.

Direct correlation of the high angle annular dark field image (HAADF) with the simultaneously recorded panchromatic CL mapping at 15 K exhibits the highest CL intensity from the GaN NCs. The spatially averaged CL spectrum from the NC region shows an intense near band edge emission of GaN at 356 nm accompanied by broad defect related luminescence band between 360 nm – 405 nm. Monochromatic CL mappings at 363 mm clearly resolve the emission of BSF I1 within the GaN NC. Additionally, we observe a luminescence at the spectral positions of BSFs type I2 at 373 nm and a luminescence from extrinsic BSFs at 378 nm which can be directly correlated to the defects in the HAADF contrast.

8986-22, Session 5

Integrated photonics on silicon with wide bandgap GaN semiconductor *(Invited Paper)*

Nicolas Grandjean, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

In this presentation we will present the properties of III-nitrides based photonic structures integrated on silicon. Wide-bandgap III-nitride compounds offer attractive features such as transparency over the visible spectrum and low losses in the mid-infrared. We will start discussing materials issues and then review various approaches to prepare high quality factor (Q) optical cavities and low-loss waveguides. We will demonstrate that two-dimensional photonic crystal cavities can be achieved with thin membranes prepared from GaN epilayers epitaxially grown on silicon substrate. Such photonic structures exhibit decent optical properties both in the blue-green spectral range [1] and in the near infra-red [2].

[1] N. Vico Trivino, G. Rossbach, U. Dharanipathy, J. Levrat, A. Castiglia, J.-F. Carlin, K. Atlasov, R. Butté, R. Houdré, N. Grandjean, Appl. Phys. Lett. 100, 071103 (2012)

[2] N. Vico Trivino, U. Dharanipathy, J.F. Carlin, Z. Diao, R. Houdré, and N. Grandjean, Appl. Phys. Lett. 102, 081120 (2013)

8986-23, Session 5

Gain saturation in InGaN superluminescent diodes

Anna Kafar, Szymon Stanczyk, Institute of High Pressure Physics (Poland); Grzegorz Targowski, TopGaN Ltd. (Poland); Tadek Suski, Piotr Perlin, Institute of High Pressure Physics (Poland)

The gain saturation is a crucial factor limiting achievable output power of superluminescent diodes (SLD), as it exponentially depends on optical gain value. Contrary to laser diodes, in SLDs gain is increasing with the increasing current even much above the transparency conditions. Therefore, SLDs provide us with an unique possibility to examine gain under high current densities (high carrier injection).

In our work we examined SLDs fabricated in a "j-shape" ridge-waveguide geometry having chips of the length of 700 ?m and 1000 ?m, emitting in the blue-violet region. By comparing the amplified spontaneous emission measured along the device waveguide with true spontaneous emission measured in perpendicular direction, we are able to extract optical gain as a function of injected current.

We show, that in our devices spontaneous emission exhibits a square-root-like dependence on current which is commonly associated with the presence of "droop", like in case of nitride light emitting diodes. However, along the waveguide axis, fast processes of stimulated recombination dominate which eliminates the efficiency reduction. Calculated optical gain shows a substantial saturation for current densities above 8 kA/cm2. Mechanisms of gain saturation will be discussed.

8986-24, Session 5

Time-resolved photoluminescence of GaN/AlN quantum dots emitting at 300 nm

Julien Sellés, Guillaume Cassabois, Thierry Guillet, Univ. Montpellier 2 (France); Fabrice Semond, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France)

Properties of self-assembled quantum dots (QDs), often referred to as artificial atoms in solid state, are very interesting in order to study physical effects specific to single quantum systems such as the single-photon emission. Thanks to their huge vertical quantum confinement, GaN QDs are emitting even at room temperature and on a large UV range. This peculiarity makes GaN QDs good candidates for fundamental physics as well as conception of devices such as UV-LEDs.

In so-called thick QDs (height larger than 2.3 nm), the energies of the confined electronic states are determined by the quantum confined Stark effect. On the contrary, in thin QDs (height smaller than 2.3 nm) the quantum confinement plays the major role, thus leading to a significantly smaller homogeneous linewidth and to the resolution of the exciton fine-structure splitting [Kindel, PRB81, 241309]. As far as time-resolved measurements are concerned, several papers reported experiments in thick QDs emitting at 350nm or more, either in polar [Bretagnon, PRB73, 113304] or non-polar nanostructures [Founta, APL86, 171901].

We report photoluminescence decay time measurements in thin GaN QDs emitting between 280nm and 360nm. For QDs emitting at 290nm we observe a monoexponential decay and the abscence of any red shift for the luminescence spectrum shows that we are in the regime of a single electronhole pair per dot. In this case, we measure the intrinsic radiative recombination time, without any perturbation due to the Stark effect. We find a radiative lifetime of about 350 ps in good agreement with our theoritical model.

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8986-25, Session 5

Cathodoluminescence study on defects in strained InGaN green laser diodes grown on semi-polar (20-21) GaN substrate

Lucja Marona, Marcin Sarzynski, Ewa Grzanka, Przemek Wisniewski, Piotr Perlin, Tadek Suski, Institute of High Pressure Physics (Poland); Robert Czernecki, TopGaN Ltd. (Poland); Robert Kucharski, Ammono Sp. z o.o. (Poland)

Nitride-based optoelectronic devices, such as light emitting diodes and laser diodes, are commonly grown along polar GaN(0001) direction. A consequence of such a design is the presence of built-in and strain induced electric fields resulting in a phenomenon known as the Quantum Confined Stark Effect. This effect consists in the reduction of holes and electrons wavefunctions overlap and lowers their radiative recombination rates and, accordingly, the radiative efficiency. We can avoid all these detrimental effects by choosing a nonpolar growth plane like (20-21) semi-polar surface. Additionally, this growth direction is known to be successful for creation high In content, green light emitters. We studied the InxGa1-xN/InyGa1-yN multiquantum well built on AlGaN bottom cladding layer and sandwiched between GaN waveguides. The structure showed optically pumped lasing at 503 nm. We performed cathodoluminescence (CL) measurements of this structure. The CL images showed checkered–like pattern corresponding to nonradiative defects. This checkered pattern is visible for the wavelength characteristic for InGaN and GaN layers, but not observed in AlGaN layers. The existence of such a pattern could be explained by relaxation of the epitaxial layers due to the strain existing in the structure. To verify this concept we performed measurements of the strain in different layers by using X-ray diffraction (XRD) reciprocal space mapping (RSM). The asymmetric RSMs were taken at [12-31] and [10-10] reflections. The results indicate that the InGaN structure with the highest In-content is fully strained in the [12-31] direction and partially relaxed in the [10-10] direction.

8986-26, Session 5

Origin of non-radiative losses in thick InGaN/GaN QWs

Felix Nippert, Technische Univ. Berlin (Germany); Anna Nirschl, Ines Pietzonka, Hans-Jürgen Lugauer, OSRAM Opto Semiconductors GmbH (Germany); Thomas Kure, Christian Nenstiel, Gordon Callsen, Max Bügler, Technische Univ. Berlin (Germany); Martin Strassburg, OSRAM Opto Semiconductors GmbH (Germany); Axel Hoffmann, Technische Univ. Berlin (Germany)

Efficient white light emitters require a drastic increase in efficacy of green LEDs. For this purpose we investigate InGaN quantum wells embedded in GaN, grown on c-sapphire by MOCVD. The QW thickness is varied between 2.2nm and 3.8nm, tuning the emission from 490nm and 540nm. The Indium content of the active regions is around 20%. The samples show a very large Stokes shift ranging from 200meV (for 2.2nm thick wells) to 500meV (for 3.8nm thick wells). This is due to the quantum-confined Stark effect, as can be seen in the power-dependent blue shift of the emission.

Temperature-dependent photoluminescence shows a drastic decrease in room temperature efficiency for well thicknesses above 3nm, indicating a strong increase in non-radiative losses in these samples. One cause for this is a longer radiative recombination time because of the larger spatial separation of electrons and holes. However, in addition, there may also be an increased amount of defects in the material grown closer to its critical thickness. To evaluate this, we perform time- and spectrally-resolved photoluminescence and find that the thinner samples conform to a Pseudo-DAP-Model, where electrons and holes are randomly distributed along the interfaces, which leads to a slight red-shift in emission over time after excitation. At 3.8nm thickness however, the red-shift is much more pronounced and time-delayed spectra show a constant emission on the red flank. This cannot be explained by QCSE or the Pseudo-DAP-Model and is a clear indicator of long-lived defect states.

8986-27, Session 5

Point defect management in GaN by Fermi-level control during growth

Marc P. Hoffmann, North Carolina State Univ. (United States); James Tweedie, North Carolina State University (United States); Ronny Kirste, Zachary Bryan, Isaac S. Bryan, North Carolina State Univ. (United States); Michael Gerhold, U.S. Army Research Office (United States); Zlatko Sitar, Ramon Collazo, North Carolina State Univ. (United States)

In n- and p-type doped AlGaN films grown by MOCVD, point defects such as hydrogen, carbon, nitrogen vacancies and their corresponding complexes lead to dopant compensation, resulting in high resistivity and

low mobilities. Theoretical and experimental results demonstrate that the use of UV-light above bandgap illumination during growth can be applied to control point defect incorporation in p-type and n-type AlGaN. This control is achieved by modifying the quasi Fermi-levels, which controls the incorporation of compensating defects by changing their formation energy. In p-type GaN:Mg the passivation and compensation of Mg acceptors by H and V(N) can be significantly reduced by above-bandgap illumination. The H concentration is reduced by an order of magnitude and no post growth annealing is needed to activate the samples. In addition, UV-growth leads to lower resistivity values and a decrease in defect photoluminescence (2.85 eV) in heavily Mg-doped GaN. In Si doped (n-type) GaN and AlGaN, UV-illumination during the growth, reduces the Si donor compensation by acceptor defects such as impurities or native defects (e.g. C or V(Al)). Here, UV-growth leads to an increase in mobility and free carrier concentrations with a maximum increase of an order of magnitude in AlGaN films grown on sapphire for doping within the self-compensation regime. A significant reduction in PL intensity related to compensating defects is also observed in these n-type films grown under UV illumination. Finally, it can be demonstrated that the UV-illumination can increase the efficiency of GaN p/n-junctions.

8986-28, Session 6

Simulatenous optical and structural investigation of defects in polar, semipolar, and nonpolar nitride heterostructures *(Invited Paper)*

Frank Bertram, Otto-von-Guericke-Univ. Magdeburg (Germany)

The combination of luminescence spectroscopy - in particular at liquid He temperatures - with the high spatial resolution of a scanning transmission electron microscopy (STEM) (dx < 1 nm at RT, dx < 5 nm at 10 K), provides a unique, extremely powerful tool for the optical nano-characterization of semiconductors. The CL-intensity is collected simultaneously to the STEM signal - typically chemical sensitive HAADF Z-contrast.

Typical results which will be presented include nm-scale correlation of the optical properties optical properties in polar, non- and semi-polar GaN: strain engineering and dislocation reduction by AlN interlayers in GaN-on-Si structures, lattice matched AlInN/GaN distributed Bragg reflectors; minority carrier diffusion lengths of ?< 17 nm, as well as the efficient carrier transfer over > 150 nm into quantum wells are directly measured in STEM-CL. The impact of structural defects like dislocations is directly visualized: Special emphasis is given to the formation and in particular the annihilation and the prevention of basal plane as well as prismatic stacking faults in non- and semi-polar GaN.

8986-29, Session 6

Radiative and nonradiative decay of excitons in GaN nanowires *(Invited Paper)*

Christian Hauswald, Timur Flissikowski, Holger Grahn, Lutz Geelhaar, Henning Riechert, Oliver Brandt, Paul-Drude-Institut für Festkörperelektronik (Germany)

Spontaneously formed GaN nanowires exhibit a high structural perfection regardless of the substrate. Extended defects which plague epitaxial GaN films grown on foreign substrates are absent in nanowires. Hence, it is expected that the exciton lifetimes of GaN nanowires rival those of high quality epitaxial GaN layers. However, for thin GaN nanowires it has been suggested that nonradiative surface recombination limits the exciton lifetime even at low temperatures.

Here, we review our investigations of the exciton decay dynamics in GaN nanowires. We focus on different ordered nanowire arrays having narrow diameter distributions and on spontaneously formed nanowire ensembles with broad diameter distributions all fabricated by molecular beam epitaxy on Si. The photoluminescence transients measured at low temperatures exhibit a biexponential decay, which impedes the extraction of a single lifetime. We show that this decay is not caused by the nanowire surface but rather by a field-induced coupling of bound exciton states. Since the extracted lifetimes are shorter than expected for purely radiative recombination, our results suggest the presence of a nonradiative decay channel different from the nanowire surface.

Since the unintentional coalescence of nanowires may result in the formation of structural defects, we investigate GaN nanowire ensembles on different substrates exhibiting vastly different coalescence degrees. The exciton lifetimes for all these samples are similar, demonstrating that this nonradiative channel is also not related to coalescence. Instead the low growth temperature in molecular beam epitaxy and the correspondingly high point defect density may ultimately limit the exciton lifetime in GaN nanowires.

8986-30, Session 6

Direct verification of commonly-used rate-equation model in III-nitride material by detailed analysis of photoluminescence decay curves

Hitoshi Manabe, Kanazawa Institute of Technology (Japan); Hiroki Goto, Haruo Sunakawa, Toshiharu Matsueda, Furukawa Co., Ltd. (Japan); Akiko Okada, Waseda Univ. (Japan); Hidetoshi Shinohara, Hiromi Nishihara, Hiroshi Goto, Toshiba Machine Co., Ltd. (Japan); Jun Mizuno, Waseda Univ. (Japan); Akira Usui, Furukawa Co., Ltd. (Japan); Atsushi A. Yamaguchi, Kanazawa Institute of Technology (Japan)

“Efficiency droop” in LEDs is a big problem for high-power applications. The droop characteristics are usually analyzed by the following rate equation called “ABC model”; dn/dt=-An-Bn^2-Cn^3, which suggests that the droop phenomenon is caused by Auger recombination. In this study, we investigated carrier dynamics in III-nitride material by time-resolved photoluminescence (PL) measurements to directly check the validity of the rate equation. We prepared the following three GaN samples with different quality; (1) a free-standing GaN substrate (dislocation density (DD) ~ 10^6 /cm^2), (2) an MOCVD-GaN film on a sapphire substrate (DD ~ 10^8 /cm^2), and (3) a newly developed GaN template fabricated by nano-channel facet-initiated epitaxial lateral overgrowth (nano-FIELO) technique (DD ~ 10^7 /cm^2). The PL decay curves for these samples were fitted by the ABC model. Here, we took the coefficients B and C as common values for all the samples while the coefficient A can be different from sample to sample, because the B and C values are material parameters and the coefficient A is quality-dependent in the model. The fitting was, however, not successful, and it is not possible to reproduce all the decay curves. In addition, the obtained B and C values are quite different from commonly-used values in literature. These results indicate that the ABC model is not valid at least for GaN material. On the other hand, the decay curves can be well-fitted by the stretched exponential functions usually used for amorphous semiconductors, suggesting that GaN material has the aspect of disordered systems.

8986-31, Session 6

Linear and nonlinear optical properties of polarity-controlled AlGaN waveguides for integrated optics

Martin Rigler, Univ. of Ljubljana (Slovenia); Jože Buh, Jožef Stefan Institute (Slovenia); Marc P. Hoffman, Ronny Kirste, Wei Guo, Isaac S. Bryan, North Carolina State Univ. (United States);

Seiji Mita, HexaTech, Inc. (United States); Ramon Collazo, Zlatko Sitar, North Carolina State Univ. (United States); Marko Zgonik, Univ. of Ljubljana (Slovenia) and Jo?ef Stefan Institute (Slovenia)

Laser technology for generation of ultraviolet light involves a number of challenges such as high threshold pump power, lack of transparent and UV resistant optical materials, increased sensitivity to defects and surface roughness, etc. Recent research on polarity control in III-nitride semiconductors shows great potential of using GaN and AlN for laser sources in the UV region through nonlinear light conversion. Optical phase matching is crucial for the effective frequency conversion. Unfortunately, conventional phase matching techniques cannot be used in AlGaN thin films; however, quasi phase matching (QPM) is possible if periodic modification of the nonlinear crystal is produced to correct the relative phase mismatch at regular intervals without matching the phase velocities. The AlGaN periodic structures used in these experiments are fabricated in such a way that the orientation of the crystalline c-axis is periodically inverted as a function of position. In the case of AlxGa1-xN the growth direction is denoted as III-metal-polar (c+) or N-polar (c– orientation). The direction of crystal growth is governed by the substrate preparation. The III-metal-polar AlxGa1-xN is grown on an annealed AlN nucleation layer, while the N-polar AlGaN is grown on a nitrated sapphire substrate.

In this research, refractive indices of III-metal-polar and N-polar AlGaN thin films are measured by ellipsometry and compared to our previous prism-coupling measurements. Also, mode propagation losses at several wavelengths are measured and compared between the different AlGaN waveguides. Second harmonic signal in the visible region is obtained in GaN waveguides by modal phase matching to test the nonlinear response. Data generated through this research is crucial for achieving efficient integrated UV laser source.

8986-32, Session 6

Correlation of optical properties and defect structures of semipolar GaN on pre-patterned sapphire substrates using cathodoluminescence microscopy

Sebastian Metzner, Frank Bertram, Thomas Hempel, Otto-von-Guericke-Univ. Magdeburg (Germany); Tobias Meisch, Univ. Ulm (Germany); Stephan Schwaiger, Univ. Ulm (Germany) and Osram Herbrechtingen (Germany); Ferdinand Scholz, Univ. Ulm (Germany); Jürgen Christen, Otto-von-Guericke-Univ. Magdeburg (Germany)

Spatially and spectrally resolved cathodoluminescence (CL) has been performed to investigate the microscopic optical properties of semipolar {11-22}GaN grown by MOVPE on pre-patterned {10-12}sapphire. The {10-12}sapphire substrate is ~58° inclined towards the polar [0001] direction which allows to achieve trenches with a c-plane-like sidewall by reactive ion etching (RIE) with a stripe mask running parallel to {10-10}. Initially, the GaN epitaxy starts at the c-plane-like sidewalls taking advantage of well-established c-plane growth, subsequently switching to semipolar growth forms individual GaN stripes of triangular shape with semipolar {11-22} facets being parallel to the initial {10-12} sapphire surface and hence, enabling a planar semipolar surface due to coalescence.

Local CL spectra at liquid-He-temperature reveal a distinct contribution of a number of structural defects like basal plane stacking faults (BSF), prismatic stacking faults (PSF), and partial dislocations (PD) at the region where the GaN is grown into -c direction after leaving the trench. In complete contrast, the main part grown in +c benefits from an epitaxial lateral overgrowth over the mask and, therefore, exhibits pure donor-bound exciton emission. CL images of the surface show the entire +c region being homogeneous and completely free of dark spots normally representing nonradiative recombination centers. Additionally, due to a delayed coalescence process the defect structures of the –c-wing run into a void and, thus are prevented from propagating further through the coalesced layer which increases the optical quality at the surface significantly. We discuss the suitability of such semipolar GaN templates for HVPE re-growth and efficient quantum structures.

8986-33, Session 7

Growth of GaN dots with semi-polar orientations for UV LEDs fabrication *(Invited Paper)*

Julien Brault, Benjamin Damilano, Aimeric Courville, Mathieu Leroux, Abdelkarim Kahouli, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France); Borge Vinter, Univ. de Nice Sophia Antipolis (France); Philippe Vennéguès, Sébastien Chenot, Philippe de Mierry, Jean Massies, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France)

(Al,Ga)N light emitting diodes (LEDs), emitting over a large spectrum range from 360 nm (GaN) down to 210 nm (AlN), have been successfully fabricated over the last decade. Clear advantages compared to the traditional mercury lamp technology (e.g. compactness, low-power operation, lifetime) have been demonstrated. However, the LED efficiencies still need to be improved. The main causes are related to the structural quality and the p-type doping efficiency. Moreover, the symmetry change of the valence band maximum in (Al,Ga)N does not favor the (0001) orientation, which is traditionally used, for surface emitting devices. Among the current approaches, GaN nanostructures, which confine carriers along both the growth direction and the growth plane, are seen as a solution for improving the radiative recombination efficiency by strongly reducing the impact of the surrounding defects. Our approach, based on a 2D - 3D growth mode transition in molecular beam epitaxy, can lead to the spontaneous formation of GaN nanostructures on (Al,Ga)N over a broad range of Al compositions. Furthermore, the versatility of the process makes it possible to fabricate nanostructures on both (0001) oriented "polar" and (11-22) oriented "semipolar" materials. We show that the change in the crystal orientation has a strong impact on the morphological and optical properties of the nanostructures. The influence of growth conditions are also investigated by combining microscopy (AFM, TEM) and photoluminescence techniques. Finally, their potential as UV emitters will be discussed and the performances of GaN / (Al,Ga)N nanostructure-based LED demonstrators are presented.

8986-34, Session 7

GaN, InGaN, and AlGaN quantum dots in nanowires heterostructures: growth and optical properties *(Invited Paper)*

Bruno Daudin, Thomas Auzelle, Gabriel Tourbot, Karine Hestroffer, Commissariat à l'Énergie Atomique (France); Aurélie Pierret, Commissariat à l'Energie Atomique (France); Luiz Zagonel, Lab. Photons Et Matière (France) and Ctr. National de la Recherche Scientifique (France); Luiz Tizei, Sophie Meuret, Lab. de Physique des Solides (France) and Ctr. National de la Recherche Scientifique (France); Catherine Bougerol, Institut NÉEL (France) and Ctr. National de la Recherche Scientifique (France); Bruno Gayral, Commissariat à l'Énergie Atomique (France); Mathieu Kociak, Lab. de Physique des Solides (France) and Ctr. National de la Recherche Scientifique (France)

Nanowires (NWs) have emerged as a platform to build complex, self-assembled, defect-free nanostructures. In particular, the growth of single islands/discs of various III-nitride combinations (InGaN in GaN, GaN in AlN, AlGaN in AlN) are possible in nanowires heterostructures, extending

the field of experimental quantum dot elaboration. Specific to nanowires, the possiblity to disperse them makes easy the study of single objects.

In the present work, the growth of GaN disks/islands, InGaN islands as well as their optical properties at the scale of nanometer will be presented in details. A special interest will be paid to the fluctuation of composition in ternary alloy nanowires, which lead to a quantum dot-like behaviour. Based on a combination of STEM-EDX, HRTEM and microPL, it will be shown that such composition fluctuations related to the growth mode of InGaN/GaN and AlGaN/GaN NW heterostructures indeed lead to marked carrier localization effects in the luminescence spectra. This has been confirmed by cathodoluminescence at the nm scale (nanoCL) performed on a statistically significant number of isolated InGaN and AlGaN NWs. As a whole, it is shown that alloy composition fluctuations present in InGaN or AlGaN 2D layers are not eliminated in the case of nitride NWs heterostructures. On the contrary, depending on growth temperature, it appears that strain/composition fluctuation may be enhanced by NW geometry, emphasizing the dominant role of kinetics and leading to peculiar optical properties such as a reduced temperature quenching of luminescence intensity.

In the case of GaN insertions in AlN NWs, it will be further demonstrated that localization may be observed at a scale smaller than the quantum disks/quantum dots, as a consequence of the reduced exciton size in nitrides.

8986-35, Session 7

Realization of the high conversion efficiency solar cells using high InN molar fraction GaInN active layer *(Invited Paper)*

Motoaki Iwaya, Hironori Kurokawa, Yosuke Katsu, Taiji Yamamoto, Tetsuya Takeuchi, Satoshi Kamiyama, Isamu Akasaki, Meijo Univ. (Japan); Hiroshi Amano, Nagoya Univ. (Japan)

Since the bandgap of GaInN ternary alloys covers a broad range from 0.65 to 3.43 eV, these alloys are suitable for solar cell applications. Therefore, high-efficiency multijunction solar cells can be obtained using these alloys. Moreover, improvement of the conversion efficiency can be realized by combination of the other material, since GaInN can realize the wide gap energy. So far, we have realized the high conversion efficiency GaInN-based solar cells up to 4 % by improving the crystal quality of GaInN and using the concentration of sunlight. However, increase of the InN molar fraction in active layer is essential for increasing the conversion efficiency. From calculation result, increase the InN molar fraction of GaInN up to 0.30 is essential for improvement of the conversion efficiency by combination of other materials. However, when GaInN-based solar cells with a high InN molar fraction were fabricated, favorable performance was not observed. In particular, it was very difficult to achieve a high open-circuit voltage (VOC). In this study, we optimized the structure in supperlattice structure for obtaining a high VOC in GaInN-based solar cells. As the result, reduction of the In segragation is necessary to realize the GaInN-based slolar cell with high VOC. We also confirmed the suppression of the In segregation by increasing the GaN barrier growth temperature. Futhermore, we discuss the correlation of growth condition in GaInN and the device perfomance. In addition, we discuss the wafer bonding method using ITO transpearent electrodes for realization of the high perfomance multijunction solar cells.

8986-36, Session 7

Dependence of emission wavelength on the growth condition of regularly patterned InGaN/GaN quantum-well nanorod arrays

Charng-Gan Tu, Che-Hao Liao, Wen-Ming Chang, Chia-Ying Su, Yu-Feng Yao, Horng-Shyang Chen, Yean-Woei Kiang, Chih-Chung Yang, National Taiwan Univ. (Taiwan)

With the nano-imprint lithography and the pulsed growth mode of metalorganic chemical vapor deposition, a regularly-patterned, c-axis nitride NR LED array of uniform geometry with simultaneous depositions of top-face c-plane and sidewall m-plane InGaN/GaN QW structures is fabricated. In this study, regularly patterned InGaN/GaN quantum-well (QW) nanorod (NR) arrays are grown under various growth conditions of indium supply rate, QW growth temperature, and QW growth time for comparing their emission wavelength variations from the top-face c-plane and sidewall m-plane QWs based on the cathodoluminescence (CL) measurements. Generally, by increasing indium supply rate, decreasing QW growth temperature, and increasing QW growth time, the emission wavelength becomes longer. With longer emission wavelengths, the difference of emission wavelength between the top-face and sidewall QWs is smaller. Meanwhile, the variation range of the emission wavelength of the sidewall QWs over the different heights on the sidewall becomes larger. Strain state analysis based on transmission electron microscopy is undertaken to calibrate the average QW widths and average indium contents of the two groups of QW. The QW widths of the top-face QWs are significantly larger than those of the sidewall QWs. However, the indium contents of the top-face QWs are smaller than those of the sidewall QWs. On the sidewall, both QW width and indium content increase with height. The variation trends of the calibrated QW widths and indium contents are consistent with those of the CL emission wavelengths.

8986-37, Session 7

The formation of hexagonal-shaped InGaN-nanodisk on GaN-nanowire observed in plasma source molecular beam epitaxy

Tien Khee Ng, Anwar Gasim, Dongkyu Cha, Bilal Janjua, Yang Yang, King Abdullah Univ. of Science and Technology (Saudi Arabia); Shafat Jahangir, Univ. of Michigan (United States); Chao Zhao, King Abdullah Univ. of Science and Technology (Saudi Arabia); Pallab K. Bhattacharya, Univ. of Michigan (United States); Boon S. Ooi, King Abdullah Univ. of Science and Technology (Saudi Arabia)

We report on the growth kinetics of defect-free (confirmed using transmission electron microscopy, TEM) and photoluminescence (PL) efficient mushroom-like nanowires (MNW) growth in the form of ~30nm thick hexagonal-shaped InGaN-nanodisk on GaN-NW, coexisting with the conventional rod-like InGaN-nanowires (RNW) on (111)-silicon-substrate. When characterized using a confocal microscope with 458nm laser excitation, with spontaneous emission measured by sweeping the detection wavelength at ~10nm steps, a circular dark-spot MNW region transited into a bright ring and then a bright spot, corresponded to no spontaneous emission, PL peak emission at 540nm and broad PL emission of 520nm–700nm, respectively. The regular rod-like InGaN nanowire were emitting at peak wavelength of 490nm. These InGaN-nano-disk (540nm emission) were obtained during molecular-beam-epitaxy (MBE) growth, where Energy-dispersive X-ray spectroscopy (EDXS) showed evidence of indium accumulation only at the disk region. While the formation of InGaN rod-like nanowire is well-understood, the formation of the hexagonal-shaped InGaN-nanodisk-on-GaN-nanowire requires further investigation. It was postulated to arise from the highly sensitive growth kinetics during plasma-assisted MBE of InGaN at low temperature, i.e. when the substrate temperature was reduced from 800-degree-Celsius (GaN growth) to <600-degree-Celsius (InGaN growth), during which sparsely populated metal-droplet formation prevails and further accumulated more indium ad-atoms due to higher cohesive bond between metallic molecules. The preferential growth along (0001), and lower InGaN growth temperature led to strain-induced lateral crystal expansion growth of hexagonal umbrella. The understanding the growth mechanism suggested a potential way of pendeo-epitaxial growth based on the coalescence of the well-oriented and equal height InGaN hexagonal-cap.

8986-38, Session 7

Room-temperature single-photon emission from site-controlled GaN quantum dots

Mark Holmes, Kihyun Choi, Satoshi Kako, Munetaka Arita, Yasuhiko Arakawa, The Univ. of Tokyo (Japan)

Quantum dots are practical candidates for use as single photon sources, but their wide spread use in devices will require site-control during their formation stage, and also operation at room temperature. Whilst there have been reports of single photon emission from site controlled quantum dots, to date these have been achieved at cryogenic temperatures.

Here we present our latest results, in which we have succeeded in measuring single photons at room temperature from a site controlled GaN nanowire quantum dot. The emission from a single quantum dot was tracked as the temperature was raised from 4K to 300K, and the single photon statistics verified.

This result shows for the first time that site controlled quantum dots can be used for the generation of single photons at such high temperatures. The site controlled nature of the dots will allow for the fabrication of arrays of devices for quantum information processing applications.

8986-39, Session 8

Strong coupling and lasing in all-dielectric GaN microcavities at room temperature *(Invited Paper)*

Pavlos Savvidis, Foundation for Research and Technology-Hellas (Greece) and Univ. of Crete (Greece); Konstantinos Daskalakis, Foundation for Research and Technology-Hellas (Greece) and Imperial College London (United Kingdom) and Univ. of Crete (Greece); Peter Eldridge, Foundation for Research and Technology-Hellas (Greece); Emmanuil Trichas, Nikolaos Pelekanos, Univ. of Crete (Greece) and Foundation for Research and Technology-Hellas (Greece); Eleufterios Iliopoulos, Foundation for Research and Technology-Hellas (Greece) and Univ. of Crete (Greece); Eva Monroy, CEA Grenoble (France)

The realization of an electrically-pumped polariton laser - the Holy Grail in microcavity - research remains elusive. As electrical injection into ZnO and organic based microcavities is technologically challenging, GaN based microcavities operating in the strong coupling regime are currently considered as the most promising candidates for implementation of such robust, ultralow threshold, room temperature polaritonic laser devices. Several crucial factors, namely the requirement for high finesse optical cavities and uniform pumping in the active region of GaN microcavities have yet to be fully addressed. The former drastically reduces the lasing threshold of polariton lasers [1] whilst the latter, as recent optical pulsed and quasi-CW pumping experiments show [2], is necessary to obtain the relatively high carrier densities required for lasing, particularly in an electrically pumped device. Although monolithic fabrication of GaN microcavities offers many advantages it does not provide the necessary flexibility in fabrication and leads to restrictively narrow reflectivity stopbands that become comparable with the large Rabi-splitting.

In this work [3] we develop an alternative route, utilizing selective photo-electro-chemical (PEC) etching of an InGaN sacrificial layer, to produce high optical quality GaN membranes shown in Figure 1. Such membranes are integrated into an all-dielectric (SiO2/Ta2O5) high finesse (Q = 600) microcavity, to demonstrate the strong coupling regime and low threshold lasing at room temperature under non-resonant optical excitation. A nonlinear increase of the emission and line narrowing marks the onset of the lasing regime with an equivalent peak threshold power density two orders of magnitude lower than previously reported for bulk GaN microcavities. This combination of low lasing thresholds and ease of fabrication allows incorporation of quantum wells and electrical contacts into the active region, paving the way for electrically driven room temperature polariton laser devices.

[1] S. Christopoulos et al., Phys. Rev. Lett. 98, 126405 (2007)

[2] E. Trichas et al., Appl. Phys. Lett. 98, 221101 (2011)

[3] K.S. Daskalakis et al., Accepted in Appl. Phys. Lett. (2013)

8986-40, Session 8

Progress on III-nitride materials for intersubband optoelectronics *(Invited Paper)*

Mark Beeler, Edith Bellet-Amalric, CEA Grenoble (France); Catherine Bougerol, Institut NÉEL (France); Eva Monroy, CEA Grenoble (France)

III-nitride semiconductors have recently emerged as promising materials for new intersubband (ISB) devices, a technology that relies on infrared optical transitions between quantum-confined electronic states in the conduction band of quantum wells or quantum dots. The large conduction band offset, and the sub-picosecond ISB relaxation time in the GaN/AlN system renders it appealing for ultrafast photonic devices with applications in near-infrared optical telecommunication networks. Research on III-nitride ISB transitions in the far infrared is motivated by the large energy of GaN longitudinal-optical phonons, which theoretically predicts room-temperature device operation with limited thermal interference. However, decreasing the energy between electronic levels towards the THz range requires band engineering to locally reduce the polarization-induced internal electric field. In this presentation we will introduce various multilayer architectures displaying ISB transitions in the THz range with improved oscillator strength.

8986-41, Session 8

p-Type InN nanowires: towards ultrahigh speed nanoelectronics and nanophotonics

Songrui Zhao, McGill Univ. (Canada); Zetian Mi, Binh Huy Le, McGill University (Canada)

Low-dimensional compound semiconductors, such as nanowires, are of fundamental interest for future nanoelectronic and nanophotonic devices. However, p-type doping into compound semiconductor nanowires has been a universal challenge, especially for narrow bandgap materials and when the surface electron accumulation is present. In this talk, we demonstrate, for the first time, that p-type InN nanowires can be realized by direct magnesium (Mg) doping. The presence of Mg-acceptors and p-type conduction has been clearly confirmed by the low-temperature micro-photoluminescence spectroscopy and single nanowire field-effect transistor characteristics, respectively.

In this experiment, Mg-doped InN nanowires with a few doping levels were grown on Si(111) substrates by a self-catalytic growth process using a radio-frequency plasma-assisted MBE system. The nanowires exhibit non-tapered morphology and well-defined hexagonal structure, and are oriented along the c-axis, with their sidewalls being non-polar m-planes. Detailed excitation power and temperature dependent PL studies clearly revealed the Mg-acceptor energy levels, which contribute to a PL peak with an energy separation of ~60 meV from the PL peak associated with the band-to-band recombination. The background electron concentration is further estimated to be less than 1x1016 cm-3. Moreover, single nanowire field-effect transistors are fabricated by the standard e-beam lithography process, and a clear p-type transistor behaviour is observed. This is the first direct evidence showing a p-type conduction in any InN structures. A more detailed study of the hole concentration, hole mobility, and surface charge properties of Mg-doped InN nanowires is being performed and will be reported.

8986-42, Session 8

Optical characterization of highly-germanium-doped GaN nanowires

Christian Nenstiel, Max Bügler, Gordon Callsen, Technische Univ. Berlin (Germany); Jörg Schörmann, Jörg Teubert, Pascal Hille, Martin H. Eickhoff, Justus-Liebig-Univ. Giessen (Germany); Axel Hoffmann, Technische Univ. Berlin (Germany)

Recent semiconductor publications have shown that group-III-nitride nanowires (NW) are outstanding candidates for sensor and lighting applications. They offer an excellent platform for monitoring electrochemical and biochemical processes. The enhanced optical, electrical and structural properties of NW promise superior light emitters. The characteristics of NW combined with very high free carrier concentrations leads to plasmonic devices. The strong optical field enhancement in plasmonic nanostructures can modify light-matter interactions to unprecedented levels. In order to achieve these level of free carrier concentrations a systematic study of all doping effects is necessary. MOCVD grown n-type GaN epilayers have shown that Germanium is an outstanding dopant for this material compared to Silicon. Free carrier concentrations up to 1020 cm-3 are achievable at remaining high crystallinity. It doesn't introduce high levels of strain or compensation effects known from Silicon. In this contribution we present a systematical study of dopants and doping concentrations of GaN NW grown by plasma assisted MBE on (111)-Si. SEM images exhibit a high density of uniformly grown and highly aligned nanowires. The NW thickness varies from 60 to 90 nm with an average length of 700 nm. PL measurements show a very bright luminescence for all samples including the highest doping concentration, an increased Burstein-Moss-shift with higher doping concentrations and no compensation effects. Additionally µPL map scans of single NWs as well as temperature and time resolved PL have been performed, enabling a detailed study of the recombination processes within these nanostructures.

8986-43, Session 8

MOCVD-grown dislocation-free InGaN nanowires with a 2.5 eV band gap for photovoltaics

Hsun Chih Kuo, Tae Su Oh, S. J. Kim, Xiaoqing Pan, Pei-Cheng Ku, Univ. of Michigan (United States)

The III-N materials tend to exhibit very strong absorption near its band edge, which allows incident light to be absorbed within couple hundred nanometers. Therefore, wide-bandgap nitride semiconductors gain a lot of attentions in photovoltaic devices, prompting the development of InGaN solar cells with a 2.48 eV band gap that can be 4th junction of photovoltaic multi-junction devices to achieve efficiencies greater than 50%. Due to the lack of high quality InGaN films of hundreds of nanometers thickness, delivering a high performance solar cell is challenge. Recently, we reported vertically aligned dislocation-free InGaN nanowires (NWs) with an indium composition up to 18.6% using metal-organic chemical vapor deposition (MOCVD). In this presentation, we show optical properties of these NWs. We isolate the nanowires by covering the bottom InGaN thin film with chromium. The photoluminescence (PL) agrees well with the X-ray diffraction (XRD) measurement. We show the PL peak can be shifted by changing the TMIn flow rate and is tunable from 3.4 to 2.5 eV at room temperature. Electrical devices made of these NWs are currently in progress and will be shown in the conference.

8986-44, Session 8

Mode and polarization control in gallium nitride nanowire lasers

George T. Wang, Sandia National Labs. (United States); Huiwen Xu, The Univ. of New Mexico (United States); Jeremy B. Wright, Sandia National Labs. (United States); Antonio Hurtado, The Univ. of New Mexico (United Kingdom); Ting-Shan Luk, Jeffrey J. Figiel, Sandia National Labs. (United States); Luke F. Lester, The Univ. of New Mexico (United States); Qiming Li, Igal Brener, Sandia National Labs. (United States)

While GaN nanowire lasers typically operate in a combined multi-longitudinal and multi-transverse mode state, single-mode lasing is desired for applications needing high beam quality and spectral purity. Here we introduce multiple schemes for controlling the optical mode and the polarization of GaN nanowire lasers. GaN nanowires were synthesized by a two-step "dry plus wet" top-down technique to create nanowires with precisely controlled geometries. As the dimensions were reduced to a critical value, the nanowire lasing behavior transitions from multiple- to single-mode. Simulations indicate that single-mode lasing arises from the interplay between narrow gain bandwidth and strong mode competition at low dimensions. For nanowires with larger dimensions, we demonstrate two alternative methods to realize single mode lasers. The first method involves placing two nanowires side-by-side in contact. The resulting coupled cavity generates a Vernier effect, which dramatically increases the free spectral range between adjacent resonant modes, giving rise to the single-mode operation. For the second method, single-mode lasing is achieved by placing GaN nanowires onto gold substrates. The nanowire-gold contact generates a mode-dependent loss, which can strongly attenuate higher modes and ensure single-mode operation. Additionally, the coupling of the GaN nanowires to an underlying gold substrate allows for lasing polarization control. The substrate breaks the symmetry of the nanowire geometry and generates an inherent polarization-sensitive loss. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

8986-45, Session 8

Comprehensive and rigorous theoretical analyses of InGaN solar cells in whole composition range and a serious bottleneck when fabricating on bulk GaN substrate

Akihiko Yoshikawa, Chiba Univ. (Japan); Kazuhide Kusakabe, Chiba Univ (Japan); Naoki Hashimoto, Chiba Univ. (Japan)

We have been studying and developing high performance InGaN-based solar cells grown on bulk GaN substrate. The fundamental structure is p-(In)GaN/pn-InGaN/n-GaN substrate. First, we performed comprehensive and rigorous theoretical analyses of InGaN solar cells in whole composition range paying special attention how their realistic material properties affect cell performances, in particular their effects on defects-induced current components resulting in extremely higher forward current than the theoretical diffusion current. Concerning the defects-induced current, the recombination current through deep level point defects and simple Ohmic leakage current thorough extended defects were taken into account. Of course, some of other material properties and device parameters as well also greatly affect the current transport mechanism through the pn-junction.

Anyway, it should be noted that the relative magnitude of each component current against the photocurrent density under operation is quite important. Simply in other words, the solar cell must be designed/fabricated so that any defects-induced current density level

must be lower than the operating photocurrent density to expect high performance.

For the theoretical study, we have quite carefully derived experimental equations for several material properties dominating solar cell performances, such as the absorption coefficient and electron/hole motilities, on the basis of many reported literatures so that they should be valid and/or plausible in whole composition range and in wide carrier concentration range at the same time.

Detailed results for the systematic theoretical study and an experimentally observed serious bottleneck originating from the surface-defects for commercially available bulk GaN will be discussed in the symposium.

8986-47, Session 9

Defects in GaN-based transistors *(Invited Paper)*

Steven A. Ringel, Aaron Arehart, Anup Sasikumar, Zeng Zhang, The Ohio State Univ. (United States); Jim Speck, Erin C. H. Kyle, Micha Fireman, Stephen Kaun, Univ. of California, Santa Barbara (United States); Ronald D. Schrimpf, Dan Fleetwood, Vanderbilt Univ. (United States)

Electrically active defects in AlGaN/GaN high electron mobility transistors (HEMTs) are the source of intense study due to their linkage to the mechanisms for GaN HEMT degradation upon a variety of stress conditions. The ability to directly characterize traps and identify their sources in GaN HEMTs is challenging, however, and this is due to a combination of the large bandgap of these materials and the complex electrostatics present in these device structures. Furthermore, the targeted extreme operating conditions intended for GaN HEMTs, whether designed for RF or power applications, greatly exacerbate the ability to identify those defects that are most relevant to device degradation under actual operation. Over the past few years, however, we have developed several electronic defect characterization methods based on deep level optical spectroscopy (DLOS) and thermally-based deep level transient spectroscopy (DLTS), which have been adapted from basic studies of defects in GaN and AlGaN to become applicable to working HEMTs. These so-called constant drain current (CID) DLOS/DLTS methods are able to directly provide individual trap concentrations and energy levels for traps that may exist throughout the AlGaN/GaN HEMT bandgap, and can discern between traps under the gate or in the transistor access regions. This talk will first review the CID-DLOS/DLTS methodology and then will focus on the application of these methods to stressed and un-stressed AlGaN/GaN HEMTs. Direct correlations of the formation of several specific traps are made with a variety of HEMT degradation mechanisms induced by stresses that include RF, DC and also proton irradiation.

8986-48, Session 9

Effect of electron density on cutoff frequency of III-N HFETs *(Invited Paper)*

Arvydas Matulionis, Ctr. for Physical Sciences and Technology (Lithuania); Hadis Morkoç, Virginia Commonwealth Univ. (United States)

Recent advances in frequency (RF) performance of III-N heterostructure field-effect transistors (HFETs) are discussed in terms of ultrafast processes in the transistor channel. The conditions for the fastest device operation almost coincide with those for the slowest device degradation. The correlation has its genesis in ultrafast dissipation of the LO-mode heat accumulated by the non-equilibrium longitudinal optical phonons (hot phonons) launched by hot electrons: this heat causes additional scattering of the electrons and defect formation in a different manner as compared with similar effects due to conventional heat accumulated by acoustic phonons. Understanding of the hot phonon phenomenon is important to unveil the dependence of transistor cutoff frequency on electron density, which in III-N HFETs differs from other transistors.

The fastest dissipation of the LO-mode heat takes place inside an electron density window where the resonant conversion of the hot phonons into acoustic phonons is assisted by plasmons. Signatures of plasmons are resolved in fluctuations and hot-electron transport as well as transistor frequency performance, phase noise, and reliability. The plasmon-assisted conversion explains the non-monotonous dependence of transistor unity gain cutoff frequency on the gate voltage: the LO-phonon–plasmon resonance can be tuned in through variation of the electron density in the active part of the transistor. The optimal gate bias and the pristine 2DEG density are in a ‘semi-universal’ relation that is almost independent of gate length for III-N HFETs of different composition.

8986-49, Session 9

Electrical characteristics of AlGaN-GaN high electron mobility transistors and AlGaN Schottky diodes irradiated with protons

Yongkun Sin, Brendan Foran, Nathan Presser, Stephen LaLumondiere, William T. Lotshaw, Steven C. Moss, The Aerospace Corp. (United States)

AlGaN-GaN high electron mobility transistors (HEMTs) are most suitable for commercial and military applications requiring high voltage, high power, and high efficiency operation. In recent years, leading AlGaN HEMT manufacturers have reported encouraging reliability of these devices, but their long-term reliability especially in the space environment still remains a major concern. In addition, degradation mechanisms in AlGaN HEMT devices are still not well understood and a large number of traps and defects present both in the bulk and at the surface lead to undesirable characteristics. Study of reliability and radiation effects of AlGaN-GaN HEMTs is therefore necessary before GaN HEMT technology is successfully employed in satellite communication systems. For the present study, we investigated electrical characteristics of the AlGaN-GaN HEMTs and AlGaN Schottky diodes irradiated with protons.

We studied two types of MOCVD-grown AlGaN HEMTs on semi-insulating SiC substrates as well as MOCVD-grown AlGaN Schottky diodes on conducting SiC substrates. Electrical characteristics of AlGaN-GaN HEMTs and AlGaN Schottky diodes were compared before and after they were proton irradiated with different energies and fluences. Current mode deep level transient spectroscopy (I-DLTS) and capacitance mode DLTS were employed to study pre- and post-proton irradiation trap characteristics in the AlGaN-GaN HEMTs and AlGaN Schottky diodes, respectively. Focused ion beam was employed to prepare both cross sectional and plan view TEM samples for defect analysis using a high resolution TEM. Lastly, we will present our preliminary results of time-resolved photoluminescence (TR-PL) techniques employed to study carrier dynamics in our HEMT and Schottky diode structures.

8986-46, Session 10

III-nitride tunnel junctions for efficient solid state lighting *(Invited Paper)*

Siddharth Rajan, Sriram Krishnamoorthy, Fatih Akyol, The Ohio State Univ. (United States)

The nanoscale engineering of highly efficient III-nitride interband tunnel junctions, and applications of tunnel junctions in new device designs will be discussed. Two approaches, using polarization engineering and rare earth nanoisland-based, can be used to overcome fundamental limits to tunneling resistance in III-nitrides. This paper discusses the design,

growth, fabrication, and experimental demonstration of GaN tunnel junctions with record low resistance in real devices such as PN junctions, LEDs, and solar cell. The demonstration of tunnel junctions could enable new optoelectronic devices with significantly higher efficiency and power.

Polarization and heterostructure engineering can be used to create large band-bending over nanoscale lengths to enhance tunneling by several orders of magnitude, overcoming fundamental limits of homojunction P-N tunnel diodes. Such tunnel junctions were incorporated in a GaN p-n junction to record low resistivity tunnel junction resistivity of 0.1 mOhm-cm2. Forward tunneling and NDR in interband III-nitride tunnel junctions was also observed. An alternate approach of using GdN nanoislands as mid gap states for tunneling was investigated. GdN nanoisland-based tunnel junction as a tunneling contact to GaN p-n junction were demonstrated with a low TJ resistivity of 1 mOhm-cm2.

Low resistance tunnel junctions were integrated with commercial blue LED (450 nm) structures for p-contact free LEDs with excellent current spreading with low metal footprint. Visible wavelength transparent GaN/GdN/GaN tunnel junction interconnects were used to cascade multiple p-n junctions with low resistance (0.5 mOhm-cm2), demonstrating the feasibility of multiple active region LEDs for higher output power or new RGB-based multi-wavelength designs.

8986-50, Session 10

Monolithic white-light-emitting diodes grown by MOCVD *(Invited Paper)*

Benjamin Damilano, Kaddour Lekhal, Hyonju Kim-Chauveau, Sakhawat Hussain, Eric Frayssinet, Julien Brault, Sébastien Chenot, Philippe Vennéguès, Philippe de Mierry, Jean Massies, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France)

Commercially available inorganic white light emitting diodes (LEDs) are essentially based on the combination of a blue InGaN based LED chip covered by a long wavelength emitting (yellow, red) phosphor. We propose to avoid this step of phosphor deposition by taking advantage of the fact that yellow to red emission can be achieved with InGaN alloys. By stacking an InGaN/GaN multiple quantum well (QW) emitting in the yellow, acting as a light converter, and a short wavelength blue-violet pump LED grown on top, white light emission can be obtained. Furthermore, if we extend the emission spectrum of the light converter into the red, a warm white light color is demonstrated when a pump LED is grown on top. However, the high In content InGaN QWs of the light converter have a low thermal stability and the QW efficiency tends to degrade during the growth of the pump LED. Three different solutions are explored to avoid the thermal degradation of the light converter. The monolithic LED structures were grown by molecular beam epitaxy (MBE), by a combination of both MBE and metal-organic chemical vapor phase epitaxy (MOCVD), or by a low temperature full-MOCVD process. The best results are obtained using a complete MOCVD growth process. The structure and the MOCVD growth conditions are specifically adapted in order to avoid the thermal degradation of the large In composition InGaN QWs emitting at long wavelength during the growth of the subsequent layers.

8986-51, Session 10

Optical properties of InGaN/GaN MQW LEDs grown on Si (111) substrates with low threading dislocation densities

Shigeya Kimura, Jumpei Tajima, Hajime Nago, Toshiki Hikosaka, Hisashi Yoshida, Kenjiro Uesugi, Shinya Nunoue, Toshiba Corp. (Japan)

We have grown blue light-emitting diodes (LEDs) with low threading dislocation densities (TDDs) of less than 2.0E+8/cm2 on Si (111) substrates. The TDDs are almost the same values as those of LEDs grown on Al2O3 (0001) substrates. External quantum efficiency (EQE) and thermal quenching are dramatically improved by reducing the TDDs. The structural and optical properties of the LEDs grown on Si (111) substrates are different from those of LEDs grown on Al2O3 (0001) substrates although their TDDs and the growth conditions are almost the same.

The blue LED structures were grown by metal-organic chemical vapor deposition on Si (111) substrates. We prepared samples with various TDDs. Active layers in the blue LEDs consist of 3.5-nm-thick In0.15Ga0.85N quantum well layers and 3-nm-thick barrier layers. Thin-film LEDs were fabricated by removing the Si (111) substrates from the grown layers.

The thermal quenching ratios 1-EQE(85°C)/EQE(25°C) are 5%, 14% and 25% at 12A/cm2 for the samples with 2.6E+8, 9.2E+8 and 1.5E+9/cm2 TDDs, respectively. The thermal quenching ratios sharply increase with decreasing current density for the samples with high TDDs. However the increase becomes slow for the samples with low TDDs. The rate of thermal decrease of non-radiative recombination lifetimes measured by time-resolved photoluminescence also decreases with reducing TDDs. It indicates that the thermal quenching of these samples dominantly originates from Shockley-Read-Hall (SRH) defects in the well layers affected by threading dislocations. Dark spots detected by micro-photoluminescence mapping spread and darken at high temperature in the samples with high TDDs.

8986-52, Session 10

Nanoscale indium fluctuation in the InGaN quantum-well LED to the efficiency droop with a fully 3D simulation model

Tsung-Jui Yang, Yuh-Renn Wu, National Taiwan Univ. (Taiwan); Jim Speck, Univ. of California, Santa Barbara (United States)

InGaN quantum well LED has started to play an important role in the lighting area. Random indium alloy fluctuation, presented even in purely random alloys, play has played an important role in influencing the LED's carrier transport and droop. In this paper, we report on the influence of nanoscale indium fluctuation in multiple quantum well light emitting diodes with a fully three dimensional (3D) simulation model. We analyzed different degrees of indium fluctuation in six InGaN/GaN quantum wells by a three dimensional Poisson and drift-diffusion solver and compared to our previous studies by two dimensional solver. In our simulation, we design the indium fluctuation by setting periodically sinusoidal distribution in both x-direction and y-direction range from 5 percent to 18 percent in quantum wells with random alloy fluctuation. Besides, we also consider different indium fluctuation condition by setting various periods of sinusoidal distribution. The simulation results show that the device behavior significant difference between 3D and 2D modeling. The turn-on voltage occurs earlier in the 3D modeling than the 2D modeling. This is because the relatively smaller active volume in three dimensional space. However, this also leads a more severe droop effect in either overflow or Auger recombination due to the smaller active volume and higher local carrier density. The emission spectrum can also be studied by the 3D model to include the quantum confined effect to model the spectrum broadening effect.

8986-53, Session 10

InGaN/GaN quantum-well light-emitting diode grown on patterned Si (110) substrate

Chia-Ying Su, Chih-Yen Chen, Zhan Hui Liu, Ta-Wei Chang, Pei-Ying Shih, Horng-Shyang Chen, Che-Hao Liao, Chieh Hsieh, Wang-Hsien Chou, Chen-Hung Shen, Yean-Woei Kiang, Chih-Chung Yang, National Taiwan Univ. (Taiwan)

The comparisons of the morphologies, material properties, and optical characteristics between an InGaN/GaN quantum-well light-emitting diode (LED) structure grown on a <1-10>-oriented 1-D trench-patterned Si (110) substrate and other samples of different trench orientations on Si (110) substrate, flat Si (110), and Si (111) substrate are demonstrated. Based on the trench-patterned Si (110) substrate, lateral coalescence is achieved only in the sample of <1-10>-oriented trench. Among the continuous top surface samples, crack-free wafer is obtained also only in the sample of <1-10>-oriented trench. This sample shows the highest crystal quality, weakest tensile strain, lowest indium content, shortest emission wavelength, and highest internal quantum efficiency based on the comparisons of the characterization results. By comparing the performances of the fabricated LEDs based on the three samples of continuous top surfaces, it is found that the sample of <1-10>-oriented trench has the strongest output power, lowest device resistance, and smallest spectral shift range in increasing injection current. The good performances and weak quantum-confined Stark effect are attributed to (1) the small lattice match between Si and AlN/GaN for reducing dislocation density along the m-axis, (2) the reduced thermal strain effect through the buried trenches for decreasing the contact area along the m-axis, and (3) the minimized dislocation density formed along the a-axis of large lattice-mismatch through the lateral overgrowth along the m-axis. The strong LED output in this sample is also due to the strong scattering of the buried trenches for reducing light absorption by the Si substrate and increasing light extraction.

8986-54, Session 11

Design and lasing characteristics of GaN vertical elongated cavity surface-emitting lasers *(Invited Paper)*

Masao Kawaguchi, Osamu Imafuji, Kentaro Nagamatsu, Kazuhiko Yamanaka, Shinichi Takigawa, Takuma Katayama, Panasonic Semiconductor Discrete Devices Co., Ltd. (Japan)

A GaN-based vertical-cavity surface-emitting laser (VCSEL) array has been attracting much attention as a potential light source for various applications. For such an array structure, uniform operation of the elements is one of the most important technical challenges. In a typical VCSEL with several-wavelength cavity, the gain peak easily goes out of the cavity mode due to the heat-induced peakshift of the gain spectrum. On the other hand, elongation of the cavity length allows several optical modes within the spectrum. In this context, the elongated cavity is robust against the thermally-induced peakshift of the gain, because other cavity modes can match the shifted gain peak.

Here, we report on design and lasing characteristics of GaN-VCSELs with the elongated cavity. Calculations taking into account the wavelength dispersion of the refractive index show that the transverse mode spacing can be significantly narrower than the gain spectrum with a small tradeoff of the differential quantum efficiency. The VCSEL with the elongated cavity fabricated by the wafer thinning technique operates under current injection by using highly reflective distributed Bragg reflectors (DBRs) made of transparent ZrO2 and SiO2 film stacks. Together with high reflectivity and wide stop band of the DBR, the elongated cavity of 6 um (36 lamda) allows multimode lasing oscillation with a mode spacing of 2.9 nm, which is one order of magnitude narrower than the gain spectrum. In addition, we demonstrate a 5x5 GaN VCSEL array.

8986-55, Session 11

Recent advances in c-plane GaN visible lasers *(Invited Paper)*

Uwe Strauss, Thomas Hager, Georg Bruederl, Teresa Wurm, André Somers, Christoph Eichler, Clemens Vierheilig, Andreas Löffler, Jelena Ristic, Adrian Avramescu, OSRAM Opto Semiconductors GmbH (Germany)

Typical power levels of blue and green single mode lasers are in the range of several ten milliwatt. Recent R&D studies on laser for mobile projection focus on two topics: speckle free brilliant light sources at low power levels and green laser for power above 100mW. We discuss both, feasibility of stimulated emitters as well as higher power of green ridge lasers. Especially, we investigate in detail the output power versus temperature by gain measurements of the green ridge laser. Another field of application is laser projection above 1000lm. The light engines use arrays of TO power blue lasers. Power level of 1.6W is available commercially. Recent R&D studies focus on higher optical output power to reduce costs. We present R&D laser with thermal roll-over as high as 5W.

8986-56, Session 11

Evolution of thermal stability of InGaN laser diodes emitting in the range of 390-436 nm

Agata Bojarska, Jakub Goss, Lucja Marona, Anna Kafar, Szymon Stanczyk, Institute of High Pressure Physics (Poland); Irina Makarowa, Grzegorz Targowski, TopGaN Ltd. (Poland); Tadek Suski, Piotr Perlin, Institute of High Pressure Physics (Poland) and TopGaN Ltd. (Poland)

Thermal stability of the laser diode is an important parameter influencing both the optical power and the threshold current of the device. We studied how this stability depends on the laser structure by determining the characteristic temperature T0 of various InGaN laser diodes emitting in the spectral range of 390 – 436 nm. All the structures were grown by MOCVD (metalorganic chemical vapor deposition) on bulk GaN crystals obtained via ammonothermal synthesis. The characteristic temperature T0 of these devices increases steeply with the increasing emission wavelength from T0=100 K at λ=391 nm to the value of 230 K for λ=427 nm. There is no correlation between the emitting wavelength and lasing differential efficiency.

In order to explain the observed evolution of T0, we measured the light – current characteristics at low current densities and at different temperatures. Analysis of obtained results revealed that the injection efficiency is lower and much more sensitive to the temperature change at shorter wavelength. The optical output powers for a fixed value of the drive current at different temperatures were also measured. Obtained data allowed us to determine activation energies of electroluminescence, which appear to be almost equal to the effective QW depths. Such result suggests that the source of observed behavior is the thermal escape of carriers from quantum wells.

8986-57, Session 11

Can hole-electron plasma oscillation stabilize cavity-free lasing in InGaN structures?

Agata Bojarska, Institute of High Pressure Physics (Poland); Igor V. Smetanin, P.N. Lebedev Physical Institute (Russian Federation); Alexandr Khachapuridze, Institute of High Pressure Physics (Poland); Robert Czernecki, Institute of High Pressure Physics (Poland) and TopGaN Ltd. (Poland); Tadek Suski, Institute of High

Pressure Physics (Poland); Piotr Perlin, Institute of High Pressure Physics (Poland) and TopGaN Ltd. (Poland)

Cavity, necessary to sustain laser oscillations in semiconductors, can be formed by plane-parallel crystal facets (Fabry-Perot lasers), or photonic structures including one-dimensional Bragg reflectors or two-dimensional photonic crystals. There exists also chaotic structures where lasing occurs due to multiple scattering processes. In the present paper we report lasing phenomenon which cannot be classified to none of the mentioned above categories.

We studied optically excited InGaN laser diode structures. The sample were unprocessed part of a standard laser epi-wafer consisting of a separate confinement heterostructure with active layer composed of 3 InGaN quantum wells. The sample was illuminated almost vertically by a triple harmonic YAG pulse laser with wavelength of 355 nm. Emitted light is collected in the back-scattering geometry. Narrow lines corresponding to typical lasing operation appears at λ=420 nm at the pumping power density of 55 kW/cm2. Position of the lasing spectra and the mode spacing are very stable. Lasing does not require the presence of sample edges and there are no scattering centers in the structure.

We suggest that this new lasing mechanism is related to 2D electron-hole plasma oscillation, which acts as a dynamical grating and resonantly couples the lasing modes separated by the plasma frequency, being similar to the case of DFB lasers. In group III nitride materials, intrinsic piezoelectric field induces spatial separation of charges in the quantum well which provides low-frequency THz-range 2D plasma oscillation mode. Such a self-generated dynamical grating could explain anomalous spacing of the observed lasing modes.

8986-58, Session 11

Advances in AlGaInN laser diode technology

Stephen P. Najda, Piotr Perlin, TopGaN Ltd. (Poland); Tadek Suski, Lucja Marona, Institute of High Pressure Physics PAS (Poland); Mike Bockowski, Mike Leszczynski, Przemek Wisniewski, R Czernecki, R Kucharski, G Targowski, TopGaN Ltd. (Poland); Scott Watson, Antony Kelly, School of Engineering, University of Glasgow (United Kingdom)

The latest developments in AlGaInN laser diode technology are reviewed. The AlGaInN material system allows for laser diodes to be fabricated over a very wide range of wavelengths from u.v., i.e, 380nm, to the visible, i.e., 530nm, by tuning the indium content of the laser GaInN quantum well. Advantages of using Plasma assisted MBE (PAMBE) compared to more conventional MOCVD epitaxy to grow AlGaInN laser structures are highlighted. Ridge waveguide laser diode structures are fabricated to achieve single mode operation with optical powers of >100mW in the 400-420nm wavelength range that are suitable for telecom applications.

High power operation of AlGaInN laser diodes is demonstrated with a single chip, AlGaInN laser diode 'mini-array' with a common p-contact configuration at powers up to 2.5W cw at 410nm. Low defectivity and highly uniform GaN substrates allow arrays and bars of nitride lasers to be fabricated. GaN laser bars of up to 5mm with 20 emitters, mounted in a CS mount package, give optical powers up to 4W cw at ~410nm with a common contact configuration. An alternative package configuration for AlGaInN laser arrays allows for each individual laser to be individually addressable allowing complex free-space and/or fibre optic system integration within a very small form-factor.

8986-59, Session 11

Understanding the aging mechanisms of InGaN-based laser diodes: a study based on micro-CL and micro-PL measurements

Matteo Meneghini, Simone Carraro, Gaudenzio Meneghesso, Univ. degli Studi di Padova (Italy); Giovanna Mura, Univ. degli Studi di Cagliari (Italy); Francesca Rossi, Consiglio Nazionale delle Ricerche (Italy); Katarzyna Holc, Thomas Weig, Lukas Schade, Joachim Wagner, Ulrich T. Schwarz, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); Enrico Zanoni, Univ. degli Studi di Padova (Italy)

This paper describes an extensive analysis of the degradation of InGaN-based laser diodes, based on combined electro-optical characterization, micro-cathodololuminescence (micro-CL) and micro-photoluminescence (micro-PL) measurements. The analysis is aimed (a) at understanding if degradation is due to an increase in non-radiative recombination, or to a worsening in the injection efficiency; (b) at clarifying if the defective regions generated after stress have a point-defect nature, or cluster around dark regions, related to dislocations.

The results collected within this work indicate that: (i) constant current stress induces an increase in the threshold current of the devices, well correlated to a decrease in sub-threshold emission. (ii) spatially-resolved cathodoluminescence measurements, carried out on untreated and degraded samples after the removal of the top metallization, reveal a significant darkening of the region under the ridge. In this area, darkening is almost uniform, without the presence of "preferential" dark spots.

Results therefore suggest that degradation is due to the generation/propagation of point defects, rather than to the darkening of localized regions, related to dislocations. (iii) from micro-CL measurements it is impossible to understand if degradation takes place in the quantum wells, or in the barrier layers, since carriers are generated in both regions. To clarify this point, we carried out micro-PL measurements with resonant excitation: results indicate that degradation occurs in the quantum wells; the decrease in optical efficiency was found to be strongly correlated to a red-shift of the peak wavelength in the aged area.

Based on the evidence collected within this paper, degradation is ascribed to the increase in non-radiative recombination within the quantum-well region of the devices; degradation is supposed to proceed through the generation/propagation of point defects, activated by the flow of carriers through the quantum wells.

8986-60, Session 11

InGaN laser diodes with graded-index separate confinement heterostructure

Szymon Stanczyk, Anna Kafar, Institute of High Pressure Physics (Poland); Tomasz Czyszanowski, Technical Univ. of Lodz (Poland); Robert Czernecki, Grzegorz Targowski, TopGaN Ltd. (Poland); Mike A. R. Leszczynski, Institute of High Pressure Physics (Poland) and TopGaN Ltd. (Poland); Tadek Suski, Institute of High Pressure Physics (Poland); Piotr Perlin, Institute of High Pressure Physics (Poland) and TopGaN Ltd. (Poland)

Graded-index separate confinement heterostructure (GRIN SCH) in GaAs laser diodes is the subject of intense investigation since the early eighties until the present day. The results show that applying optimized GRIN SCH can improve greatly optoelectronic parameters of laser diodes. According to our knowledge, until present day there are hardly any reports on applying GRIN SCH in laser diodes based on GaN system.

In this work we present our first attempt at InGaN laser diodes with graded-index separate confinement heterostructure (GRIN SCH). Investigated structure was grown by metalorganic vapor phase epitaxy

(MOVPE) on GaN substrate obtained by ammonothermal method. The devices were fabricated as p-up, ridge-waveguide diodes with 700 μm long resonator and 3 μm wide ridge. The content of Al in 330 nm thick bottom guiding layer is changing linearly from 7%, which is corresponding to Al content in cladding layer, to 0%. For p-side, 320 nm thick guiding layer, Al content is changing linearly form 0% to 4%.

The devices are characterized by low threshold current density (approximately 3.5 kA/cm2), high differential gain (approximately 0.8 cm-1mA-1) and high optical power. The emitted wavelength was 420 nm. All results were obtained under DC operation. For better understanding of influence of this type of structure on optoelectronic parameters and in order to optimize the structure we performed theoretical calculation of optical field distribution in the structure.

8986-75, Session PWed

Highly-uniform InGaN/GaN blue LED properties through the novel design of gas injector in a large scale MOCVD

Jun Woo Kim, Sun Woon Kim, In Hoe Hur, Kyung Ho Yoo, Soo Goan Park, Seong June Jo, Choo Ho Kim, Yoon Joon Choi, SAMSUNG Electronics Co., Ltd. (Korea, Republic of); Hyeong Soo Park, Semes Co., Ltd. (Korea, Republic of)

The subject of this paper deals with a new gas injector system to enable reactor scale up to 10x6" or 7x8" configuration in commercial production. This new gas injector was developed to improve the growth of epitaxial layers with highly uniform characteristics at large scale reactor above 6" wafer. The novel Pre-Mixed Gas Injector (PMGI) consists of the gas inlet premixing both group-V hydride and group-III Nitride compounds inside injector.

The PMGI which surrounded with water cooled stainless steel body is centered within the process chamber producing a symmetric flow profile directed towards the exhaust. The PMGI design consists of three inlets, the premixed MO and hydride inlet being sandwiched between two carrier gas inlets top and bottom. The role of curtain flow inlets separated from top and bottom prevents parasitic deposition at Ceiling and cover part. So, It is possible to control low particle generation and enhance growth rate inside chamber by tuning two curtain flow gas inlets. The advantage of premixed Mo and hydride inlet inside injector is enable to expand process uniformity zone and scale up larger reactor configurations. With better momentum balancing through this PMGI, a uniform laminar gas flow is supplied and is more robust for a wide range of process conditions. The water cooled injector body can reduce the risk of gas phase pre-reaction and adduct formation, therefore enhancing improved growth conditions for high Al or Mg content layers. Based on modelling results, a novel gas injector design for the 10x6" or 7x8" horizontal reactor configuration with pre-mixed gas inlet (PMGI) has been presented. The pressure dependence of growth efficiency of GaN grown in two different types of gas injector, with curtain flow inlet and without curtain flow inlet, was investigated. The effect of curtain flow prevents parasitic deposition at upper ceiling and helps the nano-particles reside for a longer at hot Susceptor surface. Due to these effects it is concluded that PMGI reactor prove more favourable for obtaining high growth efficiency of GaN at elevated pressure. Additionally, excellent growth thickness uniformity of InGaN/GaN layer was achieved by XRD analysis and wavelength uniformity was proved by PL mapping through PMGI reactor.

8986-76, Session PWed

Multi-wavelength light emission from three-dimensional AlGaN quantum wells fabricated on facet structures

Ken Kataoka D.D.S., Kyoto Univ. (Japan); Masanori Yamaguchi, Kensuke Fukushima, Ushio Inc. (Japan); Mitsuru Funato, Yoichi Kawakami, Kyoto Univ. (Japan)

AlN and AlGaN alloy have attracted much attention for deep UV light-emitting devices. Similar to InGaN, those materials are typically grown on c-plane, where strained AlGaN quantum wells (QWs) experience undesirable spontaneous and piezoelectric polarization fields. Additionally, the lowest energy optical transition from Al-rich AlGaN is dipole allowed for polarization perpendicular to the c-axis. Consequently, it is difficult to extract the light along the c-axis. To overcome these issues, the use of semipolar or nonpolar planes is promising. However, there are few reports on such AlGaN QWs due to difficulty in the crystal growth.

In this study, AlGaN/AlN multi-QWs (MQWs) were grown by a regrowth technique based on metalorganic vapor phase epitaxy. Initially, c-plane AlN/sapphire templates were patterned into stripes by reactive ion etching, and then regrowth of AlN was performed, creating three dimensional (3D) structures consisting of c-plane top facets and semipolar/nonpolar side facets. Finally, AlGaN/AlN MQWs were grown on top of 3D-AlN.

Cross sectional scanning electron microscopy indicated the successful fabrication of 3D structures with c-plane and semipolar {1-101} facets. A cathodoluminescence (CL) spectrum gathered from the entire structure was peaked at 5.0 eV with an FWHM over 600meV. This is much broader than planar c-plane QWs grown under the same condition (FWHM~300meV). CL spectra separately acquired at semipolar and c-plane facet QWs were located at energies different by ~200 meV, which is, we consider, why the broad FHWM of 600 meV was observed. We expect that optimizing the growth conditions allows high efficiency multi-wavelength UV light emitters.

8986-77, Session PWed

Optical properties of m-plane GaN grown on patterned Si(112) substrates by MOCVD using a two-step approach

Natalia Izyumskaya, Serdal Okur, Fan Zhang, Morteza Monavarian, Vitaliy Avrutin, Ümit Özgür, Virginia Commonwealth Univ. (United States); Sebastian Metzner, Christopher Karbaum, Frank Bertram, Jürgen Christen, Otto-von-Guericke-Univ. Magdeburg (Germany); Hadis Morkoç, Virginia Commonwealth Univ. (United States)

Nonpolar m-plane GaN layers were grown on patterned Si (112) substrates by metal-organic chemical vapor deposition (MOCVD) using a two-step approach to improve their optical quality. High reactor pressures (~200 Torr), despite being desired for high optical quality, result in the formation of unwanted {1-101} facets, while, as we have found earlier, {1-100} planes can be achieved only at low reactor pressures (~30 Torr). Therefore, a two-stage growth procedure involving a low-pressure (30 Torr) first stage to ensure formation of the m-plane facet and a high-pressure stage (200 Torr) for improvement of optical quality was employed.

Compared to the layers grown at low pressure in a single step, the near bandedge photoluminescence (PL) intensity was ~3 times higher and the deep emission was considerably weaker. Correlation between defect distribution and optical emission over the c- and c+ wings of the nonpolar GaN/Si was studied by spatially resolved cathodoluminescence (CL) and near-field scanning optical microscopy (NSOM). Carrier dynamics in c- and c+ wings were also investigated by time-resolved micro-PL measurements.

8986-78, Session PWed

Characterization of 380nm UV-LEDs grown on free-standing GaN by atmospheric pressure metal-organic chemical vapor deposition

Chen-Yu Shieh, National Central Univ. (Taiwan); Zhen-Yu Li, Hao-Chung Kuo, National Chiao Tung Univ. (Taiwan); Jenq-Yang Chang, National Central Univ. (Taiwan); Gou-Chung Chi, National Central Univ. (Taiwan) and National Chiao Tung Univ. (Taiwan)

We reported the defects and optical characterizations of the ultraviolet light-emitting diodes grown on free-standing GaN substrate (FS-GaN) and sapphire. Cross-sectional transmission electron microscopy (TEM) images showed that the total defect densities of grown UV LEDs on FS-GaN and sapphire including edge, screw and mixed type were 3.6x106 cm-2 and 5.5x108 cm-2. When substrate of UV LEDs was changed from sapphire to FS-GaN, it can be clearly found that the crystallography of GaN epilayers was drastically different from that GaN epilayers on sapphire. Besides, the microstructures or indium clustering can be not observed at UV LEDs on FS-GaN from TEM measurement. The internal quantum efficiency of UVLEDs on FS-GaN and sapphire were 34.8 % and 39.4 % respectively, which attributed to indium clustering in multi-layers quantum wells (MQWs) of UV LEDs on sapphire. The light output powers of 12 mil square UV LEDs chips on FS-GaN and sapphire are 10.8 mW and 6.0 mW at 20 mA. The efficiency droop was reduced from 20 % in UV LEDs with indium clustering to 3 % in UV LEDs grown on FS-GaN substrate.

8986-79, Session PWed

Internal quantum efficiency of InGaN/GaN LEDs with short period superlattice and two-colour quantum wells

Ilya E. Titkov, Univ. of Dundee (United Kingdom); Amit Yadav, Univ. of Dundee (United Kingdom) and University of Dundee (United Kingdom); Vera L Zerova, University of Dundee (Russian Federation) and University of Dundee (United Kingdom); Modestas Zulonas, Univ. of Dundee (United Kingdom); Andrei F. Tsatsulnikov, Alexey V. Sakharov, Wsevolod V. Lundin, Ioffe Physico-Technical Institute (Russian Federation); Edik U. Rafailov, Univ. of Dundee (United Kingdom)

Internal quantum efficiency (IQE) is one of the most important characteristics in LED active region development. Nevertheless, reliable IQE measurements of GaN-based LEDs remains challenging due to many reasons such as carrier localisation at low temperatures, low-current leakage, carriers redistribution between SL and MQW etc.

In this paper IQE of blue, deep green (560 nm) and monolithic white LEDs were measured by temperature dependant electro-luminescence (TDEL) and simulated with modified rate equation based on ABC model. InGaN/GaN short-period superlattices were fabricated using a method based on cycle conversion of surface In-GaN layer to GaN by application of growth interruptions in hydrogen atmosphere.

Active regions of the investigated LEDs contain a combination of the SPSLs and 3 nm width InGaN layers. SPSL was about 24 nm thickness according to TEM. Temperature of growth of the InGaN layer was varied in the range of 810-900 C to change emission wavelength. Monolithic white LED structures with CCT in the range of 5000-11000 K contained one green InGaN QW and two blue QWs in active region separated by an SPSL-based barrier.

External quantum efficiency exceeded 6% in maximum. IQE of blue and green quantum wells were analysed separately.

8986-80, Session PWed

Nanometer-scale optical and structural properties of an AlInN/GaN-based microcavity characterized by cathodoluminescence spectroscopy in a transmission electron microscope

Gordon Schmidt, Otto-von-Guericke-Univ. Magdeburg (Germany); Marcus Müller, Otto-von-Guericke Univ. Magdeburg (Germany); Anja Dempewolf, Silke Petzold, Peter Veit, Frank Bertram, Christoph Berger, Armin Dadgar, Alois J. Krost, Jürgen Christen, Otto-von-Guericke-Univ. Magdeburg (Germany)

III-Nitride based microcavities (MC) are one of the most promising candidates for the realization of polariton lasers operating at room temperature since they exhibit highly stable excitons and a large oscillator strength. These lasers operate without inversion in the strong coupling regime (SCR) where the squared strength of the light-matter coupling g has to overcome the mean value of the squared line width of exciton and cavity mode. Since g is proportional to the square root of the quantum well number (QW) within the MC, the SCR can be reached by embedding a large number of quantum wells in the cavity.

We present the optical and the structural properties at the nanometer scale of a metal organic vapor phase epitaxy grown MC structure comprising a large number of embedded InGaN QWs by cathodoluminescence spectroscopy in a scanning transmission electron microscope (STEM-CL). The sample consists of a 28-fold InGaN/GaN multiple quantum well embedded in a GaN λ cavity on top of an AlInN/GaN distributed Bragg reflector (DBR) grown on sapphire substrate.

Direct comparison of the STEM images with simultaneously recorded CL mappings resolve the complete layer sequence. In particular, the DBR layer stack is proven to be laterally and vertically homogeneous with sharp GaN/AlInN interfaces. A dominant emission with a broad spectral range of the InGaN MQW can be observed. Spectrally resolved linescans across the active region exhibit a redshift from the bottom (425 nm) to the top (465 nm) visualizing strain relaxation, higher indium incorporation, and/or increasing quantum well thickness.

8986-81, Session PWed

Impact of extended defects on optical properties of (1-101)GaN grown on patterned Si

Serdal Okur, Natalia Izyumskaya, Fan Zhang, Vitaliy Avrutin, Virginia Commonwealth Univ. (United States); Sebastian Metzner, Christopher Karbaum, Frank Bertram, Jürgen Christen, Otto-von-Guericke-Univ. Magdeburg (Germany); Hadis Morkoç, Ümit Özgür, Virginia Commonwealth Univ. (United States)

Spatial distribution of defects in semipolar (1-101)-oriented GaN layers grown on stripe patterned Si substrates has been investigated using near-field scanning optical microscopy and cathodoluminescence. The optical quality was explored by time- and polarization-resolved photoluminescence spectroscopy. High intensity bandedge emission was observed in c+ wing regions of the stripes as a result of threading dislocation (TD) bending, while c- wing regions were found to be of poorer optical quality due to a high density of TDs in addition to basal and prismatic stacking faults (BSFs and PSFs). The high-optical quality region formed on the c+ wings was evidenced also from the much slower biexponential PL decays (0.22 ns and 1.70 ns) and an order of magnitude smaller amplitude ratio of the fast decay (nonradiative origin) to the slow decay component (radiative origin) compared to the c- wing regions. In regard to defect-related emission, decay times for the BSF and PSF emission lines at 15 K (~ 0.80 ns and ~ 3.5ns, respectively) were

independent of the excitation density within the range employed (5 – 420 W/cm^2), and also much longer than that for the donor bound excitons (0.13 ns at 5 W/cm^2 and 0.22 ns at 420 W/cm^2). It is also found that the emission from BSFs had lower polarization degree (0.22) than that from donor-bound-excitons (0.35). The diminution of the polarization when photogenerated carriers recombine within the BSFs is another indication of the negative effects of stacking faults on the optical quality of the semipolar (1-101)GaN.

8986-82, Session PWed

Carrier diffusion length in p- and n-type GaN determined from photoluminescence and cathodoluminescence

Shopan D. Hafiz, Fan Zhang, Morteza Monavarian, Vitaliy Avrutin, Hadis Morkoç, Ümit Özgür, Virginia Commonwealth Univ. (United States); Sebastian Metzner, Christopher Karbaum, Frank Bertram, Jürgen Christen, Otto-von-Guericke-Univ. Magdeburg (Germany); Bernard Gil, Univ. Montpellier 2 (France)

Diffusion lengths of photo-excited minority carriers in p- and n-type GaN epitaxial layers were determined from photoluminescence (PL) measurements along the c-direction. The investigated samples incorporated a 6 nm thick In0.15Ga0.85N layer grown on a GaN/c-sapphire template by metal-organic chemical vapor deposition and capped with either 500 nm p-GaN or 1500 nm n-GaN. Different thicknesses for the top GaN layers were achieved by inductively coupled plasma etching in steps. The incident laser radiation (325 nm wavelength) was absorbed near the surface region and the intensities of PL from the InGaN active region and the underlying layers were monitored as a function of the top GaN thickness. The PL intensity of the etched region was always compared with the corresponding reference region to minimize the effect of variation in PL intensity across the wafer. Taking into consideration the absorption in the active and underlying layers, the diffusion length at room temperature was measured to be about 85 nm for Mg-doped p-type GaN and 400 nm for unintentionally doped n-type GaN. These results were compared with those obtained by cross-sectional cathodoluminescence line-scan measurements. The dependence of carrier diffusion length on growth conditions (substrate temperature and reactor pressure) of p-GaN was also investigated.

8986-83, Session PWed

Effect of temperature and electric field on the degradation in AlGaN/GaN heterojunction field effect transistors upon electrical stress

Congyong Zhu, Fan Zhang, Romualdo A. Ferreyra, Vitaliy Avrutin, Ümit Özgür, Hadis Morkoç, Virginia Commonwealth Univ. (United States)

AlGaN/GaN heterojunction field effect transistors (HFETs) were subjected to on-state-high-field (high drain bias and drain current) and reverse-gate-bias (no drain current and reverse gate bias) stress at room and elevated temperatures for up to 10 hours. The resulting degradation of the HFETs was studied by DC and uniquely phase noise before and after stress. A series of drain and gate voltages was applied during the on-state-high-field and reverse-gate-bias stress conditions, respectively, to examine the effect of electric field on degradation of the HFET devices passivated with SiNx. The degradation behaviors under these two types of stress conditions were analyzed and compared with electric field simulation results. In order to isolate the effect of self-heating/temperature on device degradation, stress experiments were conducted at base plate temperatures up to 150 oC. The degradation patterns under different bias conditions and temperatures were investigated and the underlying mechanisms were discussed.

8986-85, Session PWed

Fabrication and characterization of periodic gallium nitride subwavelength nanostructures for antireflection surfaces

Jae Su Yu, Yeong Hwan Ko, Kyung Hee Univ. (Korea, Republic of)

To improve the device performance, subwavelength grating (SWG) structures have gained enormous attention for a wide range of applications, including solar cells, light emitting diodes, and sensors. Although various fabrication methods have been developed for nanoscale patterns, some require expensive and complicated processes. The periodic nanopatterning method using a self-assembled ordered monolayer of micro- or nano-spheres is a simple and low-cost technique. For periodic SWGs, the antireflective surface-relief structure can be modified and designed predictably with theoretical calculation and analysis of its optical properties. Gallium nitride (GaN)-based semiconductors have be recognized as promising materials for novel photonic and optoelectronic device applications. Here, we fabricated the periodic GaN subwavelength nanostructures on GaN/sapphire substrate by the nanopatterning technique using a self-assembled ordered monolayer of silica micro- or nano-spheres for antireflection surfaces. The optical properties of the fabricated GaN subwavelength nanostructures were investigated. Using these GaN SWG structures, the surface reflectance was significantly reduced. These results provide a deep understanding into antireflective GaN nanostructures for various device applications.

8986-86, Session PWed

Selective area growth for p-side down InGaN/GaN light-emitting diodes by metal-organic chemical vapor deposition

Hsueh-Hsing Liu, Meng-Jie Lee, Ta Lin, Geng-Yen Lee, Nien-Tze Yeh, National Central Univ. (Taiwan); Jen-Inn Chyi, National Central Univ. (Taiwan) and Academia Sinica (Taiwan)

Reducing the efficiency droop of InGaN/GaN multi-quantum well (MQW) light-emitting diodes (LEDs) has been the subject under intensive investigations lately. Piezoelectric polarization mismatch, which induces polarization sheet charge at InGaN/GaN interfaces and impacts carrier transport, is considered an important factor in the efficiency roll-off of these LEDs. For typical Ga-face p-side up InGaN/GaN MQW LEDs grown by metal-organic chemical vapor deposition (MOCVD) on c-plan sapphire, the polarization-induced electric field in the last quantum barrier layer leads to enhanced electron spillover toward the p-type contact layer. P-side down LEDs, which have a reversed polarization field, are thus proposed to overcome this issue. However, direct growth of p-side down LEDs has not been successful due to material degradation by Mg-diffusion during epitaxy. In addition, it is difficult to obtain a low resistance contact onto the dry-etched p-type area. In this work, we develop a regrowth process for the proposed p-down LEDs. By doing so, ohmic contacts with contact resistivity of 1.53x10-3 Ω-cm2 on the etched p-type GaN contacts are successful achieved. Preliminary measurements on the p-side down LEDs prepared by this method exhibit higher output power and less efficiency droop as compared to those of conventional p-side up ones. This indicates that p-side down LEDs are indeed very promising and deserve further development.

8986-61, Session 12

Auger recombination and leakage in InGaN/GaN quantum well LEDs *(Invited Paper)*

Friedhard Römer, Marcus Deppner, Christian Range, Bernd Witzigmann, Univ. Kassel (Germany)

III-nitride light emitting diodes (LEDs) suffer from a substantial decay of the internal quantum efficiency at high current densities, the droop. This limits the output power per chip area, which is a critical factor for general lighting applications.

The physics behind the droop has not yet been fully understood. Theories for its origin include the Auger recombination and the direct carrier leakage. While both effects lead to increasing losses with increasing current density their impact on efficiency droop is still being discussed. One argument against the dominance of the Auger recombination is that theoretical model calculations on the Auger effect cannot explain the magnitude of the droop observed in experiments.

In our work we propose that the Auger recombination and the direct carrier leakage are in fact related. An Auger event in the active zone enables the transfer of the band to band recombination energy to a third particle. This particle is lifted to the continuum states because the band gap of the active zone is much larger than the band offsets to the barrier layers. Consequently, it appears as a hot carrier there and can pass any barriers such as the electron blocking layer more easily, contributing to the leakage current.

Calculations are performed using a coupled continuum and bound population drift-diffusion model that enables the non-equilibrium treatment of quantum well regions. It includes dynamic scattering of carriers into and out of the quantum regions. Evaluation of the internal quantum efficiency for both polar and non-polar III-nitride based LEDs show very good agreement with experiments. We state that with the Auger induced carrier leakage experimental data can be explained with a smaller Auger coefficient reducing the gap to the results of atomistic calculations.

8986-62, Session 13

Low-temperature studies of the efficiency droop in InGaN-based light-emitting diodes *(Invited Paper)*

Jong-In Shim, Hyunsung Kim, Dong-Pyo Han, Dong-Soo Shin, Hanyang Univ. (Korea, Republic of); Kyu-Sang Kim, Sangji Univ. (Korea, Republic of)

The efficiency droop in light-emitting diodes (LEDs) represents a gradual decrease of the internal quantum efficiency (IQE) with increasing current. Experimentally, the IQE droops are strong functions of material, epitaxial and chip structures, and operating temperature. Recently, we have proposed an IQE droop model as the saturation of the radiative recombination rate at low current and subsequent increase in the nonradiative recombination rates at high current. Once the radiative recombination rate begins to saturate at an active region, the carrier density as well as the nonradiative recombination rate rapidly increase there. Eventually, the IQE droop appears from the increase in the nonradiative recombination rate being much larger than that in the radiative one. A dominant nonradiative recombination process is not solely determined for each LED chip, but it could vary with current level and operating temperature. As temperature decreases, in general, the IQE droop becomes larger with the peak IQE occurring at an extremely small current level. We test the droop model by investigating the radiative and nonradiative recombination processes separately from the cryogenic to room temperature. The characterization methods include comparative efficiency study between photoluminescence (PL) and electroluminescence (EL), open-circuit voltage under resonant PL excitation, interrelations of current-voltage-light characteristics, and EL spectra of color-coded quantum wells (QWs). Although a sudden increase of the nonradiative recombination rate is an apparent cause of the IQE droop, the saturation of the radiative recombination rate is the common trigger behind the IQE droop issue.

8986-63, Session 14

Recent progress of deep UV LEDs and potential applications *(Invited Paper)*

Kyoung Hoon Kim, LG Innotek (Korea, Republic of)

We have been developing AlGaN based deep UV LEDs on c-plane sapphire substrate by specially designed high temperature (up to 1600 oC) MOCVDs. The high crystalline quality AlN, which is necessary to provide a template for deep UV LEDs structure, requires high growth temperature. It is believed that the efficiency of In free AlGaN quantum well structure is sensitive to the dislocation density resulted from the interface between AlGaN and sapphire substrate. Recently, thanks to the improvement of high quality AlN growth technology, we have achieved efficient and reliable deep UV LEDs with a mass producible yield. It is about to apply home appliance products. In this talk, we will present how we have improved the EQEs and reliabilities of deep UV LEDs using high quality AlN template. Also, we will discuss the potential applications of deep UV LEDs, mostly home appliances applications.

8986-64, Session 14

Performance of DUV-LEDs fabricated on HVPE-AlN substrates *(Invited Paper)*

Toru Kinoshita, Tokuyama Corp. (Japan) and Kobe Univ. (Japan); Toshiyuki Obata, Toru Nagashima, Hiroyuki Yanagi, Tokuyama Corp. (Japan); Baxter Moody, HexaTech, Inc. (United States); Ramon Collazo, North Carolina State Univ. (United States); Shin-ichiro Inoue, National Institute of Information and Communications Technology (Japan) and Kobe Univ. (Japan); Yoshinao Kumagai, Akinori Koukitu, Tokyo Univ. of Agriculture and Technology (Japan); Zlatko Sitar, North Carolina State Univ. (United States)

Disinfection to water, air and surfaces by the use of deep ultraviolet (DUV) light are attracting much attention for an efficient method without the use of chemical disinfectants. Traditionally mercury vapor lamps which have toxic mercury, short lifetime and require a measurable amount of power are used as UV light source. A promising alternative UV light source to mercury lamps is the use of AlGaN-based DUV light-emitting diodes (DUV-LEDs) with emission peaking at around 265 nm. In order to adopt AlGaN-based DUV-LEDs as practical and reliable ultraviolet light sources, bulk AlN substrates with low dislocation densities are required to fabricate high-performance DUV-LEDs on them. Recently we proposed that thick AlN layers grown by hydride vapor phase epitaxy (HVPE) on PVT substrates may offer a solution with both low dislocation density and high transparency in the ultraviolet region.

In this work, we report on the device characteristics of AlGaN-based DUV-LEDs fabricated on the HVPE-AlN substrates as well as structural and optical properties of the HVPE-AlN substrates. The HVPE-AlN substrates for growing the LED structures were prepared by growing thick HVPE-AlN layers on PVT-AlN substrates. The absorption coefficient of HVPE-AlN was 6.6 cm-1 at 265 nm. The TEM analysis revealed that the dislocation density through the LED layers was similar as that of PVT-AlN substrate, which is below 106 cm-2. DUV-LEDs exhibited single peak with emission wavelength at 260-270 nm, extracted through the HVPE-AlN substrate. The output power under DC operation at 250 mA was recorded over 30 mW.

8986-65, Session 14

High-power pseudomorphic mid-ultraviolet light-emitting diodes with improved efficiency and lifetime

James Grandusky, Jianfeng Chen, Craig G. Moe, Ken Kitamura, Mark C. Mendrick, Muhammad Jamil, Masato Toita, Shawn R. Gibb, Leo J. Schowalter, Crystal IS, Inc. (United States)

Mid-ultraviolet light-emitting diodes continue to become important light sources for chemical analysis and disinfection applications. Their small size, robustness, ability to turn on and off instantly, and ability to adjust to specific desired wavelengths have always been the inherent advantages over alternate sources such as mercury lamps. The recent improvement in efficiencies and lifetimes from the light-emitting diodes have led to serious challenges to the incumbent technology and also begun to open up new applications not suitable for mercury lamps.

Pseudomorphic growth on AlN substrates has produced epitaxial structures that are fully strained to the substrate with low dislocation densities. This results in a significant improved internal efficiency over devices with higher dislocation densities. The external quantum efficiency (EQE) remains limited by photon extraction, with greater than 5% having been achieved for a 266 nm device at currents up to 200 mA continuous wave (CW). At 300 mA CW with an output power of 66 mW, an EQE of 4.5% has been obtained.

The low dislocation density also leads to long operating lifetimes for the devices. For example, the most recent 120 devices run have a median power degradation of 3% when operated at 100 mA for 1000 hours. The primary failure mechanisms in these devices is catastrophic failure through package related faults. These failures are expected to be reduced or eliminated through encapsulation and/or hermetic sealing. The output power degradation dependencies on both input current and temperature are being investigated.

8986-66, Session 14

Boost in deep-UV electroluminescence from tunnel-Injection GaN/AlN quantum dot LEDs by polarization-induced doping

Jai K. Verma, Vladimir V. Protasenko, S. M. Islam, Huili Xing, Debdeep Jena, Univ. of Notre Dame (United States)

2 monolayer (ML) thick GaN QDs embedded in AlN barriers, grown by plasma assisted molecular beam epitaxy (PAMBE) in the SK growth mode in N-rich growth regime (III/N < 1) on commercially available AlN/sapphire templates, exhibit deep UV emission. By reducing the GaN growth time from 35 s to 25 s the wavelength can be reduced from 270 nm to 246 nm. Besides, by reducing the Ga beam equivalent pressure from 6.2e-8 Torr to 5.6e-8 Torr, a further decrease in wavelength to 238 nm can be achieved.

Further in this work, 2 UV LED structures (Samples: I and II) incorporating GaN/AlN QDs as the active region are grown at a growth rate of 0.173 ML/s. The layer structure for sample I has 73% n-AlGaN and 50% p-AlGaN, whereas sample II has 80% n-AlGaN and graded 50-25% p-AlGaN. Electron-beam deposited Ti/Al/Ni/Au and Ni/Au are used as the n-and p-type contacts, respectively. On measuring the LEDs for electroluminescence Sample II shows a peak emission at 250 nm and 290 nm at injection current of 11 A/cm2. Upon increasing the injection current the emission intensity increased. The 250 nm peak is attributed to emission from ground state of the 2 ML thick QDs and 290 nm emission occurs from carriers that recombine in the AlGaN contact region resulting from carrier spillover or by excitation of AlGaN layer by the 250 nm emission from the QDs. Sample I shows weak QD emission but prominent emission from p-AlGaN at 290 nm. The integrated EL intensity for Sample II is 26 times better than that of Sample I signifying better hole injection due to polarization doped graded p-AlGaN layer.

8986-67, Session 14

Enhanced charge carrier injection for UV LEDs emitting below 250 nm

Frank Mehnke, Tim Wernicke, Christian Kuhn, Martin Guttmann, Christoph Reich, Tim Kolbe, Technische Univ. Berlin (Germany); Arne Knauer, Ferdinand-Braun-Institut (Germany) and Leibniz-Institut für Höchstfrequenztechnik (Germany); Viola Kueller, Ferdinand-Braun-Institut (Germany); Jens Rass, Technische Univ. Berlin (Germany); Markus Weyers, Ferdinand-Braun-Institut (Germany); Michael Kneissl, Technische Univ. Berlin (Germany) and Ferdinand-Braun-Institut (Germany)

Efficient charge carrier injection proves to be a great challenge for LEDs emitting in the UV-C spectral range below 250 nm. These difficulties arise from the small band offsets between the AlGaN quantum well (QW) active region and the AlGaN:Mg electron blocking layer (EBL) as well as the reduced acceptor and donor concentrations for high aluminum mole fraction AlGaN alloys. In this paper we investigate different LED heterostructure designs and their effect on electron leakage and hole injection into the active region. The LEDs were grown by metal organic vapour phase epitaxy on (0001) epitaxially lateral overgrown AlN/sapphire. We found that UV-C LEDs with a conventional AlGaN:Mg EBL exhibit very poor QW emission near 240 nm and showed a dominant parasitic luminescence at around 280 nm. By introducing an additional AlN layer to form an AlN/AlGaN:Mg electron blocking heterostructure a significant reduction in parasitic luminescence was observed. With increasing thickness of the AlN interlayer the parasitic luminescence was suppressed without negatively affecting hole injection or QW emission power. However, this can only be achieved with a careful control of the doping profiles and optimized design of AlN/AlGaN:Mg electron blocking heterostructure that also serves as an efficient hole injector. By optimizing these designs AlGaN QW LEDs emitting in the wavelength range between 240 nm – 246 nm with very low parasitic luminescence (< 10% of total emission power) and external quantum efficiencies of 0.19% have been realized.

8986-68, Session 14

Fabrication of periodic light-extraction structures on sapphire substrate for electron-beam-pumped deep-ultraviolet light sources

Fumitsugu Fukuyo, Mie Univ. (Japan) and Hamamatsu Photonics K.K. (Japan); Hideto Miyake, Kazumasa Hiramatsu, Mie Univ. (Japan); Harumasa Yoshida, Yuji Kobayashi, Hamamatsu Photonics K.K. (Japan)

From the point of view of global environment and energy issues, mercury free, efficient deep-ultraviolet light sources have attracted strongly attention for industrial use. Research in recent years, technological progress of AlN and AlGaN epitaxial crystal growth and optimization of light-emitting diodes (LEDs) structure, the performance of AlGaN-based deep-ultraviolet (UV) LEDs has dramatically improved. However, essential issue of p-type activation have not solved yet, life time and reliability on high power operation still have been inadequate for practical use. In this background, we have focused on electron-beam (EB)-pumped p-AlGaN free AlGaN for deep-UV target of EB pumped deep-UV light sources. High refractive index of the AlGaN in the deep-UV wavelength makes difficult to improve external quantum efficiency (EQE). In order to solve this problem, any kinds of the light extraction structures for deep UV LEDs were reported and demonstrated advantages of reducing the reflectance and enhancing the transmittance. In this paper, we tried to fabricate periodic light-extraction structures on sapphire substrate to improve the EQE of the deep-UV AlGaN MQW target for EB-pumped. To improve EQE, periodic light-extraction structures on sapphire substrate were fabricated by UV nano-imprint lithography and inductively-coupled-plasma (ICP) reactive-ion-etching (RIE) for EB-pumped deep-UV light

sources. EB-pumped deep-UV light output power was evaluated with AlGaN multi quantum well (MQW) target on the sapphire substrate. A deep-UV light output power with the structure was 45% higher than that of without the structure.

8986-69, Session 15

Recombination and energy relaxation mechanisms in LEDs by energy analysis of electron emission in vacuum *(Invited Paper)*

Jacques Peretti, Lucio Martinelli, Ecole Polytechnique (France); Justin Iveland, Univ. of California, Santa Barbara (United States); Marco Piccardo, Ecole Polytechnique (France); Claude Weisbuch, Ecole Polytechnique (France) and Univ. of California, Santa Barbara (United States); Jim Speck, Univ. of California, Santa Barbara (United States)

We present novel experiments to study the physical mechanisms occurring inside LEDs based on the energy analysis of electrons emitted in vacuum under forward bias. We discuss the various experimental conditions allowing such measurements to be made including surface cleaning, sample design and constraints on contacts. The observed hot electrons peaks appear to be due to Auger non radiative recombination and their intensity is linearly correlated with the droop current. The complementarity to photoemission experiments will also be discussed.

8986-70, Session 15

Highly-efficient InGaN MQW LEDs grown on 200-mm Si substrates *(Invited Paper)*

Masaaki Onomura, Toshiba Matsushita Display Technology Co., Ltd. (Japan)

We demonstrate InGaN MQW LEDs on Si substrates have both high performance and low cost structure. The blue LED structures were grown by metal-organic chemical vapor deposition via unique buffer layers on 200 mm-diameter Si (111) substrates. The epitaxial wafers have slightly ex-situ convex bow without micro-cracks. Median and standard deviation of dominant wavelength by photo luminescence measurement were 448.9nm and 2.0 nm within 4 mm edge exclusion, respectively. XRC FWHMs of GaN (0002) and GaN (10-12) were 341 arcsec and 388 arcsec, respectively, corresponding to be estimated to edge dislocation density of 2.0 x 109 /cm2. Thin-film LED structures were fabricated by legacy 8-inch Si device equipment without remodeling, because no particular Si wafer thickness was needed for our LED epitaxial growth. The unique Au-free thin-film LEDs also help cheaper cost structure.

Encapsulated blue lamps were fabricated after dicing with 45 mil2. Median light output power of 641 mW was obtained at injection current of 350 mA at 25 deg-C. It corresponds to an external quantum efficiency, ?EQE of 63 %. The operating voltage was 2.9 V. Stable operation under accelerated lifetime testing more than 6,000 hours was confirmed. These results suggest the InGaN MQW LEDs on the large-scale Si wafers are promising for the near future solid-state lighting.

8986-71, Session 15

High-voltage LED for general lighting application *(Invited Paper)*

Schang-jing Hon, EPISTAR Corp. (Taiwan)

The breakthrough in high power GaN LED's efficiency makes the adoption of these solid state light emitting devices into general lighting application earlier than expected before. However, cost is one of the most important factors for the adoption of the general lighting application. So far, the most popular driving current for 1mm square die is about 350mA. In order to improve the lumen per cost, there is a trend to increase the driving current up to 1.5A or even higher. As well known, the droop effect plays an important roll for LED operating at high current density. Among the many factors affecting the droop effect, current crowding effect has pronouncedly degraded the performance of the LED at high current density.

In the paper we propose a novel high-voltage LED structure to achieve the extreme high power LED with high efficiency and low cost for manufacturing. The design of a series multi-junctions connection is used for high voltage LED chip. The advantages of high-voltage LED are to provide the LED device with high efficiency due to the better current spreading character and to simplify the driving circuit by using high voltage and low current operation condition.

8986-72, Session 15

LED electron leakage dependence on the material properties of the electron blocker layer

Joachim Piprek, NUSOD Institute LLC (United States)

Light-emitting diodes (LEDs) based on GaN or AlN suffer from efficiency droop, which is partially attributed to electron leakage into the p-doped layers. Such electron leakage also reduces the injection of holes into the active layer. Many studies have been published on the design of an AlGaN electron blocker layer (EBL) in order to reduce the electron leakage. However, despite intense worldwide efforts, the efficiency droop was not eliminated thus far. In good agreement with published leakage measurements, we analyze the influence of EBL material properties on the leakage current using advanced numerical simulation. Besides the expected dependence on the EBL material composition (band gap), our results reveal an extreme sensitivity of the leakage current to the conduction band offset, the net interface polarization, and the density of ionized Mg acceptors. As long as these three crucial EBL material parameters are not exactly known, reliable predictions of the leakage current are hardly possible.

8986-73, Session 15

Nanoscale imaging of GaN-based LED structures with semipolar InGaN QWs using scanning transmission electron microscope cathodoluminescence

Marcus Müller, Otto-von-Guericke Univ. Magdeburg (Germany); Sebastian Metzner, Gordon Schmidt, Peter Veit, Silke Petzold, Frank Bertram, Jürgen Christen, Otto-von-Guericke-Univ. Magdeburg (Germany); Robert Leute, Dominik Heinz, Junjun Wang, Tobias Meisch, Ferdinand Scholz, Univ. Ulm (Germany)

In c-plane GaN based optoelectronic devices the polarization field induced quantum confined Stark effect leads to a dramatically decreased efficiency. One approach to reduce these polarization fields is the growth of InGaN-based LED structures in semipolar directions.

Using low temperature cathodoluminescence spectroscopy (CL) directly performed in a scanning transmission electron microscope (STEM), we present optical and structural properties of a GaN based LED structure comprising semipolar InGaN quantum wells.

The sample was fabricated by metalorganic vapour phase epitaxy (MOVPE). Dielectric mask was patterned by laser interference and nanoimprint lithography on c GaN/sapphire templates. Subsequent MOVPE overgrowth leads to a selective GaN growth ending in a formation of n-doped GaN stripes with semipolar {10-11} side facets.

Subsequently, InGaN quantum wells (QWs) were grown on these semipolar facets, followed by p-doped GaN epitaxy planarizing to a c-oriented surface.

The cross-sectional STEM image clearly reveals the GaN/sapphire template, the TiN mask and the InGaN quantum wells grown on the GaN stripes. At room-temperature, we observe the most intense emission from the InGaN QWs with a broad luminescence band between 375 nm and 440 nm. The highly spatially resolved CL mapping of the InGaN QWs exhibits an inhomogeneous wavelength distribution due to local indium fluctuations and varying quantum well thickness. In contrast, the donor-acceptor pair (DAP) recombination at 380 nm becomes a dominating luminescence process at 16 K. Monochromatic CL mappings between 380 nm and 410 nm reveal a superposition of the DAP luminescence and the emission of the InGaN QWs.

8986-74, Session 15

Light-emitting diodes using InGaN/GaN nanowires grown on SiO2/Si

Junseok Heo, Ajou Univ. (Korea, Republic of); Shafat Jahangir, Pallab K. Bhattacharya, Univ. of Michigan (United States)

InGaN/GaN nanowires grown on silicon have attracted much interest in developing high efficiency light emitting diodes (LEDs). Previous extensive studies revealed a large surface to volume ratio mitigates the strain induced by a lattice mismatch, which results in a small number of defects and a negligible piezoelectric polarization charges in comparison to those in bulk. Auger coefficient measured in such nanowires is known so low to be suitable for high power operation. Nonetheless, the development of InGaN/GaN nanowire based LEDs has been hindered by a few things. First, at least a half of emitted visible light is absorbed by silicon substrate. Second, the SiNx layer formed during the growth blocks the carrier injection through silicon. To address the issues, the bottom emission device has been investigated by placing a reflective top contact and removing silicon substrate mechanically and chemically. However, the fabrication of such devices is very complicated and time consuming not suitable for practical devices. We have investigated the growth of InGaN/GaN nanowires on SiO2/Si. It was confirmed that the nanowires grown on SiO2 have the wurtzite crystal structure and a similar structural and optical characteristics compared to those grown on silicon. The SiO2 layer functions as a sacrificial layer owing to a selective etching in a HF acid. Hence, the silicon substrate is intact and reusable after the nanowires are separated. We will present the growth of InGaN/GaN nanowires on SiO2 and discuss the structural, optical and electrical characteristics of the LEDs fabricated with such nanowires.

8987-1, Session 1

Ultrathin ZnO films for transparent conductors and plasmonics

David C. Look, Wright State Univ. (United States); Buguo Wang, Solid State Scientific Corp. (United States); Kevin D. Leedy, Darren B. Thomson, Air Force Research Lab. (United States); Naho Itagaki, Koichi Matsushima, Iping Surhariadi, Kyushu Univ. (Japan)

Surface-plasmon-polariton (SPP) propagation at metal-dielectric interfaces is recognized as a way to manipulate visible and UV light at sub-wavelength dimensions. However, efficient propagation in the near IR regime, say ? = 1 - 5 µm, requires lower values of carrier concentration than are found in metals. A few highly-doped semiconductors can meet this requirement but semiconductor-dielectric interfaces are often poor because of lattice mismatch. In this work we test interface quality by measuring concentration n and mobility µ in extremely thin layers of Ga-doped ZnO (GZO) grown by pulsed-laser deposition at 200 ?C in Ar ambient on quartz or ZnO itself. From a previous study of AZO layers on quartz and ZnON/quartz, it was shown that the AZO/substrate interface can be characterized by parameters d* and ?d, found by fitting µ(d)=µ(?)/[1+d*/(d-?d)]. Here ?d is the "dead layer" thickness, and d* is the thickness required for reasonably good mobility, i.e., µ(d*) = µ(?)/2. We find similar results for GZO/quartz, but the best results of all for GZO/ZnO, for which good conductance can be achieved even at d = 5 nm. We conclude that: (1) common substrates, such as quartz or sapphire, lead to greatly reduced mobilities for d ? 25 nm; (2) a ZnON buffer layer helps considerably and permits good conductances for d ? 7 nm; and (3) the best buffer is ZnO itself because the GZO grains are much larger and the mobility and concentration are significantly higher.

8987-4, Session 1

Mid-infrared extraordinary transmission through Ga-doped ZnO films with 2D hole arrays *(Invited Paper)*

Justin W. Cleary, Air Force Research Lab. (United States); Nima Nader Esfahani, Solid State Scientific Corp. (United States); Shiva Vangala, Solid State Scientific Corporation (United States); Junpeng Guo, The Univ. of Alabama in Huntsville (United States); Joshua R. Hendrickson, Kevin D. Leedy, Air Force Research Lab. (United States); David C. Look, Wyle Labs. (United States)

Extraordinary optical transmission (EOT), or transmission greater than that predicted by conventional optics theory, through highly conductive ZnO films with sub-wavelength hole arrays is investigated in the long-wavelength infrared regime. EOT is facilitated by the excitation of surface plasmons on Ga-Doped ZnO films and can be tuned utilizing the physical structure sizes; i. e. film thickness, period, hole diameter, and hole shape. Ga-doped ZnO films are grown via pulsed laser deposition (PLD) as have plasma frequencies in the near-infrared. The sub-wavelength 2D hole arrays are fabricated in the Ga-doped ZnO films via standard lithography and etching processes, with the optical transmission then being measured with a microscope coupled FTIR system and quantum cascade lasers. EOT through the structures is observed and compared with finite difference time-domain simulations. This highly conductive ZnO EOT structure may prove useful in novel integrated components such as tunable biosensors or surface plasmon coupling mechanisms.

8987-34, Session 1

Low-temperature aqueous solution deposition of ZnO based TCO films for optoelectronic applications *(Invited Paper)*

Jacob J. Richardson, Evan C. O'Hara, Solution Deposition Systems, Inc. (United States)

ZnO based transparent conductive oxide (TCO) layers have become popular alternatives to indium tin oxide (ITO) in optoelectronics applications. This has largely been motivated by the high cost of indium compared to zinc. However, in some applications the raw materials costs of a TCO layer are similar to, or even significantly outweighed by, the capital equipment depreciation, energy, and other costs associated with depositing the TCO layer. Exchanging ITO with a lower cost ZnO based TCO will have a limited cost benefit as long as the complex equipment and high energy consumption of vapor deposition processes are retained. Solution Deposition Systems, Inc. (SDS) and others have recently demonstrated that intrinsically low cost aqueous solution deposition processes can be used to produce high performance ZnO based TCO layers capable of competing with vapor deposited TCO layers. Aqueous solution deposition of ZnO not only has potential to lower costs, but also presents unique capabilities not available in the vapor deposition methods commonly used for TCO layer deposition. This can all be achieved using a simple, safe, and relatively environmentally benign aqueous chemistry. An overview of SDS's low temperature aqueous solution deposition technology, as well as materials properties and device performances achieved using solution deposited ZnO based TCO layers, will be presented.

8987-68, Session 1

TiO2 anode materials for lithium-ion batteries with different morphology and additives

Xiang Liu, The Univ. of Hong Kong (Hong Kong, China); Yip Hang Ng, The Univ. of Hong Kong (China); Yu Hang Leung, The Univ. of Hong Kong (Hong Kong, China); Fang Zhou Liu, The Univ. of Hong Kong (China); Aleksandra B. Djuri?ic, Mao Hai Xie, Wai Kin Chan, The Univ. of Hong Kong (Hong Kong, China)

Lithium-ion batteries (LIBs) are among the most promising technologies for safe and stable energy storage. Titanium dioxide (TiO2) is considered as one of the alternative anode materials to graphite due to its low-cost, abundant, eco-friendly and chemical stability, especially for high operating voltage (~1.5 V) of TiO2, which may enable extra cycle life as well as enhance safety. However, due to its low electronic/ionic conductivities and the aggregation tendency of TiO2 anode nanoparticles, the practical application of this material is still a great challenge. For a better understanding of the morphology dependence of TiO2 anode and achieve a better performance, here we investigate several different TiO2 nanostructures such as: vertically aligned amorphous TiO2 nanotubes on Ti foil, TiO2 nanotube powders fabricated by rapid breakdown anodization technique as well as mesoporous TiO2 with 3D hierarchical structure. To improve the electron and ion conductivities of TiO2 anode, the optimal amount of additives as multi-wall carbon nanotubes, fullerene and reduced graphene oxide were investigated. The obtained results were discussed in detail.

8987-6, Session 2

Visible luminescence in bulk and nanostructured ZnO *(Invited Paper)*

Matthew R. Phillips, Univ. of Technology, Sydney (Australia); Suranan Anantachaisilp, Mahidol Univ. (Thailand); Liangchen Zhu, Laurent L. Cheong Lem, Univ. of Technology, Sydney (Australia); Christian Nenstiel, Technische Univ. Berlin (Germany); Siwaporn Meejoo Smith, Mahidol Univ. (Thailand); Cuong Ton-That, Univ. of Technology, Sydney (Australia); Axel Hoffmann, Technische Univ. Berlin (Germany)

Highly overlapped broad green (GL), yellow (YL) and red (RL) cathodoluminescence peaks in ZnO have been attributed to an extensive number of different deep level recombination centers, including; oxygen and zinc point defects (vacancies, interstitials, anti-sites and their complexes) as well as extended structural defects and impurities, such as Cu, Li, Fe and N. High temperature annealing in either metallic zinc vapor, O2 or N2 gas as well as thermal in-diffusion of Li can be used to produce ZnO luminescence spectra with a single GL, YL or RL peak. PL and CL studies before and after annealing have identified in bulk and nano-structured ZnO fabricated by conventional methods: GL bands centered at 2.30 eV GL1 (FWHM = 0.34 eV), 2.40 eV GL2 (FWHM = 0.50 eV) and 2.53 eV GL3 (FWHM = 0.45 eV); a YL band at 2.12 (FWHM = 0.42 eV); and a RL band at 1.76 eV (FWHM = 0.66 eV). Annealing in either forming gas (5% H2) or a H plasma was also performed. From temperature- and power-density resolved CL measurements combined with extreme sensitivity chemical analysis, it was established that all of the GL and RL relate to intrinsic defects, with GL2, GL3 and RL involving acceptor-like centers. The YL can be attributed to a donor-acceptor pair with a deep Li acceptor. Depth-resolved CL was used to investigate the role of surface states on the broad CL emission peaks. Relationships between these visible bands and the near band edge luminescence will also be discussed.

8987-7, Session 2

Exciton and phonon dynamics in ZnO nanostructures *(Invited Paper)*

Axel Hoffmann, Technische Univ. Berlin (Germany)

The advanced application of oxide semiconductors in areas like photovoltaics, optoelectronics, or photocatalysis requires a precise control over the electronic properties. The morphology (shape, size, lattice structure) of these materials is a central parameter influencing its functional properties. A comparative study of doped and undoped ZnO nanostructures reveals pronounced differences in the free and bound exciton luminescence that can be related to different impurity centers and strain levels. The properties of the shallow impurity bound excitons are compared to structural defect related deeply bound excitons. In addition, we investigate the spatial dependence of the exciton lifetimes in single ZnO nanowires. We have found that the free exciton and bound exciton lifetimes exhibit a maximum at the center of nanowires, while they decrease by 30% towards the tips. This dependence is explained by considering the cavity-like properties of the nanowires in combination with the Purcell effect. We show that the lifetime of the bound-excitons scales with the localization energy to the power of 3/2, which validates the model of Rashba and Gurgenishvili.

8987-8, Session 2

Trions and biexcitons in nonpolar homoepitaxial ZnO/(Zn,Mg)O quantum wells *(Invited Paper)*

Thierry Bretagnon, Bernard Gil, Thierry Guillet, Christelle Brimont, Univ. Montpellier 2 (France); Jean Michel Chauveau, Univ. de Nice Sophia Antipolis (France)

ZnO/(Zn, Mg)O hetero-structures have gained much interest in the last few years for its potential applications. Zinc oxide is a well-known wide band gap semiconductor exhibiting a large exciton binding energy (60 meV). It is therefore of high interest in opto-electronic applications where robust excitons and/or large oscillator strengths are required.

We report photoluminescence studies performed on a series of high quality ZnO/(Zn,Mg)O single quantum wells , with 20 % magnesium content, grown on nonpolar ZnO substrates. The CW-PL spectra measured at different temperatures ranged from 10 K to 300 K show an exchange in intensity between two peaks when temperature increases. In order to determine the physical origin of these two lines complementary investigations have been done. From CW-PL with different photon energy excitation and reflectivity measurement we attributed the dominant peak in low temperature PL spectra to the excitonic complexes formed of an exciton in interaction with an electron (negatively charged trion). Moreover, when the excitation intensity is increased a new line to a lower energy is resolved in the spectra. This line is attributed to the recombination of biexciton.

8987-9, Session 2

Nanoscale optical and electrical characterizations of ZnO nanostructures by near-field microscopy *(Invited Paper)*

Michael Molinari, Bogdan Bercu, Louis Giraudet, Univ. de Reims Champagne-Ardenne (France)

The interest in the recent years for nanostructure studies has led to the development of a wide palette of characterization techniques. If electrical characterization at nanoscale is now well developed thanks to the electrical modes in scanning probe microscopy (STM, EFM, KPFM...), optical characterization at nanoscale remains a challenge especially for wide gap semiconductors where high energy is required. In this presentation, we will present our work focusing in the development and the improvement of near-field microscopy techniques to investigate nanoscale properties of ZnO nanostructures and related semiconducting objects.

For the optical characterization, cathodoluminescence (CL) studies present many advantages over the classical photoluminescence experiments for ZnO analysis. CL can offer valuable information at nanometer scale, but the lateral resolution of the typical far-field collection systems based on parabolic mirrors is limited at several hundred nanometers due to the energy transfer volume and the diffusion length of the minority carriers. This contribution presents the development of a scanning near-field cathodoluminescence microscope where a bimorph piezoelectric cantilever is simultaneously used for both actuation and oscillation amplitude detection. Operated inside a scanning electron microscope (SEM) it offers the possibility of performing simultaneous topography and cathodoluminescence charting of the sample surface additionally to the SEM imaging with a resolution in the order of several tenths of nanometers. Different measurements of ZnO nanostructures and related objects will be presented to show the potentiality of our optical characterization setup.

As for the electrical characterization, we will focus on the local surface potential mapping of ZnO nanowires used for photoconduction using Kelvin Probe Force Microscopy. Indeed, ZnO nanowires have been of

particular interest as photoconduction gains as high as 10^10 in the UV region were reported. Nevertheless, several issues come into play when it comes to making a precise measurement of the photoconductive gain of a single nanowire. An important issue is the good quality of the injecting contacts on the nanowire and the reproducibility of its characteristics which can be made using KPFM.

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8987-10, Session 2

Emission characteristics of electrically- and optically-pumped single ZnO micro-spherical crystal *(Invited Paper)*

Daisuke Nakamura, Kyushu Univ. (Japan); Norihiro Tetsuyama, Kyushu Univ (Japan); Tetsuya Shimogaki, Kyushu Univ. (Japan); Koshi Fusazaki, Yasuaki Mizokami, Kyushu Univ (Japan); Mitsuhiro Higashihata, Hiroshi Ikenoue, Tatsuo Okada, Kyushu Univ. (Japan)

Zinc oxide (ZnO) nanocrystals have been attractive as the building blocks for the efficient opto-electronic devices in the ultraviolet (UV) region. We have succeeded in growing the ZnO micro / nanosphere by a simple laser ablation in the air, and therefore we have obtained UV lasing from the sphere under optical pumping. Recently, large size of several 10 micrometer ZnO microspheres were grown using Nd:YAG laser without Q-switching, and ZnO microsphere/PDOT:PSS heterojunction were fabricated to obtain the electroluminescence from the microsphere by electrical pumping. In this presentation, the optical characteristics of an optically- and electrically-pumped ZnO microsphere will be discussed.

8987-11, Session 2

Spatial mapping of exciton lifetimes in single ZnO nanowires

Frank Güell, Univ. de Barcelona (Spain); Juan S. Reparaz, Technische Univ. Berlin (Germany) and Institut Català de Nanociència i Nanotecnologia (Spain); Gordon Callsen, Technische Univ. Berlin (Germany); Markus R. Wagner, Technische Univ. Berlin (Germany) and Institut Català de Nanociència i Nanotecnologia (Spain); Joan Ramón Morante, Univ. de Barcelona (Spain) and Institut de Recerca en Energia de Catalunya (Spain); Axel Hoffmann, Technische Univ. Berlin (Germany)

The quest for novel semiconductor materials with improved optoelectronic performance has triggered intense research activities to exploit the great diversity of effects offered by low dimensional systems. In this work, we demonstrate that the recombination dynamics of excitons in ZnO nanowires can be well understood within the concept of optical nanocavities. We investigate the spatial distribution of the lifetimes of the near-band-edge and bound-exciton emissions in single ZnO nanowires with different dimensions by means of temperature dependent and time-resolved spectroscopy. We demonstrate that the lifetime of the excitons is systematically reduced by 30% at the tips of the nanowires with respect to their maximum value at the center, which originates from the combined effect of the cavity-like properties of these nanostructures with the Purcell effect. In addition, show that the model of Rashba and Gurgenishvili is valid even at the nanoscale, i.e. the lifetime of the bound excitons is proportional to the localization energy (Eloc) to the power of 3/2. This result provides a means to understand the spatial dependence of the lifetimes of the near-band-edge emission (NBE), which is not intuitive due to their spatially extended nature. Finally, the temperature dependence of the photoluminescence and lifetimes of the excitons in single nanowires is also briefly discussed in comparison to bulk ZnO samples.

8987-12, Session 2

Carrier dynamics in dilute II-VI oxide highly mismatched alloys *(Invited Paper)*

Yan-Cheng Lin, Wu-Ching Chou, National Chiao Tung Univ. (Taiwan); Jen-Inn Chyi, National Central Univ. (Taiwan); Tooru Tanaka, Saga Univ. (Japan)

This study explores comprehensively the carrier dynamics in ZnSeO and ZnTeO using photoluminescence (PL) and time-resolved PL spectroscopy. As the O concentration increases, the PL emissions shift toward lower energies. Additionally, the PL lifetime increases with increasing O contents and the decay curves exhibit complex behavior. In the case of ZnSeO, the mechanism of carrier recombination undergoes a complicated change from trapped to free excitons with the increase in temperature. The incorporation of O in ZnTe generates a wide distribution of electron localization below the energy of the E- conduction subband, and these cause broad PL emission and serve as another intermediate band. Electrons in both the E+ and the E- conduction subbands favor rapid relaxation to low energy states. Moreover, temperature-independent long carrier lifetimes (> 130.0 ns) that are induced by localized electrons increase with O concentration.

8987-13, Session 2

Optical characterization of laterally- and vertically-structured oxides and semiconductors *(Invited Paper)*

Péter Petrik, Research Institute for Technical Physics and Materials Science (Hungary); Nitish Kumar, Technische Univ. Delft (Netherlands); Emil Agocs, Balint Fodor, Research Institute for Technical Physics and Materials Science (Hungary); Silvania F. Pereira, Technische Univ. Delft (Netherlands); Tivadar Lohner, Miklós Fried, Research Institute for Technical Physics and Materials Science (Hungary); Hendrik Paul Urbach, Technische Univ. Delft (Netherlands)

Optical techniques have been intensively developed for many decades

in terms of both experimental and modeling capabilities. Involving spectroscopy and scatterometry material structures can be measured and modeled from the atomic scale (binding configurations, electronic band structure) through the nanometer scale (nanocrystals, long range order) to the micron sizes (photonic structures, gratings, critical dimension measurements). Using optical techniques atomic scale structures, morphology, crystallinity, doping and a range of other properties related to the change of the electronic band structure can most sensitively be measured for materials having interband transition energies in the optical photon energy range. This will be demonstrated by different models for the dielectric function of ZnO, a key material in optoelectronics and in numerous other fields. Using polarimetry such as spectroscopic ellipsometry sub-nanometer precision has long been revealed for the thickness of optical quality layers. The lateral resolution of spectroscopic ellipsometry is severely limited (>50 micron) by the use of incoherent light sources. Using single-wavelength imaging ellipsometry a sub-micron lateral resolution can be reached. In case of sub-wavelength structures the morphology (of e.g. porous or nanocrystalline materials) can be characterized using the effective medium theory. For structure sizes comparable with the wavelength, scatterometry is applied in a broad versatility of configurations from specular to angle resolved, from coherent to incoherent, from monochromatic to spectroscopic, from reflectometric to polarimetric. In this work coherent Fourier scatterometry will be presented for the characterization of periodic lateral structures.

8987-14, Session 3

Polymorphism, band-structure, band-lineup, and alloy energetics of the group II oxides and sulfides MgO, ZnO, CdO, MgS, ZnS, CdS

(Invited Paper)

Stephan Lany, National Renewable Energy Lab. (United States)

Transition metal oxides often have poor semiconducting properties, which is caused by carrier self-trapping, e.g., of electrons in Fe2O3 and of holes in MnO. In order to widen the materials base for electronic oxide materials, it would be desirable to design novel transition metal oxides that are dopable and exhibit a semiconducting band transport instead of a small polaron transport mechanism. In our recent study [1] of the prototypical d5 oxides Fe2O3 and MnO, we discovered that a hypothetical tetrahedral zinc-blende (ZB) structure of MnO would have a smaller band gap of 2.1 eV compared to 3.4 eV in the normal octahedral rock-salt (RS) structure and that this polymorph would avoid hole self-trapping that hinders hole transport in the RS structure. In order to predict the stability of tetrahedral MnO structures, we performed computing intensive total energy calculations in the random phase approximation [2], which overcome difficulties experienced in standard density functional or even in more advanced hybrid functional approaches. Based on these initial results, we predict (MnO)1-x(ZnO)x alloys to assume the tetrahedral wurtzite structure above x > 0.38, and to exhibit favorable semiconducting properties with a direct band gap of about 2.1 eV at around x = 0.5.

[1] “Semiconducting transition metal oxides based on d5 cations: Theory for MnO and Fe2O3”, H. Peng, S. Lany, Phys. Rev. B 85, 201202(R) (2012).

[2] “Polymorphic energy ordering of MgO, ZnO, GaN, and MnO within the random phase approximation”, H. Peng, S. Lany, Phys. Rev. B 87, 174113 (2013).

8987-15, Session 3

Development of blue excitable persistent phosphor of Ce3+-doped garnet ceramics by bandgap engineering and metal-sensitization

(Invited Paper)

Jumpei Ueda, Setsuhisa Tanabe, Kyoto Univ. (Japan)

Persistent luminescent materials doped with rare earth ions are of practical interest as luminous paints for safety indication and emergency lighting. So far, there have been a number of reports of the persistent luminescence in materials doped with rare earth ions, such as Eu2+ and Ce3+. Most of the persistent phosphors show the best performance after UV and violet light excitation, such as a fluorescent lamp. Recently, however, white light emitting diodes (LEDs) consisting of blue LEDs and various phosphors have started to be widely used as indoor illumination in place of fluorescent lamps. Therefore, blue-light excitable persistent luminescent materials have been the subject of considerable development.

We have developed blue-excitable persistent phosphors in Ce3+-doped garnet crystals with the composition of Y3Sc2Al3-xGaxO12:Ce3+ and Y3Al5-xGaxO12:Ce3+ by band gap engineering. Based on the photocurrent excitation spectra and thermoluminescence curves, both threshold of photoionization and electron trap depth decreased with increasing Ga content. In these materials, with increasing Ga content, energy gap between lowest 5d1 excited level of Ce3+ and conduction band becomes closer. As a result, the photocurrent by blue light was induced. One of these materials also shows the persistent luminescence by blue excitation. In addition, persistent luminescence intensity and duration time were improved by co-doping with some metal ions. We have demonstrated that the threshold of excitation wavelength for the persistent luminescence and electron trap depth can be controlled.

8987-16, Session 3

Doping of Ga2O3 bulk crystals and nanowires by ion implantation

Katharina Lorenz, João G. Correia, Luis C. Alves, Eduardo Alves, Univ. Técnica de Lisboa (Portugal); I. López, Emilio Nogales, Bianchi Méndez, J. Piqueras, Univ. Complutense de Madrid (Spain); M. B. Barbosa, João P. Araujo, Univ. do Porto (Portugal); Jorge N. Gonçalves, Joana Rodrigues, M. Peres, Teresa Monteiro, Univ. de Aveiro (Portugal); Encarna Garcia Villora, Kiyoshi Shimamura, National Institute for Materials Science (Japan)

Ga2O3, with its wide band gap of 4.8 eV, is a promising material for photonic devices working in the visible and ultraviolet spectral region, as transparent conductive oxide with high transparency down to 260 nm as well as for gas sensing applications. Doping Ga2O3 with optically active rare earth (RE) ions may extend these functionalities taking advantage of the sharp and temperature stable RE emission lines which span a wide spectral range from the infrared to the ultraviolet.

Ga2O3 bulk crystals and nanowires (NWs) have been implanted with Europium ions to fluences ranging from 1x10^13 to 4x10^15 at/cm^2. In bulk crystals, the damage build-up and lattice site location of Eu was assessed by Rutherford Backscattering Spectrometry in the channeling mode (RBS/C). RBS/C results suggest a mixture of defect clusters and extended defects such as dislocations. Amorphisation starts at the surface for fluences around 1x10^15 at/cm^2. Amorphous regions and defect clusters are efficiently removed during rapid thermal annealing at ~1100 ºC and RE ions are optically activated. However, extended defects still remain and higher annealing temperatures lead to the diffusion of Eu towards the surface. Similar damaging behavior is found for the NWs as suggested by Raman and transmission electron microscopy studies.

Implantation at elevated temperature considerably reduces implantation damage and promotes the incorporation of Eu on substitutional sites. Further damage and dopant incorporation studies were performed using the Perturbed Angular Correlation technique allowing probing the immediate lattice surroundings of an implanted radioactive probe on an atomic level.

8987-17, Session 3

Carrier doping into infinite-layer iron oxide thin films by rare-earth substitution *(Invited Paper)*

Akira Chikamatsu, The Univ. of Tokyo (Japan) and Japan Science and Technology Agency (Japan); Tsukasa Katayama, Ryosuke Takagi, The Univ. of Tokyo (Japan); Yasushi Hirose, The Univ. of Tokyo (Japan) and Japan Science and Technology Agency (Japan) and Kanagawa Academy of Science and Technology (Japan); Tomoteru Fukumura, The Univ. of Tokyo (Japan) and Japan Science and Technology Agency (Japan); Tetsuya Hasegawa, The Univ. of Tokyo (Japan) and Japan Science and Technology Agency (Japan) and Kanagawa Academy of Science and Technology (Japan)

An antiferromagnetic insulator $SrFeO_2$ has attracted much attention because it is an isostructural analog of the infinite-layer cuprate, $SrCuO_2$, which exhibits high transition-temperature superconductivity by carrier doping [1]. We recently reported that the resistivity (ρ) of a $SrFeO_2$ thin film is substantially decreased by Eu^{3+}-substitution [2,3]. This suggests that rare-earth substitution is an effective way to introduce a substantial amount of carriers into SrFeO2. In this study, we fabricated rare-earth (R: La, Pr, Nd, Sm, and Eu) substituted $SrFeO_2$ epitaxial thin films by combining pulsed laser deposition of $Sr_{0.95}R_{0.05}FeO_{3-\delta}$ precursor films and solid-phase reduction using CaH_2.

All X-ray diffraction patterns of the $Sr_{0.95}R_{0.05}FeO_2$ films on $KTaO_3$(001) substrates showed the (002) diffraction peaks of infinite-layer $SrFeO_2$ with c-axis orientation. The La, Pr, Nd, and Sm doped films exhibited metallic resistivity behavior ($d\rho/dT > 0$) while the Eu doped one was characterized by a semiconducting temperature slope ($d\rho/dT < 0$). Hall measurements revealed that n-type carriers were responsible for the electric conduction in the $Sr_{0.95}R_{0.05}FeO_2$ films. These suggest that the ionic radii of rare-earth dopants play an essential role in the metal-insulator transition of $SrFeO_2$ films by rare-earth substitution. In this paper we will also discuss a possibility as electron carriers of hydrogen ions which were inserted in the films in the reduction process [4].

[1] Y. Tsujimoto et al., Nature 450, 1062 (2007).

[2] T. Matsuyama et al., Appl. Phys. Express 4, 013001 (2011).

[3] A. Chikamatsu et al., J. Cryst. Growth 378, 165 (2013).

[4] K. Katayama et al., submitted.

8987-5, Session 4

Effects of aluminum doping on Fermi level in polycrystalline ZnO films *(Invited Paper)*

Junjun Jia, Yuzo Shigesato, Aoyama Gakuin Univ. (Japan)

Al doped ZnO (AZO) thin films have attracted much attention as transparent electrode in various optoelectronic devices such as organic light-emitting devices (OLEDs). For the application of OLEDs, AZO films can be used to inject holes in the highest occupied molecular orbitals (HOMO) of the organic semiconductors. The efficiency of hole injection critically depends on the interface barrier height between the transparent electrode and the organic layer, and the Fermi level of AZO films has been considered to be a key parameter for tailoring the interface barrier height.

The variation of the Fermi level in polycrystalline AZO films, which were coated on silica glass substrates by dc magnetron sputtering using an AZO ceramic target (Al_2O_3: 3.0 wt. %, Tosoh), was studied by investigating the carrier density (ne) dependence of the optical band gap and work function. The optical band gap showed a positive linear relationship with $n_e^{2/3}$, and the work function showed a negative linear relationship with $n_e^{2/3}$. These two phenomena are well explained on the basis of Burstein-Moss effect by considering the nonparabolic nature of the conduction band, indicates that the shift of the Fermi level shows a nonparabolic nature of the conduction band for the polycrystalline AZO film. The variation of work function with the carrier density reveals that the shift of the surface Fermi level can be tailored by the carrier density in the polycrystalline AZO films. The controllability between the work function and the carrier density in the polycrystalline AZO films offers great potential advantages in the development of optoelectronic devices.

8987-18, Session 4

Issues in the growth of p-type zinc oxide *(Keynote Presentation)*

Takafumi Yao, Tohoku Univ. (Japan) and National Institute of Advanced Industrial Science and Technology (Japan)

There have been numbers of publications on the growth of -type ZnO. However many of p-type ZnO films have been grown on substrates with large lattice mismatch, which inevitably resulted in the growth of ZnO films with deteriorated crystal quality. Such films consist of domains, which, in macy cases, cause serious errors in Hall measurements. I will review the experimental studies on the growth of p-type ZnO films and discuss clues to the growth of p-type ZnO.

8987-19, Session 4

Interstitial zinc complexes in ZnO *(Invited Paper)*

Norbert H. Nickel, Marc A. Gluba, Nicole Karpensky, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany)

Research devoted to ZnO is mainly driven by its potential use in optoelectronic devices. The major drawback of ZnO is the doping asymmetry naturally favoring n-tpye conductivity. The fabrication of stable p-type ZnO with reasonable hole concentrations is extremely difficult and hence, the real potential of ZnO cannot be fully exploited.

Closely related to its doping issue, ZnO exhibits a set of peculiar vibrational modes in the range of 270–860 cm-1 which are reported now and then to be caused by extrinsic dopants. Among the group V elements nitrogen is the most prominent candidate for p-type doping and it is routinely associated with these vibrational modes. In this work, we revisit the role of nitrogen and intrinsic defects on the anomalous vibrations by means of isotope experiments. For this purpose ZnO films with different composition of 64Zn, 68Zn and natural natZn were grown on sapphire substrates using pulsed laser deposition (PLD). N doping was achieved by adding N2O during the PLD growth. Raman measurements performed with different excitation wavelengths showed that the vibrational mode at 577 cm-1 is due to resonantly enhanced LO phonons. Interestingly, the local vibrational mode at 274 cm-1 is observed independent of doping but sensitive to the stoichiometry of the ZnO films. By analyzing the frequency shift and line shape of samples containing an equal amount of 64Zn and 68Zn we conclude that the LVM at 274 cm-1 is caused by the vibration of interstitial Zn clusters.

8987-20, Session 4

Theoretical investigations of electronic and optical properties of functionalized zinc-oxide nanowires

Michael Lorke, Adriel D. Garcia, Andreia Luisa da Rosa, Thomas Frauenheim, Univ. Bremen (Germany)

We investigate the electronic and optical properties of semiconductor nanowires via surface modification and doping.

ZnO is an oxide semiconductor, that shows a huge potential for technological applications since their physical properties can be optimized via functionalization.

One possible strategy for surface modification involves attachment of functional groups to the nanowire surfaces. Furthermore, doping of rare-earth or transition metal ions in wide gap semiconductors such as GaN, AlN, and ZnO has become a subject of intense investigations over the past years, due to potential applications in optoelectronic or spintronic devices.

We present density functional theory (DFT) calculations of functionalized nanostructures, specifically ZnO nanowires functionalized via molecules on the surface or via rare-earth doping.

Using both hybrid-DFT and beyond-DFT many-body methods like the GW approximation or the Bethe-Salpeter equation, we investigate both the electronic structure as well as the opto-electronic properties of these nanostructures.

For rare-earth doping of ZnO, we show the influence of lattice relaxation on the electronic structure.

Moreover, we discuss various complexes of rare-earth ions with intrinsic defects of ZnO such as oxygen vacancies zinc vacancys and interstitials. We find strongly localized rare-earth f-states, whose energetic position depend on the local geometry. For surface functionalized ZnO nanowires various molecular groups such as -NH2 (amines), -COOH (carboxylic groups), -SH (thiols) are discussed. We investigate the band alignment of various functionalized wires, compared to bare wires, and study the resulting electronic properties as well as the optical properties of these systems.

8987-46, Session 4

Electronic properties modification in ZnO thin films via surface modification by carboxylic acids *(Invited Paper)*

Josef W. Spalenka, Univ. of Wisconsin-Madison (United States); Yu Liu, Johns Hopkins Univ. (United States); Padma Gopalan, Univ. of Wisconsin-Madison (United States); Howard Katz, Johns Hopkins Univ. (United States); Paul G. Evans, Univ. of Wisconsin-Madison (United States)

Modifying the surface of polycrystalline ZnO films using a monolayer of organic molecules with carboxylic acid attachment groups modifies the electronic properties of field-effect transistor (FET) devices. Ultrathin ZnO active layers were created using a solution-phase deposition techniques and incorporated into top-contact FETs. The field-effect electron mobility and zero-bias conductivity of the ZnO layers are increased when the surface of the ZnO is modified by the solution attachment of molecules with carboxylic acid groups, resulting in improved transistors and transparent conductors. The improvement is consistent with the passivation of defects via covalent bonding of the carboxylic acid. The electronic properties can be reversibly cycled by exposure to a UV-ozone lamp, degrading the conductivity and mobility, and by subsequent re-exposure to the functionalization step. The properties of the solvent used for the attachment are crucial because solvents with high acid dissociation constants (Ka) for carboxylic acids lead to high proton activities and etching of the nanometers-thick ZnO films, masking the electronic effect.

8987-21, Session 5

Atomic collision effect during PLD processes: nonstoichiometry control in transparent superconductors *(Invited Paper)*

Taro Hitosugi, Tohoku Univ. (Japan)

Developing high-capacity lithium ion batteries is an important research in materials science, and the realization of high-quality thin films of lithium metal oxides is a step toward this goal. Pulsed laser deposition (PLD) is a method of creating such films. In this technique, atoms from a lithium-containing source land on a substrate surface through a ‘plume.’ We have investigated the model that should significantly improve the quality of PLD lithium-based thin films, a model that describes collisions between high-energy atoms in the plume.

The theory correctly mirrored the experimental results and revealed that the presence of oxygen gas caused lithium ions to scatter in erratic trajectories, often violently. Heavier manganese atoms pushed through oxygen practically unimpeded. According to the team, these findings indicate that lighter atoms will always show deficiencies when background gas pressures rise above a certain threshold — thus, source materials must be chosen carefully to achieve desired lithium compositions (Packwood et al., Phys. Rev. Lett. 111, 036101 (2013)).

Further, taking into account the above model and experiments, we developed ‘transparent conductor’ with superconducting transition temperature of 13.3 K, by optimizing the stoichiometry (Kumatani et al., Appl. Phys. Lett. 101, 123103 (2012)).

8987-22, Session 5

Augmented methods for growth and development of novel multi-cation oxides *(Invited Paper)*

Hideki Yamamoto, Yoshiharu Krockenberger, NTT Basic Research Labs. (Japan); Michio Naito, Tokyo Univ. of Agriculture and Technology (Japan)

The search for new functional materials, e.g., new superconductors with higher Tc, is the most challenging subject in materials science. Multi-cation oxides are materials of choice as they show a remarkable wide degree of functionality. Here, we demonstrate that MBE is a promising approach not only for the preparation of high-quality films of the existing multi-cation oxides [1] but also for the synthesis of new multi-cation oxides beyond approaches of alternate stacking of the existing oxides. Our unique, multi-source, oxide MBE system equipped with a high precision rate control system lies beneath the successful development of new superconducting materials, e.g., superconducting end-member T’-cuprates [2]. Besides the superior crystalline quality of materials grown by MBE, the list of merits of our setup might be extended to (1) low temperature reaction by ultimately small reactants, (2) quasi-stable phase formation by epitaxy, (3) contamination-free environment under UHV utilizing pure metal sources, (4) high throughput screening of synthesis conditions. In addition, a key factor, surface-to-volume ratio, can be readily exploited in film materials as oxygen engineering plays a fundamental role in certain oxides. Although so far our research efforts have been devoted in large part to the development of new cuprate superconductors, our studies on titanates, ruthenates, and scandates thin films emphasizes that MBE has unparalleled capabilities for materials synthesis beyond the stacking of existing lattices, irrespective of cuprates or non-cuprates.

[1] Y. Krockenberger et al., Appl. Phys. Express 5 (2012) 043101.

[2] Y. Krockenberger et al., Sci. Rep. 3 (2013) 2235.

8987-23, Session 5

Synthesis of epitaxial rutile-type VO2 and VO2(B) polymorph films *(Invited Paper)*

Franklin Wong, Shriram Ramanathan, Harvard School of Engineering and Applied Sciences (United States)

Metal-insulator transitions offer unique opportunities for the design of novel electronic and optoelectronic devices. Potential advantages include ultra-fast switching of optical constants and reconfigurability. Transition-metal oxides that exhibit metal-insulator transitions often possess orbital degrees of freedom, which in turn lead to their cations assuming oxidation states that are typically not the most stable under standard conditions. Therefore, along with the rich materials physics exhibited by such oxides, stabilization of precise stoichiometric phases can be extremely challenging. In thin-film synthesis, heteroepitaxy is the oft-chosen means to achieve high-quality materials. A material of much current interest, VO2 (a 3d1 system) undergoes a metal-insulator transition at a convenient temperature of 68 oC. The one 3d electron of the octahedrally coordinated V4+ cation occupies one of the three t2g orbitals; thus it has an orbital degree of freedom, and in fact the preferred valence state of V is 5+. We demonstrate the growth of VO2 films on a variety of single crystalline substrates, including (111) perovskite LaAlO3, (111) spinel MgAl2O4, (111) rocksalt MgO, and (0001) corundum Al2O3. In each of these cases, there are well-defined in-plane orientational relationships. We show that the choice of not only substrate material, but also crystal orientation is crucial for robust growth of high-quality VO2 films with bulk-like properties. The vibrational, electrical, and optical properties of the VO2 films grown on the various substrates are compared. Our work provides a foundation for the synthesis of diverse heterostructure combinations containing VO2 for future optoelectronic applications.

8987-24, Session 5

Infrared near-field study of stripe states in strained vanadium dioxide films *(Invited Paper)*

Mengkun Liu, Univ. of California, San Diego (United States)

Phase transitions in solids form the foundations of numerous technologies including but not limited to: memory elements, liquid crystal displays, sensors, smart coatings and transistors. Among solid-state phase transition materials, vanadium dioxide (VO2) is unique since it exhibits a transition from an insulating to metallic state close to room temperature: an advantageous property crucial for widespread application. Different forms of VO2 crystals have been extensively studied however the available findings for high quality single crystal films are incomplete and riddled with inconsistencies, limiting our ability to control the transition. Here we report for the first time on the nano-scale physical properties of sub-micron domains forming in strained VO2 films as revealed by infrared nano-imaging and spectroscopy. We directly image the unidirectional conducting stripes in VO2 films on [110]R and [100]R TiO2 through a wide range of temperatures. Investigating the formation of this stripe state resolve important physics of high quality single crystal VO2 films including the spontaneous electronic/structural phase separation, Tc anomaly, and the origin of electronic and optical anisotropy. Furthermore, with nano spectroscopy, we show that the insulator-to-metal transition proceeds via distinct stages, which exhibit specific real-space characteristics paired with distinct structural and electronic behaviors. The discovery of the stripe state physics in our work on VO2 is likely to be generic to many classes of oxides and other phase transition materials under epitaxial strain.

8987-25, Session 5

Metal-insulator phase transition oxide materials for micro- and nano-electronics *(Invited Paper)*

Guy Garry, Thales Research & Technology (France)

New fast radio-frequency passive and active electronic devices are under development taking benefit of the Metal-Insulator Phase transition (MIT) exhibited by some oxides. The electronic transition from Semiconductor to Metallic (SMT) states can be either optically or electrically switched on and off at a timescale down to picosecond and can be used for ultrafast switching devices. This brings opportunities to enable continued advances in information processing and storage beyond conventional CMOS technology as well as new functionalities of signal processing and sensing. In this review we discuss the synthesis of these materials and their applications for signal processing devices. A particular emphasis is placed on vanadium oxide and its use for the fabrication of new Radio Frequency (Rf) devices.

8987-26, Session 5

Transient Faraday rotation and magnetization precession in EuO *(Invited Paper)*

Takayuki Makino, Univ. of Fukui (Japan) and RIKEN (Japan)

The ultrafast spin dynamics have been investigated in ferromagnetic EuO thin films by transient Faraday rotation spectroscopy. We found that the photoinduced magnetization increases in a transient manner and the photoinduced magnetization precession. The decays time for the magnetization enhancement is about 1?ns. The circularly polarized light can control the magnetization precession in an ultrafast time scale. The intrinsic Gilbert damping coefficient was evaluated for EuO from the magnetic field dependences of the frequency and of the damping parameter.

8987-27, Session 6

Photocarrier recombination and localization dynamics of LaAlO3/SrTiO3 heterostructures

Yasuhiro Yamada, Kyoto Univ. (Japan); Hiroki K. Sato, SLAC National Accelerator Lab. (United States) and Univ. of Tokyo (Japan); Yasuyuki Hikita, SLAC National Accelerator Lab. (United States); Harold Y. Hwang, SLAC National Accelerator Lab. (United States) and Stanford Univ. (United States); Yoshihiko Kanemitsu, Kyoto Univ. (Japan)

The interface between two insulating transition metal oxides can generate unique electronic systems, which is currently under intensive research as the most exciting areas of materials science. One of the most studied of such systems is the LaAlO3/SrTiO3 (LAO/STO) interface, which is characterized by the formation of quasi-two-dimensional electronic gas (2DEG) at the interface. The 2DEG displays a high conductance and a rich variety of exotic phenomena such as two-dimensional superconductivity and magnetism. It is significantly important to understand the carrier dynamics that determines the unique electronic properties. We studied the dynamics of electrons in an n-type LAO/STO heterointerface at low temperatures by using femtosecond transient absorption (TA) measurements and compare this interface to bulk SrTiO3 crystals.

In both LAO/STO heterostructures and electron-doped SrTiO3 bulk crystals, the TA spectrum shows a Drude-like free carrier absorption immediately after excitation. In SrTiO3 bulk crystals, we observed a broad TA band in SrTiO3 bulk crystals gradually appears within 40

ps, which we assigned to the energy relaxation of photoexcited free electrons into localized state. Surprisingly, we found an extremely reduced relaxation rate, in comparison, of photoexcited electrons at the LAO/STO heterointerface, which could be attributed to the splitting of t2g subbands at the LAO/STO interface. Our results demonstrate the new optical functionalities of oxide heterointerface and provide important insights into their unique electronic conduction mechanisms.

8987-28, Session 6

Analysis of Low Temperature Magnetoresistance of LaAlO3/SrTiO3 Interfaces *(Invited Paper)*

Stefano Gariglio, Alexandre Fete, Univ. of Geneva (Switzerland); Daniela Stornaiuolo, Danfeng Li, University of Geneva (Switzerland); Marc Gabay, Université Paris-Sud 11 (France); Jean-Marc Triscone, University of Geneva (Switzerland)

The conducting interface between the two band insulators LaAlO3 and SrTiO3 has drawn a large share of attention, as it presents a variety of exciting electronic properties that are tunable by an electric field [1]. At low temperatures, magnetotransport analysis has revealed a strong Rashba spin-orbit interaction originating from the breaking of inversion symmetry [2] and, in field effect devices, the ground state has been tuned from an insulating to a superconducting state.

I will discuss these results in light of recent experiments on nano-devices [3] to probe spectroscopically the superconducting gap and its evolution across the phase diagram.

To this aim, using a patterning technique based on electron beam lithography, we realize nanodevices with width down to 200 nm where the use of a side-gate field effect approach allows the tuning of the superconducting state. A magnetotransport study of the effect of the spin-orbit interaction on the superconducting phase will be also presented.

I will show our approach to realize interfaces with LaAlO3 layers grown on artificial SrTiO3 films. Our findings suggest that by controlling the top surface termination of the SrTiO3 layers and optimizing the SrTiO3 growth conditions, the 2DEG can be maintained, offering an approach to realize LaAlO3/SrTiO3 multilayers.

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8987-29, Session 6

Epitaxial growth of LaAlO3 on SrTiO3-buffered Si(001) substrates by atomic layer deposition *(Invited Paper)*

John G. Ekerdt, Thong Ngo, Daniel J. Groom, Agham S. Posadas, Martin D. McDaniel, Alexander A. Demkov, The Univ. of Texas at Austin (United States)

Lanthanum aluminate (LAO) films were grown epitaxially on Si(001) by atomic layer deposition (ALD) using a buffer layer of four unit cells of strontium titanate (STO) grown by molecular beam epitaxy. The ALD growth of LAO was done at 250 °C by using tris(N,N'-diisopropylformamidinate)-lanthanum, trimethylaluminum, and water as co-reactants. The as-deposited LAO films were amorphous and became crystalline after vacuum annealing at 600 °C for 2 h. Reflection high-energy electron diffraction, X-ray diffraction and transmission electron microscopy were used to determine film crystallinity. In-situ X-ray photoelectron spectroscopy (XPS) was used to characterize the LAO/STO/Si interfaces at various stages throughout the growth and annealing process. By keeping the annealing temperature relatively low (2 h at 600 °C under vacuum), the interfacial amorphous layer at the STO/Si interface was minimized to about one monolayer as observed by XPS and confirmed by TEM. The results demonstrate that highly crystalline, epitaxial LAO films can be formed on STO-buffered Si with a minimal amorphous interfacial layer between STO/Si by maintaining the annealing temperature as low as possible. The ability to obtain high crystalline quality epitaxial LAO films on Si using ALD provides an alternative chemical route for fabricating complex oxide heterostructures and superlattices, and is also potentially suitable as a replacement high-? gate dielectric in Si based-transistors for the sub-22 nm technology.

8987-30, Session 6

Photon-induced thermoelectric voltages in complex oxide superlattices *(Invited Paper)*

Hanns-Ulrich Habermeier, Max-Planck-Institut für Festkörperforschung (Germany); Stefan Heinze, Max-Planck-Institut für Festkörperforschung (Germany) and Max-Planck-Institut für Festkörperforschung (Germany)

Heterostructures composed of transition metal oxides with strong electron correlation offer a unique opportunity to design new artificial materials whose electrical, magnetic and optical properties can be manipulated by tailoring the occupation of the d-orbitals of the transition metal in the compound. This possibility is an implication of symmetry constraints at interfaces with the consequence of a delicate interplay of spin-, charge-, orbital and lattice interactions of electrons. They in turn are sensitive to external perturbations such as strain, electrical and magnetic fields and photon flux as well.

In this contribution we explore the consequences of superlattice formation of YBCO/LCMO on the Laser-induced thermoelectric voltages (LITV) appearing in films deposited on substrates with a vicinal cut. This well-known principle (Lengfellner et al . Appl. Phys. Lett. 60 (1992) 501, Habermeier et al. Solid State Commun. 110 (1999) 473) serves as a technique to investigate the anisotropic transport properties and the components of the Seebeck tensor in these superlattices. It could be shown that the normalized LITV signals scale linearly with the number of interfaces in the structures. We observed an enhancement of the LITV signals by a factor of four due to superlattice formation.

8987-31, Session 6

Signatures of uncondensed electron-hole Cooper pairs in highly-excited ZnO *(Invited Paper)*

Marijn A. M. Versteegh, Kavli Institute of Nanoscience Delft (Netherlands); A. J. van Lange, H. T. C. Stoof, Jaap I. Dijkhuis, Utrecht Univ. (Netherlands)

Electrons and holes in a semiconductor form hydrogen-atom-like bound states, called excitons. At high electron-hole densities, the attractive Coulomb interaction between electrons and holes becomes screened and excitons can no longer exist. BCS theory predicts that at such high densities at low temperatures co-operative many-body effects induce a bound state, an electron-hole Cooper pair, comparable to an electron-electron Cooper pair in a superconductor. These electron-hole Cooper pairs were predicted already in 1964 by Keldysh and Kopaev [1], but they were never observed, neither in a condensed, nor in an uncondensed or “preformed” state. We present here experimental evidence for uncondensed electron-hole Cooper pairs in highly excited ZnO [2]. Employing three-photon absorption of high-intensity 160-fs 800-nm laser pulses, we excited the bulk of a ZnO single crystal. When the ZnO crystal was cooled to 4 K, a strong new emission peak emerged in our measurements. The comparison of the measurement data with theoretical gain spectra, calculated using our recently developed and experimentally tested quantum many-body theory for ZnO [3], indicates that this new peak is the result of stimulated emission from uncondensed electron-hole Cooper pairs. Also we measured the light emission at 4 K for increasing electron-hole density. The spectral evolution of the new gain peak for inceasing density from a position within the band gap to a position near the electron-hole Fermi level reveals a crossover from excitons to uncondensed electron-hole Cooper pairs.

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8987-95, Session 6

Raman study of magnetic phase transitions of hexagonal manganites

Ji-Yeon Nam, Ewha Woman's Univ. (Korea, Republic of); Nguyen Thi Minh Hien, Ewha Womans Univ. (Korea, Republic of); Nguyen Thi Huyen, Kiok Han, Ewha Woman's Univ. (Korea, Republic of); Xiang-Bai Chen, Konkuk Univ. (Korea, Republic of); S. W. Cheong, Rutgers, The State Univ. of New Jersey (United States); D. Lee, T. W. Noh, Seoul National Univ. (Korea, Republic of); N. H. Sung, Beongki Cho, Gwangju Institute of Science and Technology (Korea, Republic of); In-Sang Yang, Ewha Womans Univ. (Korea, Republic of)

Results of Raman studies of magnetic phase transitions of hexagonal $LuMnO_3$ single crystal and $RMnO_3$ (R=rare earths) thin films are compared directly with the results of magnetic measurements. Our results show that the temperature dependent Raman study of magnon scattering provides a single and accurate method for investigating magnetic phase transitions, especially in $RMnO_3$ thin films. In single crystal, our optical method provides results as good as magnetization measurements. But, the Raman spectroscopy method can deduce not only Néel temperature, but also weak spin reorientation transition temperature of the $RMnO_3$ thin films, which are not readily observed in magnetization measurements.

8987-33, Session 7

Novel method for reclaim/reuse of bulk GaN substrates after MOVPE GaN growth via sacrifical ZnO buffer layers *(Invited Paper)*

Abdallah Ougazzaden, Georgia Tech-Lorraine (France); Subramanian Sundaram, GeorgiaTech-CNRS (France); K. Pantzas, Georgia Tech-Lorraine (France); Tarik Moudakir, GeorgiaTech-CNRS (France); David J. Rogers, Ferechteh Hosseini Teherani, Philippe Bove, Vinod E. Sandana, Nanovation (France); Ryan McClintock, Manijeh Razeghi, Northwestern Univ. (United States)

GaN based devices are now very extensively used in wide-bandgap opto-electronic applications. The overwhelming majority of these devices are grown heteroepitaxially on c-sapphire substrates because the ideal “native” GaN substrates of sufficient quality are not available in sufficient volumes at a competitive price. C-sapphire, however, has significant lattice and thermal-expansion mismatches with GaN.

This paper describes a novel process in which ZnO-buffered bulk GaN substrates are used for MOVPE regrowth of GaN. Since ZnO is much more susceptible to chemical etching than GaN, the ZnO film can be wet-etched away, so that the GaN overlayer can be lifted-off and bonded to a substrate of choice [1-3]. Such a process offers a work-around for the limited supply of bulk GaN wafers thanks to the prospect of reclaim/recycling. This new paradigm opens up the perspective for an accelerated adoption of superior GaN substrates by industry.

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8987-35, Session 7

Off-axis sputter deposition of ZnO films on c-sapphire substrates with buffer layers prepared via nitrogen-mediated crystallization *(Invited Paper)*

Naho Itagaki, Koichi Matsushima, Daisuke Yamashita, Hyunwoong Seo, Kazunori Koga, Masaharu Shiratani, Kyushu Univ. (Japan)

ZnO and its related semiconductors are remarkable multi-functional materials with a distinctive property set and a huge range of existing and emerging applications especially in optoelectronic devices. Here, we demonstrate a fabrication method based on magnetron sputtering, “Nitrogen Mediated Crystallization (NMC)”, where nitrogen atoms play important roles in determining the crystal growth mode. Single crystalline ZnO films with atomically-flat surfaces have been fabricated on the ZnO buffer layers prepared by NMC method (NMC-ZnO buffer layers) on c-Al_2O_3 substrates. The ZnO films have atomically-flat surfaces with steps of 0.26nm-hight, corresponding to a half of c-axis length of ZnO. NMC-ZnO buffer layers also reduce the residual carrier concentration in ZnO films down to 1?10^15 cm^-3, which is the lowest value for ZnO films sputtered on c-Al_2O_3 substrates. AFM observation reveals that nitrogen has significant effects on the increase in the grain density as well as the enhancement of the migration of adatoms at growth surface. Thus, single crystalline ZnO films obtained here is attributed to the NMC-ZnO buffer layers that provide high density of nucleation site, smooth surface, and hence reduce the interfacial/strain energy between ZnO and the substrates coming from the large lattice mismatch, which enhances the lateral crystal growth of ZnO on the NMC-ZnO buffer layers. These results indicate that NMC is a powerful method to fabricate high quality oxide materials, which can open up new pathways for high-performance optoelectronic devices. This work was partially supported by JSPS KAKENHI Grant Number 25630127, JST-PRESTO, and Foundation for Promotion of MST Japan.

8987-36, Session 7

Role of grain boundaries in ZnO *(Invited Paper)*

Yukio Sato, Yuichi Ikuhara, The Univ. of Tokyo (Japan)

ZnO has long been used as electroceramic devices such as varistors, and is currently intensively investigated for transparent conductors and light emitting device applications. For the former case, the grain boundaries (GBs) are the origin of the nonlinear current-voltage characteristics, and the GBs may degrade the electrical conductivity in thin films for the latter case. It is therefore important to understand the role of ZnO GBs, and the atomic-scale structure of the GBs should be investigated.

For this purpose, we have fabricated well defined ZnO single GBs by bicrystal method, where two ZnO single crystals are bonded by thermal

diffusion. The ZnO single GBs obtained were characterized by scanning transmission electron microscopy (STEM) observations, which allows us to observe the GB atomic structure directly. It is revealed that ZnO GBs possess the underfold coordinated and the overfold coordinated atom that are unusual in bulk crystals. On the other hand, when dopant element such as praseodymium (Pr) is added for obtaining the nonlinear current-voltage characteristics for varistor applications, Pr strongly localizes to particular atomic columns of the GBs. Our further investigations with the first-principles calculations suggest that formation of the acceptorlike defects such as zinc vacancies are promoted by the Pr doping, and this leads to the formation of double Schottky barrier at the GBs.

8987-37, Session 7

Optical and electrical properties of ZnO bulk crystals with and without lithium grown by the hydrothermal technique

Buguo Wang, Air Force Research Lab. (United States) and Solid State Scientific Corp. (United States); Bruce Claflin, Air Force Research Lab. (United States); David C. Look, Air Force Research Lab. (United States) and Wright State Univ. (United States); Michael Callahan, Teleos Solar, Inc. (United States)

Lithium is usually added into the solution to improve ZnO hydrothermal growth; however, lithium doping affects the properties of the resulting crystals. Optical and electrical properties of ZnO bulk crystals without lithium, which were grown by the hydrothermal technique, have been studied by photoluminescence and Hall-effect measurements. High quality ZnO crystals without lithium were grown in H2O/D2O and in NH3-H2O solutions. The crystals grown from H2O/D2O are conductive with resistivities of 0.6-0.7 ohm-cm and mobilities of ~ 100 cm^2/Vs, while lithium doped ZnO grown under the same conditions have resistivities of ~ 103 ohm-cm and mobilities of ~ 200 cm^2/Vs. Crystals grown in NH3-H2O solution have resistivities of 1?100 ohm-cm and sometimes show p-type conduction; the resistivity increases to ~ 1?108 ohm-cm after annealing at 600 C in air. Lithium and nitrogen co-doped ZnO crystals have resistivities of 10^8-10^12 ohm-cm and are semi-insulating. For lithium-doped samples, a 3.357 eV peak can be seen in the photoluminescence spectra, which is close to indium donor-exciton peaks in indium-doped ZnO where 3.3586 eV and 3.357 eV were found on the C+ and C- faces, respectively. Detailed growth characteristics, optical and electrical properties of the ZnO bulk crystals will be presented in this paper.

8987-58, Session 7

Is ZnO as a universal semiconductor material an oxy-moron? *(Invited Paper)*

Na Lu, Ian T. Ferguson, The Univ. of North Carolina at Charlotte (United States)

This paper will explore the use of ZnO in various applications including thermal energy harvesting, spintronics and nuclear detection. It will show that despite well-known limitations with semiconducting properties of ZnO it can be used in many non-tradition applications.

8987-96, Session 7

Solvothermal crystal growth of ZnO *(Invited Paper)*

Dirk Ehrentraut, Soraa, Inc. (United States) and Tohoku Univ. (Japan)

Zinc oxide (ZnO) is a versatile material with potential or realized application in electronics and opto-electronics. Consequently, there is the need for high quality ZnO wafers which have to be prepared from excellent ZnO bulk crystals. ZnO can be grown by different techniques from the vapor and liquid phase. This paper will review some recent developments in the solvothermal crystal growth of bulk and homoepitaxial thin film ZnO.

The hydrothermal growth of ZnO has produced large crystals of 3 inch in size; however, the incorporation of impurities (Li, Al, Cu, etc.) remained to be solved. We will discuss how cautious chemical and crystal engineering can yield ZnO crystals with impurity concentrations below detection limit for SIMS: Li at < 5?1012 cm-3; Na, K, Al < 5?1013 cm-3; Cu < 5?1014 cm-3. Colorless crystals were grown under supercritical conditions (T = 350 °C, p = 80 MPa) at rates of 15 ?m per hour. X-ray rocking curve FWHM < 20 arcsec was measured for (0002) reflection. Luminescence characteristics were investigated by PL and EUV. Upon femtosecond excitation, single exponential decay around 10-100 ps was measured for some dopant combinations, which makes such crystals promising for application as scintillator and in DUV lithography.

8987-38, Session 8

Plasma-enhanced ALD of MgO as a passivation layer for enhanced photoluminescence of ZnO nanowires *(Invited Paper)*

Jusang Park, Yonsei Univ. (Korea, Republic of)

The growth characteristics and film properties of plasma enhanced atomic layer deposition (PE-ALD) and thermal ALD (Th-ALD) of magnesium oxide (MgO) thin films were comparatively investigated for the application as a passivation layer. For both processes, well-saturated growth characteristics were observed with higher saturate growth rate for Th-ALD. X-ray photoemission analysis has shown that very high purity MgO film is deposited with almost no carbon contamination by PE-ALD. X-ray diffraction and transmission electron microscopy analysis has shown that PE-ALD MgO thin film has larger grain size than Th-ALD MgO thin films and are dominantly (111) crystal orientation. The photo luminescence analysis shows that enhanced luminescence properties of ALD MgO shell/ZnO nanowires. Especially, PE-ALD MgO resulted in more enhancements in luminescence property than using Th-ALD MgO.

8987-39, Session 8

ZnO micro/nanocrystals grown by Laser Assisted Flow Deposition *(Invited Paper)*

Joana Rodrigues, António J. S. Fernandes, Diogo Mata, Univ. de Aveiro (Portugal); Tiago Holz, Ricardo Carvalho, I3N/FSCOSD - Aveiro (Portugal); Rabie Fath Allah, Teresa Ben, David Gonzalez, Departamento de Ciencia de los Materiales e I. M. y Q. I, Facultad de Ciencias, Universidad de Cádiz (Spain); Rui F. Silva, António F. da Cunha, Maria R. Correia, Univ. de Aveiro (Portugal); Luis C. Alves, Katharina Lorenz, Univ. Técnica de Lisboa (Portugal); Armando J. Neves, Florinda M. Costa, Teresa Monteiro, Univ. de Aveiro (Portugal)

Laser assisted flow deposition (LAFD) is a very high yield method allowing the production of ZnO crystals in a very short time. By using a vapor-solid mechanism the LAFD was employed in the growth of ZnO micro/nanocrystals with different morphologies (mainly nanoparticles, tetrapods and microrods) and their microstructural characterization confirms the excellent crystallinity of the wurtzite structure. The optical properties of the as-grown ZnO crystals, investigated by photoluminescence, evidence a well-structured near band edge

emission. The role of the surface states in the ultraviolet recombination was found to be strongly dependent on the decreasing of the excitation intensity which promotes the enhancement of the D0X luminescence in detriment of the 3.31 eV transition.

The LAFD technique was used to directly deposit ZnO particles on the surface of vertically aligned multi-walled carbon nanotubes (VACNTs) forests without employing any foreign catalyst. This new deposition technique preserves the CNTs structure and avoids the collapse of the VACNTs array, which is a major advantage of this method.

New ZnO/CNT hybrids are developed as a buckypaper nanocomposites. The samples prepared using both approaches were fully characterized by optical, structural and electrical techniques envisaging photovoltaic applications.

8987-40, Session 8

Metal-oxide semiconductor nanostructures for energy and sensing applications *(Invited Paper)*

Jae Su Yu, Kyung Hee Univ. (Korea, Republic of); Yeong Hwan Ko, Kyung Hee University (Korea, Republic of)

Recently, wide-bandgap metal-oxide semiconductor materials like zinc oxide, indium tin oxide, gallium oxide hydride, copper oxide, etc. have attracted much attention as novel candidates for various energy and sensing device applications. These materials can be fabricated by various methods such as metal organic chemical vapor deposition, molecular beam epitaxy, thermal chemical vapor deposition, sputtering, hydrothermal synthesis, electrochemical deposition and so on. Especially, low-dimensional nanostructured materials including nanorods, nanowires and nanocones exhibit superior transport and optical properties compared to the bulk materials. Therefore, metal-oxide semiconductor nanostructures have high promising potentials for achieving high-performance devices. In this presentation, the growth and structural/optical properties of metal-oxide semiconductor nanostructures by a simple, low-cost, and large-scalable fabrication method were studied. These nanostructures were applied to optoelectronic devices, such as solar cells, light emitting diodes, nanogenerators, and sensors, to improve the device performance. The morphologies and crystallinity of the fabricated nanostructures were observed by scanning electron microscope/transmission electron microscope images and X-ray diffraction patterns, respectively. The optical properties were investigated by UV-vis-IR spectrophotometry and photoluminescence. These results can contribute to the fundamental understanding of the mechanisms in improving device performance by applications of metal-oxide semiconductor nanostructures in energy and sensing devices.

8987-41, Session 8

Effect of electrical field and atmosphere on the processing of nanocrystalline ZnO *(Invited Paper)*

Benjamin Dargatz, Jesus Gonzalez-Julian, Olivier Guillon, Friedrich-Schiller-Univ. Jena (Germany)

The retention of nanocrystallinity in dense polycrystalline oxide materials is still a challenge, even with the application of stress-assisted methods like Spark Plasma Sintering. Interestingly, the combined effect of high heating rates and the presence of bound water seems to significantly promote densification of zinc oxide nanoparticles. Hence, dense nano-grained ZnO could be synthesized at a temperature of only 400 °C. In contrast, the sintering behavior of coarser powders is not affected by these conditions. The complementary roles of atmosphere, applied electrical field and heating rate on densification and coarsening mechanisms of zinc oxide will be highlighted in this talk.

8987-42, Session 8

Fabrication of nanodiamond-doped tellurite fibers with decreased loss

Yinlan Ruan, Hong Ji, The Univ. of Adelaide (Australia); Brant C. Gibson, The Univ. of Melbourne (Australia); Tanya M. Monro, Heike Ebendorff-Heidepriem, The Univ. of Adelaide (Australia)

Diamond nitrogen-vacancy(NV) centers exhibit room-temperature quantum effects, single spin initialisation and readout as well as single photon emission. Its integration with fibers opens up new approaches to ultrasensitive magnetic and bio-chemical sensors capable of probing living cells.

By dispersing nanodiamonds(NDs) into tellurite glass, which is then drawn into fibers, this approach allows the possibility to couple the NV emitter to a bound mode in a hybrid photonic structure. In our previous work, the tellurite glass was firstly batched and melted at 900 degree in a gold crucible to create defect-free tellurite melt, then the temperature was reduced to 700 degree and 10ppm NDs were added to the melt. These first fibers had a detrimental high loss(~350dB/m) at the NV excitation and emission wavelength (500-700nm).

We attributed the high fiber loss to gold nanoparticles that were formed from gold dissolved from the crucible at high glass melting temperature. Thus we explored reducing the glass melting temperature to 750 degree to reduce the dissolution of gold. The lower melting temperature decreased the fiber loss to 20dB/m in the wavelength range of 400-600nm, significantly lower than that of the previous fibers. Using lower glass melting temperature, we fabricated open core tellurite fibers doped with 10ppm ND in order to allow excitation of the NV emitters from the side direction to avoid background fluorescence. By further improving fiber drawing processing, the loss of the ND doped open core fiber is expected to be further decreased to enable characterisation of single photon source and fiber-based magnetometers.

8987-43, Session 8

Upconversion properties of Er^{3+}-doped oxyfluoride glass-ceramics containing SrF_2 nanocrystals

C. R. Kesavulu, Univ. de São Paulo (Brazil); K. Kiran Kumar, C. K. Jayasankar, Sri Venkateswara Univ. (India)

Oxyfluoride glass-ceramics (GCs) doped with different rare earth (RE) ions have been investigated widely for the past few decades, as they provide a desirable fluoride based low phonon energy environment for the active RE ions besides maintaining the advantages of oxide glasses. The RE-doped GCs are very much useful for increasing the efficiency of solar cells due to their inhomogeneous broadening in absorption spectra of RE ions, which allows absorption of larger portion of the solar spectrum. In the present work, the Er^{3+}-doped oxyfluoride glass and GCs containing SrF_2 nanocrystals have been prepared and investigated their spectroscopic and luminescence properties. The formation of SrF_2 nanocrystals in GCs were confirmed by X-ray diffraction (XRD). Judd-Ofelt (JO) parameters have been evaluated from absorption spectra of the Er^{3+}-doped glass, GCs which inturn used to predict radiative properties for the luminescent levels of Er^{3+} ions. The intensities of both Stokes and upconversion emissions significantly increase with increase of the size of the fluoride crystals in the glass matrix. The mechanism of green and red upconversion emissions have been ascribed to two photon processes. The lifetime of the $^4S_{3/2}$ level of the Er^{3+} ions in GCs is found to be slightly higher than that in the glass, which may be due to the incorporation of Er^{3+} ions into the low phonon sites of SrF_2 nanocrystals.

8987-89, Session 8

Flexible binder free functionalized carbon nanotube electrodes for ultracapacitor

Badekai Ramachandra Bhat, Aravinda L. S Bhat, Udaya K. Bhat, National Institute of Technology, Karnataka (India)

Over the thousands of years human civilization used the stored energy what is now referred to as fossil fuels. This chemical energy is able to be converted to other forms of usable energy, including that of electrical energy. But today this primary energy source is under serious extinction. Global warming became an alarming bell for the human society. So one has to think seriously about storing of available energy and retrieving it whenever required. Ultracapacitor are receiving remarkable attention as an energy storage device and being used in applications involving high power requirements, consumer electronics, medical electronics, electrical utilities, transportation and military defense systems. Carbon based materials are widely used as electrodes in electrical double-layer capacitor (EDLCs). The dramatic development of portable electronics and wearable electronics such as e-paper, sportswear, embedded health monitoring device and other flexible devices, power sources with superior flexibility become an important demand during the past few years. In order to full fill these requirements, it is important to prepare flexible electrode material for ultracapacitor. The traditional electrode fabrication involves the mixing of active material powder with a polymer binder to form a sheet or film and it can be used as electrode material. However, the incorporation of the polymer binder introduces several disadvantages. In this article we are introducing simple method for the preparation of binder free flexible electrode material for ultracapacitor. The prepared flexible ultracapacitor test cell exhibit a specific capacitance of 50 Fg-1 at a current density of 1mAcm-2 with excellent cycle stability.

8987-44, Session 9

Flexible aluminum-doped zinc-oxide thin-film transistor fabricated on plastic substrates *(Invited Paper)*

Dedong Han, Peking Univ. (China); Zhuofa Chen, Nannan Zhao, Wei Wang, Fuqing Huang, Shengdong Zhang, Peking Univ. (China) and Shenzhen Graduate School (China); Xing Zhang, Yi Wang, Peking Univ. (China)

Flexible electronics has become a hot topic in the field of semiconductor technology. Flexible displays will play an important role in next generation displays. Transparent ZnO-based thin-film transistors (TFTs) have been considered as a potential alternative candidate to amorphous silicon (a-Si) TFTs. We know that Indium Gallium Zinc Oxide (IGZO) TFTs is the most popular in recent years due to high performance, but In is a toxic rare element on earth. So that, a non-In active channel layer material offers competitive advantages such as lower cost and green. In this study, we choose Al-doped ZnO thin film as active channel layer. It is well known that Al is abundant on earth, harmless to human beings, thereby, very low manufacturing cost for large-scale industrial production. Some early articles about AZO materials have been reported in the literature as transparent oxide conductor (TOC) materials. We found that AZO also is good semiconductor materials. So that, we studied process and characteristics of the aluminum-doped zinc oxide thin film transistor. We have fabricated aluminum-doped zinc oxide thin film transistor (AZO-TFT) on flexible plastic substrates. The flexible TFT showed good properties with a low threshold voltage, a high on/off ratio and a high field effect mobility. To improve the performance of flexible TFT, we studied process and characteristics of the aluminum-doped zinc oxide thin film transistors with difference device structures. This work is supported by the 973 program (Grant No. 2011CBA00600) and by the National Natural Science Foundation of China (Grant No. 61275025).

8987-45, Session 9

ZnO-based transparent nanodiodes and thin-film-transistor applications *(Invited Paper)*

Toshihiko Maemoto, Yi Sun, Satoshi Sasaki, Kazuto Koike, Mitsuaki Yano, Osaka Institute of Technology (Japan); Seiya Kasai, Hokkaido Univ. (Japan); Shigehiko Sasa, Osaka Institute of Technology (Japan)

We report the fabrication and characterization of ZnO self-switching nanodiodes (SSDs) on glass and flexible plastic substrates. SSDs have been considered for use as new unipolar rectifiers without pn junctions [1, 2]. SSDs also show promise for use in low cost RFID tags and smart cards. The SSD is based on an asymmetric nano-channel with insulating grooves fabricated by electron beam lithography. The effective channel width of the SSDs, depending on the sign of the applied voltage, increases or decreases producing clearly observable diode-like characteristics. For channel widths of 230 and 190 nm, turn-on voltages of 5 and 8 V were obtained, respectively. We observed an increase in the turn-on voltage when the channel width was decreased. These results show that it is possible to use the channel width to control the turn-on voltage of the ZnO-SSD.

ZnO based semiconductors such as InGaZnO films have accelerated the development of thin-film transistors, which are the building blocks for active matrix flat-panel displays including liquid crystal displays. In this conference, we also discuss ZnO thin-film transistors (TFTs) on flexible polyethylene napthalate (PEN) substrates fabricated by pulsed laser deposition at room temperature. ZnO-TFTs on PEN substrate were fabricated using a SiO2 buffer layer. A transconductance of 21.5 mS/mm and an on/off ratio 1.4?107 were obtained. The ZnO-TFTs operation characteristics did not change significantly when the device was bent with a curvature radius of 10 mm. The results will be presented in detail at the conference.

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8987-47, Session 9

MgZnO/ZnO heterojunction-based high-electron mobility field effect transistors grown by PLD

David J. Rogers, Ferechteh Hosseini Teherani, Philippe Bove, Vinod E. Sandana, Nanovation (France); Ryan McClintock, Manijeh Razeghi, Northwestern Univ. (United States)

In previous studies the authors found that MgZnO/ZnO/sapphire heterostuctures grown by Pulsed Laser Deposition showed conductivities which were more than two orders of magnitude higher than for comparable MgZnO layers and an order of magnitude higher than for comparable ZnO layers [1]. Temperature dependent Hall measurements confirmed that such heterojunctions exhibit correspondingly high enhancement of carrier mobility. In this paper we explore the potential of such heterojunctions for use in high mobility field effect transistors.

[1] D. J. Rogers et al. Proc. of SPIE Vol. 8626 (2013) 86261X-1

8987-54, Session 10

High response solar-blind MgZnO photodetectors grown by molecular beam epitaxy *(Invited Paper)*

Winston V. Schoenfeld, Ming Wei, Casey Boutwell, Huiyong Liu, CREOL, The College of Optics and Photonics, Univ. of Central

Florida (United States)

High quality MgxZn1-xO thin films were grown epitaxially on c-plane sapphire substrates by plasma-assisted Molecular Beam Epitaxy. ZnO thin films with high crystalline quality, low defect and dislocation densities, and sub-nanometer surface roughness were achieved by applying a low temperature nucleation layer. Several critical growth conditions were optimized to obtain high quality films: the sequence of Zn and O sources for initial growth of nucleation layer, growth temperatures for both ZnO nucleation and MgxZn1-x O growth layers, and Zn/O ratio. By tuning Mg/Zn flux ratio, wurtzite MgxZn1-xO thin films with Mg composition as high as x=0.46 were obtained without phase segregation. Steep optical absorption edges were observed with a cut-off wavelength as short as 278nm, indicating the potential suitability of such material for solar-blind photodetectors. Metal-Semiconductor-Metal (MSM) photoconductive and Schottky barrier devices with interdigitated electrode geometry and active surface area of 1 mm2 were fabricated and characterized. Resultant devices showed ~100 A/W peak responsivity at wavelength of ~260nm.

8987-55, Session 10

Contact properties and surface reaction kinetics of single ZnO nanowire devices fabricated by dielectrophoresis *(Invited Paper)*

Jose Luis Pau Vizcaíno, Carlos García Núñez, Antonio García Marín, Carlos Guerrero, Pedro Rodríguez, Univ. Autónoma de Madrid (Spain); Susana Borromeo, Universidad Rey Juan Carlos (Spain); Juan Piqueras, Univ. Autónoma de Madrid (Spain)

ZnO nanowire UV detectors present some of the largest responsivities and photoconductive gains ever found in solid-state light sensing devices. Values above 10^6 A/W has been repeatedly reported since these structures were considered as an active part of photodetector devices. Despite this response is, for instance, much larger than the one found in linear-mode avalanche photodiodes and close to that exhibit by single photon avalanche photodiodes, the devices have not reached the market due to the slow response and high noise induced by surface effects. Another issue that has limited their applicability has been the lack of a reliable technique to produce devices at a large scale. In this work, we will present the results obtained from single nanowire ZnO devices fabricated by dielectrophoresis (DEP), a technique that enables the fast and simultaneous alignment of nanowires in specific sites over large surface areas. Conditions used for optimizing nanowire alignment during the DEP process will be discussed. Single nanowire UV detectors have been fabricated from the aligned structures allowing the analysis of the photoresponse and device speed as a function of nanowire diameter. Finally, the inherent surface sensitivity to moisture and alcohols will be used to assess the performance of single nanowire ZnO devices as gas sensors in electronic noses.

8987-57, Session 10

Controlling the properties of electrodeposited ZnO nanowire arrays for light emitting diode, photodetector and gas sensor applications. *(Invited Paper)*

Thierry Pauporté, Oleg Lupan, Bruno Viana, Ecole Nationale Supérieure de Chimie de Paris (France); Lee Chow, Univ. of Central Florida (United States); Maria Tchernycheva, Univ. Paris-Sud 11 (France)

ZnO is a wide bandgap II-VI semiconductor (Eg = 3.4 eV) with a large exciton binding energy (60 meV) which is widely studied for optical and electronic applications. It can be grown from solutions by several techniquess such as hydrothermal deposition, sol-gel, and electrodeposition. Electrochemical deposition (ECD) is of utmost interest for integration of the films in optoelectronic devices since they are low-temperature, low cost methods which can be scaled-up for film preparation on large surface area substrates. Moreover, due to the electron exchange process at the origin of the oxide deposition, a good electrical continuity is insured between the substrate and the oxide layer [1].

We will describe how the growth of ZnO nanocolumn and nanowire arrays can be achieved by the method and how the aspect ratio, the density, the doping and the optical properties of the nanostructures can be controlled [2-4]. The final structure can be finely tuned by adjusting the precursor concentration in the bath, the deposition time, the substrate and so on. The substrate is especially important to control the aspect ratio of the nanostructures. For instance, this parameter can be dramatically increased by using a nanocrystalline buffer layer. We have also shown that using GaN single-crystals as a substrate gives rise to perfectly verticaly oriented ZnO rods with an epitaxial relationship with GaN and a very high crystallographic quality. We will illustrate the large application range of these wires, showing for example their integration in light emitting diodes, in nanosensors and photodetectors.[4,5]

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8987-48, Session 11

Blue/red electroluminescence from hybrid Eu:phosphors/ZnO-nanowires/p-GaN LED *(Invited Paper)*

Bruno Viana, Thierry Pauporté, Oleg Lupan, Ecole Nationale Supérieure de Chimie de Paris (France); Lucie Devis, Thierry Gacoin, Ecole Polytechnique (France)

Nanowire (NW) based light emitting diodes (LEDs) have drawn large interest due to many advantages compared to thin film based devices. Marked improved performances are expected from nanostructured active layers for light emission. Nanowires can act as direct waveguides and favor light extraction without use of lens and reflectors. Moreover, the use of wires avoids the presence of grain boundaries and then the emission efficiency is boosted by the absence of non-radiative recombinations at the joint defects.

In this context, europium (Eu):chelate/ZnO:Mg-nanowires/p-GaN and Eu:Y2O3-nanoparticles based light-emitting-diode (LED) structures have been fabricated showing near-UV/violet electroluminescence and red emission from trivalent europium [1]. The magnesium (Mg)-doped ZnO (ZnO:Mg)-nanowires/p-GaN structures were covered on their top by nanoparticle of yttrium oxide doped with trivalent europium ions (Eu3+:Y2O3) or by Eu:chelate layers. Samples exhibit UV/blue light at about 380 nm coming from the ZnO:Mg structure and a sharp red emission at ?611 nm related to the intra-4f transition of Eu ions. It is found that while Cu permits the emission to be shifted in the blue range, in the case of the ZnO:Mg, the emission wavelength of is shifted to smaller wavelength to be well adapted to the trivalent europium excitation band [2, 3]. Radiative energy transfer is achieved through strong overlap between the emission wavelength from n-(ZnO:Mg)/p-GaN heterojunction and 7F0-5L6 absorption of Eu3+ ions in the case of Eu:Y2O3 or of the chelate ligand intensive absorption band. Indeed the

Eu:chelate/(ZnO:Mg)-nanowires/p-GaN structure appears more adapted to UV/blue and red dual emission compared to Eu:Y2O3 since the low absorption of the phosphor prevents efficient emission. Our results demonstrate that the design of LED structures and of the chelate ligands are crucial to enhance the performance of electroluminescence devices based on ZnO nanowire arrays and rare-earth metal complexes.

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8987-49, Session 11

[beta]-Ga2O3 and single-crystal phosphors for high-brightness white LEDs and LDs, and [beta]-Ga2O3 potential for next generation of power devices *(Invited Paper)*

Encarna Garcia Villora, National Institute for Materials Science (Japan); Stelian Arjoca, Kiyoshi Shimamura, National Institute for Materials Science (Japan) and Graduate School of Advanced Science and Engineering, Waseda Univ. (Japan); Daisuke Inomata, Kazuo Aoki, KOHA Co., Ltd. (Japan)

[beta]-Ga2O3 is a transparent conductive oxide, with unique properties, which is attracting increasing attention in the recent years. It possesses two major features. The first characteristic is its very wide bandgap of 4.8 eV. This leads to a very high breakdown voltage and to a Baliga's figure of merit over three times larger than that of GaN and SiC. The second feature, the capability to grow large size single crystals from the melt, also surpasses the counterparts by means of an efficient and cheaper mass-production of high-quality substrates.

[beta]-Ga2O3 single crystals are grown by the Edge-defined Film-Fed Growth (EFG) technique, like Al2O3. Wafers of 2 inch are successfully grown, and 4 inch are already in progress. N-type carrier concentration control is carried out by Si- and Sn-doping. Conductive [beta]-Ga2O3 wafers are used as transparent conductive substrates for high-brightness vertically structured LEDs based on InGaN multi-quantum wells. Schottky barrier diodes and transistors have been demonstrated, indicating the high potential of [beta]-Ga2O3 for efficient power devices.

Additionally, a new phosphor concept for high-brightness LEDs & LDs is presented. Single crystal phosphor plates (SCPPs) can be used instead of current powder phosphors embedded in resins. The resins suffer a continuous degradation under strong light irradiation, and the powders show a decreasing quantum efficiency as the temperature rises with the current intensity. SCPPs overcome these two critical issues related with powder phosphors.

8987-50, Session 11

Effects of surface treatment of ITO anode layer patterned with shadow mask technology on characteristics of organic light-emitting diodes *(Invited Paper)*

Jong-Ho Lee, Bum-Ho Choi, Korea Institute of Industrial Technology (Korea, Republic of)

We investigated the effects of various surface treatments of indium tin oxide (ITO) on the electrical and optical characteristics of organic light-emitting diodes (OLEDs). A 150-nm-thick ITO anode layer was patterned directly with a shadow mask during the sputtering process without the use of a conventional photolithography patterning method. The sputtered ITO layer was subjected to thermal and oxygen plasma treatments to reduce the sheet resistance and improve surface roughness. The measured sheet resistance decreased from 30.86 for the as-sputtered samples to 8.76 Ω/sq for the samples thermally treated at 380 °C for 1 h followed by oxygen plasma treatment. The rms surface roughness measured by AFM considerably decreased to 3.88 nm with oxygen plasma treatment. The thermal treatment considerably decreased the sheet resistance of the ITO anode layer patterned with the shadow mask. The spike-like structures that are often formed and observed in shadow mask–patterned ITO anode layers were almost all removed by the oxygen plasma treatment. Therefore, a smooth surface for shadow mask–patterned ITO layers with low sheet resistance can be obtained by combining thermal and oxygen plasma treatments. A smooth surface and low sheet resistance improves the electrical and optical characteristics of OLEDs. The surface-treated ITO layer was used to fabricate and characterize green phosphorescent OLED devices. The OLED devices fabricated by thermal treatment at 380 °C for 1 h followed by oxygen plasma treatment for 180 s showed the highest luminance and current density. Furthermore, the leakage current that might be induced by the rough ITO surface was dramatically reduced to 0.112 mA/cm2.

8987-51, Session 11

Investigation of ZnO-based ultraviolet light-emitting diodes *(Invited Paper)*

Ching-Ting Lee, Hao-Yu Chang, National Cheng Kung Univ. (Taiwan)

(Invited Talk) Recently, ZnO-based semiconductors have been deposited on various substrates using various methods. Furthermore, they were used in ultraviolet lighting-emitting diodes (UVLEDs) due to inherent properties including wide direct bandgap and high binding energy. Using two different deposition systems to deposit and fabricate ZnO-based UVLEDs. Firstly, the double-heterostructured MgZnO/ZnO/MgZnO layers were deposited at low temperature using the vapor cooling condensation system to enhance light intensity of the resulting p-AlGaN/i-MgZnO/i-ZnO/i- MgZnO/n-ZnO:In UVLEDs. The peak intensity of electroluminescence (EL) spectra of UVLEDs were 3.08 times high-er than those of the p-AlGaN/i-ZnO/n-ZnO:In UVLEDs. The EL spectra shows only band edge emission owing to the high performances of deposited active i-ZnO films. Secondly, various component ratios of i-MgZnO and i-MgBeZnO thin films were deposited using a radio frequency (RF) magnetron co-sputter system. Consequently, the deposited films with various energy bandgaps were stacked alternately to form the active layer of multiple-quantum well-structured UVLEDs. To compare properties of the films with various components, a traditional p-i-n structure and two kinds of multiple-quantum well-structured active layer of UVLEDs were fabricated, in which has the same well layers (emission layers) but different barrier layers, as well as p-i-n structure with the same emission layer. The light emitting intensity of multiple-quantum well-structured UVLEDs was better than p-i-n structure. This phenomenon was attributed to the carrier confinement in well layers and improvement probability of radiative recombination. Moreover, turn-on voltage, breakdown voltage, and EL emission wavelength of a multiple-quantum well-structured p-ZnO/i-MgZnO/i-MgBeZnO/n- MgZnO:Al UVLEDs were 4.32 V, -11.3 V, and 360.2 nm, respectively.

8987-52, Session 11

Functional metal oxide nanostructures fabricated by 3D-nanotemplate PLD *(Invited Paper)*

Azusa N. Hattori, Hidekazu Tanaka, Osaka Univ. (Japan)

There requires an ideal balance between the size of the nanostructures and their shape and position in space in terms of functional nanodevice fabrication. So far, many nanofabrication have been proposed, however, they can be adapted for one or some limited materials with less controllability. To achieve the construction of extremely small high quality nanostructures of any materials (metal, insulator, and semiconductor) with well-defined shapes and locations, we have established our original three-dimensional (3D) nanofabrication technique, namely "3D nanotemplate PLD technique". In this method, by combining inclined pulsed-laser deposition (PLD) with nanoimprint lithography, the target materials are deposited onto the sidewalls of a well-defined patterned template. 3D nanotemplate PLD enables to fabricate the large arrays of programmable ZnO nanostructures: nanoboxes and nanowires with a width of ~20 nm. Cathodoluminescence (CL) measurements at 300 K showed an intense luminescence peak around 380 nm corresponding to near-band-edge (NBE) emission from even a single ZnO nanobox. The CL intensity mapping also showed the brilliant NBE luminescence from the entire single ZnO nanobox. The architecturally designed ZnO nanostructures with an excellent wide-gap luminescent semiconductor character should be good candidates for optoelectronic materials for nanoscale device applications. On the basis of this nanofabrication technique, large arrays of programmable structures for building reconfigurable architectures can be achieved for use in various applications.

8987-53, Session 11

UV detectors and LEDs in different metal oxide nanostructures and the influence from the piezoelectric effect *(Invited Paper)*

Magnus Willander, Mazhar Ali Abbasi, Kimleang Khun, Mushtague Hussain, Zaffar Hussain Ibupoto, Omer Nur, Linköping Univ. (Sweden)

I will discuss our latest results regarding UV detectors based on different metal oxide nanostructures grown by chemical methods. Particularly I will discuss the hybrids of these nanostructures. The same I will do for visible light emissions from these structures.

An important effect to improve the performance is to use the piezo effect. I will review this field for UV nanosensors but also for light emitting diodes based on nano materials in oxide materials.

Finally I will review the field of driving LEDs by nanogenerators particularly ZnO nanogenerators but also show our results on nanogenerators from different nanostructures.

8987-94, Session 11

Excitation process and LED applications of samarium-doped TiO2 thin films *(Invited Paper)*

Xinwei Zhao, Yutaka Aizawa, Susumu Harako, Tokyo Univ. of Science (Japan); Shuji Komuro, Toyo Univ. (Japan)

Rare earth ions doped oxide semiconductors have received great interests due to their potential application as optoelectronic devices. It has been recognized that oxygen co-doping and use of wide bandgap materials as the hosts are effective to enhance the emission from the rare earth ions. TiO2 is a wide bandgap semiconductor and is generally known to excite the rare earth ions effectively at room temperature. A single phase TiO2 thin film can be achieved by controlling the formation process and post annealing condition. In this paper, we report the local microstructure of Sm ions in TiO2 matrix by which the doped Sm3+ ions form stable luminescent centers. A n-TiO2:Sm/p-NiO/p+-Si hetero junctions light emitting diode (LED) formed by laser ablation will be presented. Room temperature operation and low threshold have been achieved.

8987-32, Session 12

Ferrite engineering for oxide spintronics and photonics *(Invited Paper)*

Hitoshi Tabata, Munetoshi Seki, The Univ. of Tokyo (Japan)

During recent years, a lot of interests are focused on the development of oxide semiconductors due to various advantages. Among these materials, ferrite oxides such as Fe2O3 Fe3O4 are regarded as a promising system because of their probabilities of band gap engineering and friendly for the environmental affinity as the green photonics. Here we have reported our two topics on spintronics of oxide semiconductors and oxide photonincs for water splitting. The one is hetero epitaxial p-n junctions of magnetic oxides based on magnetite (Fe3O4) and their polaron conducting and magnetic properties. The other is ferrite engineering for light energy harvesting system. Especially for the solid-liquid type solar cells formed by hematite (Fe2O3) hetero structures. The efficient use of solar energy is now one of the great challenges in science and technology. Hematite lies well within the visible-IR spectrum, as well as their low costs, electrochemical stabilities, and environmental compatibilities. Therefore, a considerable number of studies have been performed on the photoelectrochemical (PEC) properties of∝-Fe2O3. We have demonstrated that enhanced photocurrent in Rh-substituted ∝-Fe2O3 thin films grown by a pulsed laser deposition. The optimum Rh content lies at around x=0.2, where the photocurrent is significantly enhanced over a wavelength range of 340–850 nm. The bandgap of the films decreased with increasing Rh content. The PEC efficiency was significantly enhanced in the films with lower Rh contents, in the visible and NIR regions. The findings of this research are expected to be useful in the development of the solar fuel conversion systems based on Fe-oxides.

8987-59, Session 12

High-efficiency heterojunction solar cells on crystalline germanium substrates *(Invited Paper)*

Bahman Hekmatshoar, Davood Shahrjerdi, Marinus Hopstaken, IBM Thomas J. Watson Research Ctr. (United States)

Crystalline germanium (c-Ge) solar cells are mainly used as the bottom cells of high-efficiency multi-junction III-V solar cells. In principle, c-Ge may be used as the bottom cell in various other technologies as well;

however, the high cost of c-Ge limits the practicality of such applications. This includes thin-film large-area applications compatible with flexible low-cost substrates [1]. In order to enable such applications, (i) a low-temperature processing technology is required to provide compatibility with low-cost flexible substrates and (ii) the high cost of the starting c-Ge substrates must be reduced for instance by employing a kerf-free layer transfer technique such as controlled spalling which allows multiple substrate re-use [2]. This talk will focus on the development of solar cell structures and processes that allow the implementation of high-efficiency c-Ge solar cells at temperatures close to 200°C, while conventional c-Ge solar cells require process temperatures up to 600°C. This is realized by low-temperature PECVD growth of hydrogenated amorphous and micro-crystalline Si layers on c-Ge substrates [3]. Application of this technique to c-Si solar cells and other devices such as transistors will be also briefly discussed.

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8987-60, Session 12

Material properties of high-mobility TCOs and application to solar cells *(Invited Paper)*

Florian Ruske, Steffi Schönau, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Sven Ring, Sebastian Neubert, Bernd Stannowski, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany) and PVcomB (Germany); Stefan Götzendörfer, Berliner Glas KGaA Herbert Kubatz GmbH & Co. (Germany); Volker Sittinger, Fraunhofer-Institut für Schicht- und Oberflächentechnik (Germany); Bernd Rech, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany)

The benefit of achieving high electron mobilities in transparent conducting oxides (TCOs) is twofold: they first exhibit superior optical properties, especially in the NIR spectral range, and secondly their low resistivity enables the usage of thinner films, which is beneficial from a cost point of view. Remarkably high mobilities above 60 cm?/Vs can be obtained in Al-doped zinc oxide by post-deposition annealing under a protective layer. The procedure has not only shown to increase mobility, but also strongly reduces sub-bandgap absorption.

Extensive optical, electrical and structural characterization is carried out in the films in order to clarify the microscopic origins of the changes in material properties. While the annealing of defect states, most likely deep acceptors, seems clear, earlier results also suggest some influence of grain boundaries.

In application to a-Si:H/µc-Si:H thin film solar cells the films have shown to increase spectral response and solar cell efficiency significantly. A suitable light trapping scheme, needed for thin film silicon solar cells, is normally achieved by a wet chemical etching step in diluted HCl, which provides a surface structure with applicable light scattering properties. When reducing the TCO film thickness, the main challenge is to provide a sufficient texture and, hence, light trapping scheme via this technique. Therefore a light scattering approach using texture-etched glass in conjunction with thin high mobility zinc oxide was applied enabling high efficiency a-Si:H/µc-Si:H tandem cells.

8987-61, Session 12

Ag nanowire-embedded ITO thin films as a near-infrared transparent and flexible anode for the flexible organic solar cells *(Invited Paper)*

Han-Ki Kim, Kyung Hee Univ. (Korea, Republic of)

We investigated Ag nanowire (NW) network embedded in transparent ITO electrodes fabricated on collarless PI substrate for flexible organic solar cells (FOSCs). By embedding Ag NWs network between ITO thins films using simple brush painting method, we achieved a flexible ITO/Ag NW/ITO multilayer electrode with a low sheet resistance of 38.7 Ohm/square and a high diffusive transmittance of 87.62 % as well as superior mechanical flexibility. The existence of the Ag NW network led to a metallic conductivity, high near infrared transparency, and mechanical durability of the ITO/Ag NW/ITO multilayer. These indicate that the Ag NW embedding into the ITO films is a key solution to solve the critical drawbacks of the conventional ITO electrodes or Ag NW network film. Better performances of the FOSC with the ITO/Ag NW/ITO multilayer electrode to those of the FOSC with a conventional ITO electrode demonstrate that the flexible ITO/Ag NW/ITO electrode is a promising alternative to ITO films for high performance FOSCs.

8987-62, Session 12

Light trapping considerations in self-assembled ZnO nanorod arrays for quantum-dot sensitized solar cells *(Invited Paper)*

Juan A. Zapien, ChunYan Luan, City Univ. of Hong Kong (Hong Kong, China); King Tai Cheung, The Univ. of Hong Kong (Hong Kong, China); Yishu Foo, City Univ. of Hong Kong (Hong Kong, China); Qing Shen, The Univ. of Electro-Communications (Japan)

Current performance of solar cells based on 1-D ZnO nanorods arrays (NRAs) is well below expectations; the interest in NRA materials, in particular ZnO, for use in quantum dot- and dye- sensitized solar cells (QDSCs and DSSCs, respectively) arises from multiple proposed advantages: (i) size effects in nano-arrays for modification of physical properties, such as photon confinement; (ii) large surface-to-volume ratio for high QD/dye loading density; (iii) direct path for charge collection; and (iv) high electron mobility and superior electron injection kinetics in ZnO. All of these perceived advantages are well documented in multiple reviews. However, the same reviews conclude that (a) most one-dimensional nanostructures reported to date show much lower performance compared to mesoporous films and (b) TiO_2 enables higher solar cell performance compared to ZnO. We have study the light trapping effects of ZnO NRAs as it relates to array density, length and CdS/CdSe QD loading. Our experimental results supported by numerical simulations using Finite Difference Time Domain (FDTD) demonstrate that, contrary to perceived conventional wisdom, a higher NRA density does not necessarily correspond to higher solar cell performance. Instead, light trapping efficiency depends significantly on the array density, QD axial distribution and index contrast between NR and the effective index of the QDs thus suggesting strategies for improved QDSC fabrication.

8987-63, Session 12

Oxides for sustainable photovoltaics with Earth-abundant materials *(Invited Paper)*

Alexander Wagner, Mathieu Stahl, Nikolai Ehrhardt, Andreas Fahl, Johannes Ledig, Andreas Waag, Andrey Bakin, Technische Univ. Braunschweig (Germany)

Energy conversion technologies, especially photovoltaics, exibit enormous growth aiming to extremely high power capacities per year. Therefore nontoxicity and abundance of the materials are among the key requirements to a sustainable photovoltaic technology. Oxides and related materials are promising as the key materials to reach these goals. For an all-oxide solar cell p-type Cu2O is a promising absorber material with a 2.1 eV band gap and a high absorption coefficient. Theoretical predictions promise efficiencies of ZnO/Cu2O solar cells up to 18%. Recently a breakthrough has been reported demonstrating of ZnO/Cu2O thin film layer cell with efficiency of ~3.8% and ~5% under implementation of ZnO and Ga2O3 buffer layer respectively [Minami et al, 2012, 2013]. Nevertheless, the fabricated device is still far from commercial applications. Further fundamental investigations are needed in order to understand in depth the physics behind the devices on the base of these materials and to improve the efficiency of the cells. An overview of the recent advancements in the area is presented. Special attention is given to the effect of the materials properties on the device efficiency, phenomena at interfaces, band gap alignment and surface manipulation. Influence of different buffer layers on the performance of an all oxide solar cell is discussed with special focus on atomic layer deposition as one of the most promising approaches to fabricate such a layer. Controllably grown Cu2O layers are also prerequisites for fabrication of high efficiency solar cells. Vapor phase epitaxial growth of Cu2O is presented.

8987-64, Session 12

Optical and photovoltaic properties of silicon wire solar cells with controlled ZnO nanorods antireflection coating *(Invited Paper)*

Jae Hyun Kim, Seong-Ho Baek, Daegu Gyeongbuk Institute of Science & Technology (Korea, Republic of)

Nano and micro-structured three-dimensional (3D) Si has been attracting much attention for future applications in photovoltaic devices due to their superior properties. A new type of silicon micro-wire (SiMW) solar cell with a conformal zinc oxide (ZnO) nanorods anti-reflection coating (ARC) were fabricated. Radial p-n junction was formed in vertically aligned silicon micro-wire solar cell. The vertically aligned silicon micro-wire arrays were fabricaged by optimized metal assisted etching. It iwas found that the combination of Si wire geometry and ZnO ARC was very efficient to maximize the light absorption and to minimize the light reflectance. The growth time of ZnO nanorods were varied from 1 hr to 4 hr. The best efficiency of solar cell was obtained in the sample that has ZnO nanorods grown for 4 hr. The Illuminated current–voltage (I–V) results showed that the photovoltaic efficiency of SiMW solar cells with optimized ZnO ARC was enhanced more than 50% and the short-circuit current density was improved by over 43% compared to SiMW solar cells without ZnO ARC.

8987-65, Session 13

ZnO nanowires and PbS quantum dots for third-generation solar cells *(Invited Paper)*

Basma M. El Zein, Institut d'Electronique, de Microélectronique et de Nanotechnologie (France) and King Abdullah Univ. of Science and Technology (Saudi Arabia); Mutalifu Abulikemu, Erkki Alarousu, Omar F. Mohammed, Enrico Traversa, King Abdullah Univ. of Science and Technology (Saudi Arabia); Elhadj Dogheche, Univ. des Sciences et Technologies de Lille (France)

The ability to design flexible solar panels from semiconductor quantum dots make them an excellent candidate as light-harvesting materials, opening up an optimistic view to utilize this new technology in the next generation solar cells. More specifically, the incorporation of nanostructures into thin films solar cells represents a potentially new path towards increasing the conversion efficiency of the solar cell devices and lower their total cost.

Nanowires and quantum dots hold promising potency to enhance the performance of solar cells by improving light absorption, light trapping, exciton generation, and photoexcited-carrier collection. Quantum dot sensitized solar cells consist of three components: semiconductor quantum dots, one dimensional metal oxide n-type and hole-transport layer materials. Quantum dots are characterized by a tunable absorption, multiple exciton generation and good photo-stability. Moreover, the sufficient electron transport from quantum dots to ZnO will also improve the efficiency of the quantum dot sensitized solar cells. In addition, due to the excellent optical and electrical properties and the ability to control the synthesis of various ZnO nanostructures such as nanowires, nanorods and other nano-architectures, ZnO nanowires are very promising materials for energy harvesting, especially in photovoltaics. These nanowires will be employed as an electron acceptor to transport the charge carriers to electrodes during the solar cell performance.

In this paper, the synthesis and characterization of ZnO nanowires by pulsed laser deposition and the in-situ growth and characterization of lead sulfide (PbS) quantum dots on the top and lateral sides of the grown nanowires are presented, highlighting the importance of electron transfer process from quantum dots to nanowires for photovoltaic applications.

8987-66, Session 13

Graphene oxide: preparation, functionalization, and electrochemical applications *(Invited Paper)*

Yang Liu, Jinghong Li, Tsinghua Univ. (China)

Graphene, which consists of a one-atom-thick planar sheet comprising a sp2-bonded carbon structure with excellent electronic quality, is a novel material that has emerged as a rapidly rising star in the field of material science and has been making a profound impact in many areas of science and technology due to its remarkable physicochemical properties, such as high specific surface area, extraordinary electronic properties and electron transport capabilities. As a graphene derivative, graphene oxide (GO) consists of a single-layer of graphite oxide in which various oxygen-congtaining functional groups such as hydroxyl and epoxy groups are presented. The oxygenated groups in GO can strongly affect its electronic, mechanical, and electrochemical properties. With respect to electrochemical properties and applications, the main advantages of GO over other kinds of carbon-based materials, such as pristine graphene, carbon nanotubes and fullerene, include its facile synthesis, substantial solubility and processability, adjustable moderate conductivity, high surface area, excellent biocompatibility, and abundance of inexpensive source material. Owing to these advantageous structural and physicochemical properties, GO based materials have been used to design and prepare GO based electrodes for a wide range of applications in electroanalytical chemistry and electrochemical sensors.

8987-67, Session 13

Chemical bonding and stability of multilayer graphene oxide layers *(Invited Paper)*

Yves J. Chabal, Cheng Gong, The Univ. of Texas at Dallas (United States); Suenne Kim, Si Zhou, Yike Hu, Georgia Institute of Technology (United States); Muge Acik, The Univ. of Texas at Dallas (United States); Walter A. de Heer, Claire Berger, Angelo Bongiorno, Eliso Riedo, Georgia Institute of Technology (United States)

The chemistry of graphene oxide (GO) and its response to external stimuli such as temperature and light are not well understood and only approximately controlled. This understanding is however crucial

to enable future applications of the material that typically are subject to environmental conditions. The nature of the initial GO is also highly dependent on the preparation and the form of the initial carbon material. Here, we consider both standard GO made from oxidizing graphite and layered GO made from oxidizing epitaxial graphene on SiC, and examine their evolution under different stimuli.

First, we investigate the effect of the solvent on the thermal evolution of standard GO in vacuum. In situ infrared (IR) absorption measurements clearly show that the nature of the last solvent in contact with GO prior to deposition on a substrate for vacuum annealing studies substantially affect the chemical evolution of the material as GO is reduced. Second, we examine the stability of GO derived from epitaxial graphene (on SiC) as a function of time. We show that hydrogen, in the form of CH, is present after the Hummers process, and that hydrogen favors the reduction of epoxide groups and the formation of water molecules, as illustrated in the figure. Importantly, this transformation can take place at room temperature, albeit slowly (~ one month). Finally, the chemical interaction (e.g. bonding) between GO layers in multilayer samples is examined with diffraction (XRD) methods, spectroscopic (IR, XPS, Raman) techniques, imaging (APF) and first principles modeling.

8987-69, Session 13

Energy generation and storage: combining ZnO piezogenerators and graphene-based ultracapacitors

Vinod E. Sandana, Graphos (France)

Graphene and ZnO are both remarkable, multifunctional materials with distinctive and unique property sets [1,2] and their synergy opens up uncharted possibilities. For instance, highly conductive graphene-based ultracapacitors are currently considered to be one of the most promising energy storage devices [3] while ZnO (with one of the largest piezoelectric coefficients of any semiconductor) is a leading piezogenerator material [2]. In this paper, we investigate the potential of the combining of graphene ultracapacitors and ZnO nanogenerators for the production of new generation of nanodevices integrating energy generation and storage.

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8987-70, Session 13

Engineering metal oxide structures for efficient photovoltaic devices

Isabella Concina, Univ. degli Studi di Brescia (Italy)

The most common semiconductor metal oxide (MOx) applied as photoanode in DSCs is currently a nanoparticulated thick film of TiO_2, but increased efforts are devoted to seek for alternative, cheeper and less toxic, materials. ZnO is at present the best alternative candidate, due to its band structure similar to TiO_2 and a better electron mobility.

Herein we present the application of i) single crystal ZnO nanolamellae organized in hierarchical structures and ii) hierarchically assembled ZnO structures for high efficient completely ZnO-based DSC, built up according to three main aims, namely: high optical density of the sensitized layer, high light scattering of the active layer and inhibition of the back electron transfer between anode and electrolyte through the engineering of interfaces along the photoanode structure. By applying this material design strategy DSCs can be fabricated with impressive high performances (photoconversion efficiency up to 7.5% and photocurrent up to 19.8 mA/cm2).

Emphasis will be given on both the advantages provided by the mentioned photoanode configurations and simple and environmental friendly preparation approaches, allowing to be easily scaled up.

8987-71, Session PWed

Crystal, magnetic and dielectric studies of the 2D antiferromagnet: β-NaMnO2

Ionna T. Bakaimi, Foundation for Research and Technology-Hellas (Greece) and Univ. of Crete (Greece); Artem Abakumov, Univ. Antwerpen (Belgium); Mark A. Green, Univ. of Kent (United Kingdom); Alexandros Lappas, Foundation for Research and Technology-Hellas (Greece)

Spin-driven ferroelectricity on the two-dimensional (2D) antiferromagnet β-NaMnO2, is reported for the first time. Tuning the dielectric/ferroelectric properties of materials by applying external electric or magnetic fields is a major challenge in fundamental physics and a great necessity in the technology of multifunctional devices. Neutron powder diffraction shows that β-NaMnO2 undergoes two magnetic phase transitions, a commensurate at 200 K and an incommensurate one at 90 K. Clear dielectric anomalies that occur at each magnetic transition indicate significant spin/lattice coupling. The complex non-collinear antiferromagnetic structure induced by the frustrated interactions of the corrugated triangular network of the Mn cations, breaks the inversion symmetry and induces ferroelectricity, since weak polarization and sharp dielectric anomaly appear concurrently with the 90 K transition. The most striking feature of this dielectric anomaly is the unusually large dependence of the dielectric constant under different magnetic fields. HRTEM studies reveal structural heterogeneity due to coherent intergrowth of two near equivalent in energy polymorphs (distorted β-NaMnO2 and β-NaMnO2 phases). We argue that the various intergrown nanodomains, make the local and global symmetries different with important consequences in the manner with which magnetic interactions are established and polarisation builds up in the bulk compound. The above findings provide new insight on the importance of nanodomains in bulk oxides associated with the appearance of the enchanced magnetodielectric effect that can be controlled by external fields.

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8987-72, Session PWed

Optical properties of ZnO thin films dispersed with noble metal nanoparticles synthesized by sol-gel method

Moriaki Wakaki, Takushi Noguchi, Eisuke Yokoyama, Tokai Univ. (Japan)

Zinc Oxide is an inexpensive n-type semiconductor with a direct band gap of 3.3eV. Noble metal nanoparticles show a surface plasmon resonance in the visible region due to collective oscillations of electrons at the surface of nanoparticles. The unique features in these composite systems have potential applications in optoelectronic devices such as transparent conductive films, solar cells and photocatalyts.

In this study, ZnO thin films doped with Ag or Au nanoparticles were prepared by the sol-gel method. Zinc acetate and silver nitrate or tetrachroloaurate were used as the precursor materials of ZnO matrix and each nanoparticle, respectively. The structural properties of the composite films were analyzed by scanning electron microscope and X-ray diffractometer. Size and shape of the nanoprticles were observed with a transmission electron microscope. The optical properties of the films were characterized by an UV-Vis-NIR spectrophotometer.

The XRD peaks of ZnO corresponding to hexagonal wultzite structure were observed. In the TEM analysis of Au/ZnO film, the spherical Au nanoparticles were observed in a ZnO crystalline matrix. The distribution of the diameter of Au nanoparticles was centered at around 20nm and spread with the half width of about 20nm. The optical absorption peak was observed at 580nm due to the surface plasmon resonance of gold nanoparticles. The absorption spectra were analyzed by effective medium approximation such as Maxwell-Garnett and Bruggeman models. The spectra were discussed relating with the size and shape of the nanoparticles, and the refractive index of the matrix.

8987-73, Session PWed

Lattice location of Hf and its interaction with other impurities in LiNbO3: an integrated review

Jose Gonçalves Marques, Katharina Lorenz, Univ. Técnica de Lisboa (Portugal)

Lithium niobate (LiNbO3) is an important material for applications in bulk optoelectronics and integrated optics devices. LiNbO3 exists in a wide range of compositions, from congruent (Li deficient) to stoichiometric. Undoped congruent LiNbO3 suffers from a relatively low optical damage threshold which constitutes its major disadvantage for optoelectronic devices. The optical damage threshold is dependent on the amount of intrinsic defects, and is considerably increased in stoichiometric material and in congruent material doped with specific impurities, such as Mg, In and Zn. It has been recently shown that doping with Hf leads to a significant increase of the photorefractive resistance at a threshold concentration between 2 and 3 mol% [1]. This brought a significant interest on the location and role of Hf in LiNbO3. The study of the lattice location of Hf in LiNbO3 and its interaction with other impurities and intrinsic defects had started more than a decade before the discovery of the role of this impurity, as Hf was a convenient probe for combined studies using the Rutherford Backscattering Spectrometry / Channeling and Perturbed Angular Correlations nuclear techniques. In this work we provide an integrated review of the main results obtained with these techniques, which are scattered in the literature.

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8987-74, Session PWed

Fiber-optic surface plasmon resonance-based ammonia sensor utilizing ITO/ bromocresol purple thin films

Satyendra K. Mishra, Shivani Bhardwaj, Banshi D. Gupta, Indian Institute of Technology Delhi (India)

The demand of ammonia sensor is due to its hazardous and toxic nature. Even a small concentration of ammonia gas is very harmful for human body. Due to this, the development of ammonia sensor is always an active area of research. Contrary to disadvantages, ammonia gas has lot of applications in agriculture, industrial, medical and biological sciences.

Surface plasmon is a transverse magnetic (TM) polarized electromagnetic wave excited by external radiations at metal-dielectric interface. If one solves the Maxwell's equations for metal-dielectric kind of refractive index distribution, two important properties of surface plasmons appear.

In this paper, we have carried out the fabrication and characterization of a surface plasmon resonance (SPR) based fiber optic ammonia sensor using ITO and bromocresol purple (BCP) thin film. The sensor works under the principle of the wavelength interrogation technique. The refractive index of the BCP and the ITO change when the ammonia gas comes in contact with it. To prepare the probe we deposit thin films of ITO (40 nm) and BCP (50 nm) over the unclad portion of the fiber by thermal evaporation technique. To calibrate the sensor the resonance wavelength of is determined from the SPR spectrum of the sensor for a given concentration of ammonia around the probe. It is observed that as the concentration of ammonia increases the resonance wavelength increases. The shift in resonance wavelength has been observed 13 nm for ammonia gas concentration 1-10 ppm.

8987-75, Session PWed

Fibre-optic surface plasmon resonance-based hydrogen sulphide gas sensor utilizing Cu/ZnO nanoparticles

Satyendra K. Mishra, Charul Varshney, Banshi D. Gupta, Indian Institute of Technology Delhi (India)

Hydrogen sulphide is extremely hazardous, toxic compound. It is colorless, flammable gas and can be identified in relatively low concentration. Industrial sources of the hydrogen sulphide gas include petroleum and natural gas extraction and refining, pulp and paper manufacturing. Therefore its detection is important. Zinc oxide is a conducting metal oxide which is used in different applications such as gas sensing, biosensing and chemical sensing. Also, ZnO is not easily oxidized when comes in contact with the environment. Zinc oxide has excellent optical properties.

These charge density oscillations along the metal-dielectric interface are known as surface plasma oscillations. The quantum of these oscillations is referred to as surface plasmon (or surface plasmon wave).

In this paper we report the fabrication and characterization of a fiber optic H2S gas sensor utilizing zinc oxide nanoparticles. The probe is prepared by coating unclad core of the fiber with thin film of copper using thermal evaporation technique followed by a coating of ZnO nanoparticles. The nanoparticles are prepared using Pacholski method and two solutions, one of NaOH in methanol and the other of zinc acetate dehydrate in methanol. The localized surface plasmon resonance (LSPR) absorption spectra are recorded for different concentrations of H2S gas around the probe. It is observed that the wavelength corresponding to maximum absorption peak increases with the increase in the concentration of the gas. The total shift in absorption peak has been observed 23 nm for gas concentration 10-100 ppm.

8987-76, Session PWed

Numerical and experimental study of SnOx | Ag | SnOx multilayer as indium-free transparent electrode for organic solar cells

Adrien Bou, Institut Matériaux Microélectronique Nanosciences de Provence (France) and Crosslux (France); Philippe Torchio, Damien Barakel, Thierry François, Institut Matériaux Microélectronique Nanosciences de Provence (France); Pierre-Yves Thoulon, Marc Ricci, Crosslux (France)

Indium Tin Oxide (ITO) is one of the most used Transparent Conductive Oxide (TCO) for Organic Solar Cells (OSC) transparent electrode. Unfortunately, indium is rare on earth and becomes very expensive due to its massive use. We propose a SnOx | Ag | SnOx multilayer, deposited in a continuous vacuum atmosphere by e-beam evaporation, as transparent anode for a (poly-3-hexylthiophene):[6,6]-phenyl-C61-butyric acid methyl ester (P3HT:PCBM) bulk heterojunction based OSC. Ellipsometric characterization of the SnOx is performed to determine the complex refractive index dispersion. A numerical Transfer Matrix Method (TMM) is carried out to calculate the optical properties so that the intrinsic absorption inside the sole active layer of the OSC. This allows us to perform an optical optimization on the intrinsic absorption efficiency inside the active area by considering the media embedding the electrodes, then to deduce the optimal thicknesses of each layer of

the electrode. The aggregated island-like morphology of the 10 nm-thick silver film, inserted between both oxide layers, can be considered by using a Finite Difference Time Domain (FDTD) method. SnOx | Ag | SnOx multilayers are manufactured with the objective to give to the electrode its best conductivity and transparency in the visible spectral range. These indium-free electrodes show low sheet resistance (<10 Ω/?) and high transparency in the spectral band of interest for organic photovoltaics.

8987-77, Session PWed

Surface plasmon resonance-based fiber-optic ammonia gas sensor using polymer films containing ester group

Satyendra K. Mishra, Sandeep N. Tripathi, Veena Choudhary, Banshi D. Gupta, Indian Institute of Technology Delhi (India)

Exposure to low concentrations of ammonia in air or solution may produce rapid skin or eye irritation. Higher concentrations of ammonia may cause severe injury and burns. Contact with concentrated ammonia solutions such as industrial cleaners may cause corrosive injury including skin burns, permanent eye damage or blindness.

The technique of surface plasmon resonance (SPR) has attracted people for centuries because of its applications in sensing. The sensors made by using SPR technique provide a means for investigating surface interactions and are used for the sensing of various parameters.

In this paper, the fabrication and characterization of a surface plasmon resonance (SPR) based fiber optic ammonia sensor using copper and polymer films containing esters groups have been reported. The sensor works under the principle of the wavelength interrogation technique. The refractive index of the polymer films changes when the ammonia gas comes in contact with it. To prepare the probe, a thin film of copper of thickness 40 nm was deposited over the unclad portion of the fiber by thermal evaporation technique. After that the thin film of different ester containing polymers such as poly(methyl methacrylate) [PMMA], Poly(2-hydroxyethyl methacrylate) [PHEMA], Poly(?-caprolactone) [PCL], Poly(lactic acid) [PLA], Polycarbonate [PC] coated over the copper film by dip coating. To calibrate the sensor the resonance wavelength of is determined from the SPR spectrum of the sensor for a given concentration of ammonia around the probe. It was observed that as the concentration of ammonia increases the resonance wavelength increases.

8987-78, Session PWed

Control of optical and electrical properties of ZnO nanocrystals by nanosecond-laser annealing

Tetsuya Shimogaki, Taihei Ofuji, Norihiro Tetsuyama, Hirotaka Kawahara, Mitsuhiro Higashihata, Hiroshi Ikenoue, Daisuke Nakamura, Tatsuo Okada, Kyushu Univ. (Japan)

Effects of laser annealing on electrical and optical properties of Zinc oxide (ZnO) nanocrystals, which are expected as building blocks for optoelectronic devices, have been investigated in this study. In the case of fabricating p-n junction in single one-dimensional ZnO nanocrystal, phosphorus-ions implanted p-type ZnO nanocrystals were recrystallized and recovered in the optical properties by nanosecond-laser annealing using a KrF excimer laser. Antimony-doped p-type ZnO nanocrystals were synthesized by irradiating with the laser laminated structure which antimony thin film were deposited on ZnO nanocrystals. Additionally, it is possible to control the growth rate of ZnO nanowires by using laser annealing. Irradiating with pulsed laser a part of ZnO buffer layer deposited on the a-cut sapphire substrate, then ZnO nanowires were grown on the ZnO buffer layer by the nanoparticle assisted pulsed laser deposition method. As a result, the clear boundary of laser annealed and non-laser annealed region was appeared. It was observed that ZnO nanowires were grown densely at non-laser annealed region, on the other hand, sparse ones were grown at laser annealed region. In this report, the possibility of laser annealing techniques to establish the optimum fabrication process of ZnO nanowires-based LD and LED are discussed on the basis of experimental results above mentioned.

8987-79, Session PWed

Electroluminescence from ZnO nanowire-based heterojunction LED

Daisuke Nakamura, Norihiro Tetsuyama, Tetsuya Shimogaki, Mitsuhiro Higashihata, Hiroshi Ikenoue, Tatsuo Okada, Kyushu Univ. (Japan)

Zinc oxide (ZnO) nanowires are very attractive for optoelectronic devices in ultra-violet (UV) region due to the unique structure and optoelectronic properties, which are wide band gap (3.37 eV) and large exciton binding energy (60 meV). We have demonstrated that fabrication of the ZnO nanowire/GaN hetero-junction light emitting diode (LED) and UV electroluminescence from the pn junction. In this study, we apply the selective laser irradiation to the pn junction of the ZnO-based LED. In the presentation, the effect of laser irradiation on I-V and optical characteristics of the ZnO-based LED will be discussed.

8987-80, Session PWed

Investigation of the cathodic electrochemical deposition of iron oxide films on nickel-based alloy substrates

Thierry Pauporté, Christophe Goujon, Ecole Nationale Supérieure de Chimie de Paris (France); Carine Mansour, Sophie Delaunay, EDF (France)

Abundant in nature, iron oxides, including iron hydroxides and iron (oxy) hydroxides, have been used as catalysts, pigments, and magnetic coatings due to their chemical and physical properties.[1,2] The iron oxide magnetite (Fe3O4) is a ferrimagnetic material with an inverse spinel structure, space group Fd3m. This mixed-valence transition metal oxide has Fe3+ and Fe2+ ions in the octahedral sites and Fe3+ ions in the tetrahedral sites. For Fe3O4, ferrimagnetism is observed below the Curie temperature of 860 K.

Iron oxide films have been deposited from an alkaline Fe(III)-Triethanolamine electrolytic solution at constant applied potential. [3] The electrochemical behavior of the deposition bath has been investigated by cyclic voltammetry and the electrochemical quartz microbalance techniques. The polycrystalline films prepared over a large electrochemical range have been thoroughly characterized by X-ray diffraction, scanning electron microscopy, profilometry and magnetometry measurements.

Well-crystallized Magnetite films with a thickness up to several tens of micrometers have been grown on nickel-based alloy substrates. The electrochemical potential range of magnetite deposition was identified between -1.00V and -1.08 V versus the saturated calomel reference electrode. Other species such as ferrihydrite and iron were identified at more negative applied potentials.

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8987-81, Session PWed

Multi-layer insulator for low voltage and breakdown voltage enhancement in electrowetting-on-dielectric

Anggita Hapsari Grisatya, Yong Hyub Won, KAIST (Korea, Republic of)

Low applied voltage in electrowetting-on-dielectric (EWOD) can be achieved by using thin dielectric thickness. However it follows by high possibility of dielectric failure. On the other hand, multi-layer dielectric has been known as a way to enhance the dielectric reliability by delaying the dielectric breakdown. In this paper, we report on the comparison between several EWOD with different numbers of insulator layers. Firstly, we examine the performance of single layer dielectric using a sufficiently thin layer of Parylene C as a widely used insulator in EWOD application. For the next sample, thin layer of Aluminum Oxide (Al2O3) is stacked below the Parylene C layer. Furthermore, the thickness of Parylene C layer in previous sample is divided into two layers and thin Al2O3 are inserted in between. Total capacitance of two last sample are identic but one layer addition is expected to give more prevention to dielectric failure while keep maintaining the same operational voltage. Breakdown voltage is investigate by measuring the current flow through the dielectric. We also observed the operational voltage for every sample.

8987-82, Session PWed

Tailor-made ZnO@SnO2 networks for high-efficiency photovoltaic devices

Riccardo Milan, Isabella Concina, Alberto Vomiero, Gurpreet Singh Selopal, Giorgio Sberveglieri, Univ. degli Studi di Brescia (Italy); Mauro Epifani, Consiglio Nazionale delle Ricerche (Italy)

The dye sensitized (DSSC) and semiconductor solar cells are a low-cost and high-efficiency alternative to the traditional photovoltaic devices1. Semiconductor metal oxides, after sensitization treatment, are a critical part of these devices, acting as electron transporters toward the external circuit. Suitable functional properties of such oxides like proper conduction band alignment with respect to the other components of the cell scheme and high electron mobility are desirable to increase the collected photocurrent.

The most commonly used oxide in the DSSC is the TiO2, being cheap, chemically stable and non toxic, but an increasing interest is focused on the application of other materials with suitable conduction band and electronic mobility. In this frame, SnO24 and ZnO2,3 are good candidates as reliable alternative to TiO2, although at present TiO2 still remains the best performing material.

The aim of this work is the study of composite networks of SnO2 nanoparticles and ZnO nano and macro-structures to increase the performances of DSSCs based on these photoanodes.

We found the optimal set of parameters (composition, thickness and interface of layers and sensitization time) allowing to built DSSCs with high functional performances in terms of injected photocurrent and photo conversion efficiency (JSC=14.78 mA/cm2 PCE=5.0%). These results highlight the role of ZnO as blocking layer towards exciton recombination at SnO2-light harvester-electrolyte interfaces.

Strategies successful in optimizing the functional performances of this kind of solar cells through material interface engineering will be presented and discussed.

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8987-83, Session PWed

Photoluminescence study of nitrogen doped MgZnO thin films grown by RF-plasma assisted MBE

Muhammad M. Morshed, Jianlin Liu, Univ. of California, Riverside (United States)

Magnesium Zinc Oxide (MgxZn1-xO) is an important material in Zinc Oxide (ZnO) family. One can increase the band gap by using MgxZn1-xO which is essential for ZnO hetero-structure applications. For better performance of ZnO based hetero-structure devices, good quality p-type MgxZn1-xO is required. Hence, it is necessary to investigate the p-type conductivity and the acceptor states in MgxZn1-xO. In this presentation, we report our recent results on photo-luminescence (PL) study of nitrogen (N) doped MgxZn1-xO thin films. These materials were grown on c-plane sapphire substrates in a radio-frequency (RF) plasma-assisted molecular beam epitaxy (MBE) system. The sources include Mg and Zn effusion cells and O RF plasma. The dopant source is N2O. X-ray diffraction (XRD) and transmission electron microscopy (TEM) measurements indicated that the thin films are wurtzite single crystals. Mg composition in these films was estimated to be about 10%. Hall-effect measurements showed that the films exhibit p-type conductivities. Temperature dependent PL of N doped MgxZn1-xO thin films was carried out. Structural defects related bound exciton was identified, which is positioned around 50meV lower energy than the near band edge (NBE) acceptor bound exciton. 'S shape' behavior of energy position with temperature was observed due to polarization induced internal field. N related acceptor ionization energy was found to be ~210meV.

8987-84, Session PWed

Effect of lithium-ion implantation of varying fluence on the optical properties of ZnMgO

Shantanu Saha, Saurabh Nagar, Indian Institute of Technology Bombay (India); S.K. Gupta, Bhabha Atomic Research Ctr. (India); Subhananda Chakrabarti, Indian Institute of Technology Bombay (India)

The optical characteristics of the Zn(1-x)Mg(x)O(x=0.15) films implanted with Li ions of low energy (40 KeV) with fluences of 5x10^13 ions/cm^2 and 10^14 ions/cm^2 has been reported in this paper. Prior to implantation Zn(1-x)Mg(x)O films were deposited via RF sputtering on Si substrate followed by annealing at 650°C and 750°C. For dosage of 5x10^13 ions/cm^2 the low temperature(15K) and room temperature photoluminescence (PL) spectra is dominated by the emission at 3.67 eV which is the bandgap energy of Zn(1-x)Mg(x)O, that shifts to 3.63 eV at higher dosage of ions. The splitting of conduction band and valence band into multiple sub-bands causes a transition between the sub-band of conduction band and sub-band of heavy-hole and an emission occurs at 3.59 eV referred as 11H. After implantation and annealing D°X was confirmed at 3.52 eV. At low temperature the low thermal energy carriers are localized at low energy level due to interface roughness. With increasing temperature, the carriers get enough thermal energy to come out of the local potential hollows. Some of the carriers might got delocalized causing a delocalized peak at 3.44 eV. All the annealed samples confirmed A°X around 3.33 eV. Moreover, the presence of DAP at 3.24 eV was also observed in the implanted samples. These peaks provide strong evidence of increased acceptor concentration in ZnMgO. However, further optimization of implanted parameters need to be done to achieve strong p-type ZnMgO which may open a new door for Zn(1-x)Mg(x)O in the optoelectronics area. DST, India is acknowledged.

8987-85, Session PWed

Plasma treatment of p-GaN/n-ZnO nanorod light-emitting diodes

Yu Hang Leung, The Univ. of Hong Kong (Hong Kong, China); Alan M. C. Ng, South Univ. of Science and Technology of China (China); Aleksandra B. Djurišic, Wai Kin Chan, The Univ. of Hong Kong (Hong Kong, China); Patrick W. K. Fong, Hsien Fei H. Lui, Charles C. Surya, The Hong Kong Polytechnic Univ. (Hong Kong, China)

Zinc oxide (ZnO) is a material of great interest for short-wavelength optoelectronic applications due to its wide band gap (3.37 eV) and high exciton binding energy (60 meV). Due to the difficulty on stable p-type doping in the material, other p-type materials such as gallium nitride (GaN) have been used in complementary with ZnO to form heterojunctions. p-GaN/n-ZnO heterojunction devices, in particular light-emitting diodes (LED) have been extensively demonstrated. There was a huge variety on the electronic properties and emission colors on the reported devices. It is due to the different energy alignment at the interface caused by different properties of the GaN layer and ZnO counterpart in the junction. Attempts have been made on modifying the heterojunction by various methods, such as introducing a dielectric interlayer and post-growth surface treatment, and changing the growth methods of ZnO. In this study, heterojunction LED devices with p-GaN and ZnO nanorods array are demonstrated. The ZnO nanorods were grown by a solution method. The ZnO nanorods were exposed to different kinds of plasma treatments (such as nitrogen and oxygen) after the growth. It was found that the treatment could cause significant change on the optical properties of the ZnO nanorods, as well as the electronic properties and light emissions of the resultant LED devices. The effects of the plasma treatment and the physical mechanism responsible for the observed performance differences will be discussed in detail.

8987-86, Session PWed

Nanostructured ZnO for energy-harvesting applications

David J. Rogers, Ferechteh Hosseini Teherani, Philippe Bove, Vinod E. Sandana, Nanovation (France); Ryan McClintock, Manijeh Razeghi, Northwestern Univ. (United States)

ZnO is a remarkable multifunctional material with a distinctive and unique property set. In particular, it exhibits one of the largest piezoelectric coefficients of any semiconductor and has a relatively high thermoelectric figure-of-merit. This has often led to it being considered for use in piezogenerators [1] and thermoelectric energy harvesting [2]. In this paper, we investigate the enhancement in the potential of ZnO for parallel kinetic and thermal energy scavenging through nanostructuration.

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[2] P. Jood et al. Nano Lett. 11 (2011) 4337

8987-87, Session PWed

Investigation of ZnO nanorod array ultraviolet photodetectors

Ching-Ting Lee, Hsin-Ying Lee, Tzu-Shun Lin, National Cheng Kung Univ. (Taiwan)

Zinc oxide (ZnO)-based semiconductors have been intensively investigated as promising materials for advanced electronic, optoelectronic, and sensing devices due to their wide direct band gap, large exciton binding energy, and high radiation hardness. Furthermore, the ZnO nanostructure was also widely studied due to large surface-to-volume ratio. In this work, the novel vapor cooling condensation system was used to grow the p-type, intrinsic, and n-type ZnO nanorod arrays with high quality and low defect. Using the deposition method, the ZnO-based nanorod array ul-traviolet photodetectors were then successfully fabricated. To improve the specific detectivity of the ultraviolet photodetectors, the photoelectrochemical (PEC) oxidation method was carried out to suppress the surface states and the dangling bonds resided on the sidewall surface of the ZnO nanorods. At a reverse bias voltage of -1 V, the measured peak photoresponsivity of the ZnO-based nanorod array photodetectors without and with passivation were 8.9?10^2 A/W and 3.2?10^3 A/W, respectively. The corresponding detectivity was 4.43E13 cmHz^1/2W^-1 and 3.51E15 cmHz^1/2W^-1, respectively, at a light wavelength of 360 nm. Moreover, the noise power density spectrum of the ZnO-based nanorod array ultraviolet photodetectors was changed from the dependence of 1/f^2 to 1/f by photoelectrochemical oxidation treatment. The obtained results clearly indicated that the performance of the devices was improved by the passivation treatment.

8987-88, Session PWed

InGaZnO and ZnO/Al2O3 multilayer structures measured by optical and x-ray techniques

Péter Petrik, Emil Agocs, Balint Fodor, Research Institute for Technical Physics and Materials Science (Hungary); Beatrix Pollakowski, Sabine Zakel, Physikalisch-Technische Bundesanstalt (Germany); Thomas Gumprecht, Erlangen Graduate School in Advanced Optical Technologies (Germany); Burkhard Beckhoff, Physikalisch-Technische Bundesanstalt (Germany); Zoltan Labadi, Zsofia Baji, Research Institute for Technical Physics and Materials Science (Hungary); Michael Jank, Fraunhofer-Institut für Integrierte Systeme und Bauelementetechnologie IISB (Germany); Andreas Nutsch, Physikalisch-Technische Bundesanstalt (Germany)

Non-destructive optical and X-ray methods have been applied for the characterization of Ga- and In-doped sputtered and atomic layer deposited ZnO structures. Several metrologies including spectroscopic ellipsometry, vacuum ultra violet reflectometry, Raman spectrometry, X-ray fluorescence and X-ray photoelectron spectroscopy have been tested, the evaluation methods and optical models developed, their limitations investigated. The parameterization of the dielectric function was investigated using different approaches. The importance of taking into account the surface nanoroughness is pointed out. The sensitivity of the different methods on low doping concentrations have been systematically investigated.

8987-90, Session PWed

Design and synthesis of new low band gap organic semiconductors for photovoltaic applications

Murali M. G., Indian Institute of Science (India); Udaya K. Dalimba, National Institute of Technology, Karnataka (India)

Donor-acceptor (D?A) conjugated polymers have attracted a good deal of attention in recent years. In D?A systems, the introduction of electron withdrawing groups reduces Eg by lowering the LUMO levels whereas, the introduction of electron donating groups reduces Eg by raising the HOMO levels. Also, conjugated polymers with desired HOMO and LUMO energy levels could be obtained by the proper selection of donor and acceptor units. Because of this reason, D?A conjugated polymers are emerging as promising materials particularly for polymer light emitting diodes (PLEDs) and polymer solar cells (PSCs).

We report the design and synthesis of four new narrow band gap donor-acceptor (D-A) conjugated polymers, PTCNN, PTCNF, PTCNV and PTCNO, containing electron donating 3,4-didodecyloxythiophene and electron accepting cyanovinylene units. The effects of further addition of electron donating and electron withdrawing groups to the repeating unit of a D-A conjugated polymer (PTCNN) on its optical and electrochemical properties are discussed. The studies revealed that the nature of D and A units as well as the extent of alternate D-A structure influences the optical and the electrochemical properties of the polymers. All the polymers are thermally stable up to a temperature of 300 oC under nitrogen atmosphere. The electrochemical studies revealed that the polymers possess low-lying HOMO energy levels and low-lying LUMO energy levels. In the UV-Vis absorption study, the polymer films displayed broad absorption in the wavelength region of 400?700 nm. The polymers exhibited low optical band gaps in the range 1.70 ? 1.77 eV.

8987-91, Session PWed

Graphene versus oxides for transparent electronics applications

Vinod E. Sandana, Graphos (France); David J. Rogers, Ferechteh Hosseini Teherani, Philippe Bove, Nanovation (France); Manijeh Razeghi, Northwestern Univ. (United States)

Due to their combination of good electrical conductivity and optical transparency, Transparent Conducting Oxides (TCOs) are the most common choice for transparent electronics applications. In particular, Indium Tin Oxide (ITO) is the most used TCO as transparent electrodes in a range of opto-electronic devices, such as solar cells, touch screens, LEDs and LCDs. However, Indium has some significant drawbacks including toxicity issues (which are hampering manufacturing), an increasing rarification (due to market growth [1]) and resulting price increases. Thus alternative materials solutions are actively being sought. This review will compare the performance and perspectives of graphene with respect to TCOs for use in transparent conductor applications.

[1] Rapport JRC Commission Européenne: « Critical Metals in Strategic Energy Technologies, Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies » (2011)

8987-92, Session PWed

Thermal expansion and electron-phonon interaction in TiO2 thin films studied by spectroscopic ellipsometry

Rong-Jun Zhang, Fan Zhang, Fudan Univ. (China)

Titanium oxide (TiO2) is one of the most commonly used materials for planar waveguides, antireflective, photocatalysts, and high refractive index component of multilayer optical filter due to its good durability, high transmittance in the visible spectral region, wide band gap of around 3.2 eV and high refractive index of more than 2.0 at wavelength of 550 nm.

Now we have fabricated TiO2 thin film on Si (100) substrate by the electron-beam evaporation (EBE) method. The optical constants of the thin film determined by variable angle spectroscopic ellipsometry (VASE) in the spectral range from 300 to 800 nm were studied in a temperature range from room temperature to 533 K, which can be qualitatively elucidated by thermal expansion and electron-phonon interaction in Prod'homme model. The absorption edge emerging in extinction coefficient spectra shows a redshift at elevated temperature, which is attributed to temperature dependence of band gap shift and electron lifetime loss in optical electron transition calculated from the fitting of FB dispersion model. Moreover, the Urbach energy produced by thermal fluctuation disorder shows an increase from around 40 meV to 80 meV with increasing temperature from 293 K to 533 K. Results from this study shed light on design and fabrication of TiO2 based photonic devices in integrated optics and solar cell application at different temperature.

8987-93, Session PWed

Optical properties and storage capabilities of AB2O4:Cr3+ (A=Zn, Mg, B=Ga, Al)

Suchinder Sharma, Aurelie Bessiere, Didier Gourier, G. Sraiki, Bruno Viana, Ecole Nationale Supérieure de Chimie de Paris (France); Przemyslaw J. Deren, D. Rudnicka, A. Watras, Institute of Low Temperature and Structure Research (Poland); Neelima Basavaraju, Kaustubh Priolkar, Goa Univ. (India); Thomas Maldiney, Daniel Scherman, Cyrille Richard, Univ. Paris Descartes (France)

In the recent past, we have focused our interest on the research of long-lasting phosphorescence (LLP) materials useful as biomarker for small animal in-vivo imaging [1, 2]. In that case, the traps depth for the persistent luminescence should be well released at room temperature. The luminescence is at about 700 nm. Varying cations in the spinel compounds doped with Cr3+ AB2O4:Cr with A=Zn, Mg and B=Ga, Al, the compounds present either interesting persistent luminescence or a release of luminescence at controlled temperature [1-3]. It was therefore possible to enlarge the possible applications to these spinel materials as storage phosphors for instance [3] as storage phosphors are commercially the most successful detectors for replacing film-screen systems.

Therefore, we will report in this study our investigations on the optical features of chromium doped AB2O4 system (A=Zn, Mg and B=Ga, Al…). In the AB2O4 system, it is possible to tune either the emission wavelengths of Cr3+ by a crystal field variation and for instance to be well centered in the biological window but it is also possible to adjust the traps depth in order to better control the release of the traps. For instance in MgGa2O4:Cr, the emission wavelength is shifted toward longer wavelength (at 726 nm as average wavelength) while Cr3+:ZnAl2O4 nanopowders exhibit good emission properties at about 700 nm with traps depths located at about 1 eV, corresponding to a thermoluminescence curve at about 530 K [3]. These traps are therefore stable at room temperature and could be emptied by thermal or near infrared source making this material a potential new phosphor [3].

Works are now in progress for the elaboration of some of these compounds as transparent ceramics.

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8987-97, Session PWed

Nickel oxide growth on Si(111) and c-Al2O3 by pulsed laser deposition

Vinod E. Sandana, David J. Rogers, Ferechteh Hosseini Teherani, Philippe Bove, Nanovation (France); Ryan McClintock, Manijeh Razeghi, Northwestern Univ. (United States)

Because of their potential cost-effectiveness [1], dye sensitized solar cells (DSSCs) have attracted a lot of interest for the past two decades. Most researchers are focusing on DSSCs, in which the photoelectrode is an n-type semiconductor (usually TiO2 [2]). Recently, there has been increasing interest in the development of p-type semiconductor electrodes for DSSCs and the production of tandem cells which combine a photosensitized anode (e.g. TiO2) and a photocathode (e.g. a sensitized p-type SC) as a means to boost the solar conversion efficiency [3]. So far, NiO is the only p-type semiconductor found to give significant photocurrent and photovoltage [4]. This NiO electrode is usually synthesized by either solvothermal growth or electrodeposition. In this work, we examine the potential of pulsed laser deposition [5,6] for the growth of NiO with superior materials characteristics.

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8988-1, Session 1

Graphene-based photonic waveguide devices *(Invited Paper)*

Choon-Gi Choi, Electronics and Telecommunications Research Institute (Korea, Republic of)

Graphene has attracted great attention due to its extraordinary electronic, thermal, mechanical, and optical properties [1]. In photonics, graphene has been exhibited outstanding properties such as transparency, wavelength-independent optical absorption, satuable absorption, electron-hole pair generation, third-order nonlinearity, and electro-absorption. In addition, graphene has been used as a transparent electrode for photovoltaics, light emitting diodes, and touch panels [2]. In optical communication applications, graphene has been considered as a versatile photonic material to modulate, detect, control, and even guide light [3-5].

Recent theoretical investigations on graphene-based photonic devices exhibited that graphene embedded in a homogenous dielectric can serve as a lightwave guiding medium [6–8]. For further development of graphene-based PICs (photonic integrated circuits), planar-lightwave-circuit (PLC)-compatible integrations of the graphene-based flexible optoelectronic devices are being consistently demanded, thereby a flexible PIC platform has been proposed [9].

In this talk, we demonstrate recent progress in graphene-based photonic waveguide devices such as polymer waveguide polarizer, thermo-optic mode extinction modulator and PLC-type photodetector for graphene-based PICs [10-12].

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8988-2, Session 1

On-chip dynamic optical power splitter with liquid crystal waveguides on a silicon backplane

Florenta A. Costache, Martin Blasl, Kirstin Bornhorst, Haldor Hartwig, Andreas Rieck, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

Optical power splitter devices (OPSs) divide or combine optical signals in fiber optic networks. We report on integrated dynamic OPSs based on field-induced waveguides (FIWs). As electro-optical (EO) core materials, these waveguides employ specifically developed liquid crystal mixtures. We show that the characteristic of these mixtures is that, when brought to their paranematic phase by heating and in the presence of electrical fields, they exhibit large EO Kerr constants, very good transparency from visible to infrared range as well as sub-microsecond response time, which are very useful parameters for EO waveguide applications.

The fiber-coupled 1 ? 2 dynamic OPS device concept is based on FIWs in liquid crystals in paranematic phase and a special arrangement of electrodes. This device was designed using FEM simulation and optimized for operation at the 1.55 µm telecommunication wavelength. Fabricated by means of silicon bulk micro-machining processes, the chip assembly includes two structured silicon wafers bonded together and enclosing in between a core layer made of liquid crystal mixtures.

We show that this concept enables continuously voltage controlled adjustment of the device optical output characteristics. Hence, dynamic, micro-second, bi-directional, as well as both polarization dependent and independent operation could be achieved. Basically, by adjusting the voltage on the electrodes corresponding to the two output ports, a reconfigurable device combining continuously variable optical power splitting and sub-microsecond switching could be obtained.

8988-3, Session 1

Polymer waveguide end facet roughness and optical input/output coupling loss for OPCB applications

Hadi Baghsiahi, David Selviah, Univ. College London (United Kingdom); Richard C. Pitwon, Kai Wang, Xyratex Technology Ltd. (United Kingdom)

Electro-optical printed circuit board technology (EOCB) based on integrated planar polymer optical waveguides has been the subject of research and development for many years to provide a cost viable, fully integrated system embedded optical interconnect solution, however a number of constraints of this technology have yet to be overcome. Optical coupling loss at the input and output of the waveguides is one of the major issues and waveguide end facet roughness is one of the main sources of the coupling loss which is investigated in this paper.

The results of a comprehensive investigation of the end facet roughness of multimode polymer waveguides, fabricated on FR4 printed circuit boards, PCBs, are presented theoretically and experimentally. The waveguide end facet roughness was measured using an atomic force microscope, AFM, when the waveguides were cut using a milling router with various numbers of cutting edges called flutes. The optimized cutting parameters are derived and optical coupling loss, between the laser source and waveguide, due to the different roughness magnitude is measured by experiment for the first time. Also, optical insertion loss is shown to be linearly proportional to the ratio of the waveguide core end facet RMS roughness to its autocorrelation length.

To improve the surface quality and decrease the waveguide optical loss, a new fabrication technique for reducing the end facet roughness after cutting is proposed and demonstrated. The insertion loss was reduced by 2.60 dB ± 1.3 dB which is more than that achieved by other conventional methods such as index matching fluid.

8988-4, Session 1

III-V semiconductor waveguides for photonic functionality at 780 nm

Jessica O. Maclean, Mark T. Greenaway, Richard P. Campion, Tadas Pyragius, Christopher J. Mellor, The Univ. of Nottingham (United Kingdom)

We have designed III-V semiconductor photonic integrated circuits based on rib waveguides of 2.5 microns width for application in a compact cold-atom gravimeter at an operational wavelength of 780 nm. Compared with optical fibre-based components, semiconductor waveguides achieve very compact guiding of optical signals for both passive functions, such as splitting and recombining, and for active functions, such as switching or modulation. The waveguides are fabricated from AlGaAs / GaAs 75 mm epiwafers grown in-house and have a polarisation-maintaining epitaxial structure. The epiwafers have been characterised by X-ray diffraction and photoluminescence to assess structural and optical quality. The short wavelength of operation of the devices dictates stringent requirements on the device fabrication in terms of anisotropy and smoothness of plasma etch processes, cross-wafer uniformities and (re-)alignment tolerances. In order to facilitate integration with other fibre-based modules in the system, a novel 780 nm mode-size converter has been designed for efficient coupling of light from optical fibres onto and off the semiconductor chip.

8988-5, Session 1

Demonstration of high-performance, sub-micron chalcogenide glass photonic devices by thermal nanoimprint

Yi Zou, Loise Moreel, Jie Zhou, Danning Zhang, Hongtao Lin, Lan Li, Qingyang Du, Juejun Hu, Univ. of Delaware (United States); Sylvain Danto, Kathleen A. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Jonathan David Musgraves, IRradiance Glass, Inc. (United States); Kevin D. Dobson, Robert Birkmire, Univ. of Delaware (United States)

High-index-contrast optical devices form the backbone of densely integrated photonic circuits. While these devices are traditionally fabricated using lithography and etching, their performance is often limited by defects and sidewall roughness arising from fabrication imperfections. This paper reported a versatile technique for the fabrication of high-performance, high-index-contrast photonic structures in composition-engineered chalcogenide glass (ChG) thin films that have emerged as important materials for photonic applications due to their high refractive index, excellent transparency in the infrared, and large Kerr non-linearity. Both thermally evaporated and solution processed As-Se thin films were successfully employed to imprint waveguides, micro-ring resonators and gratings with high pattern fidelity and low surface roughness (0.9 nm). The imprinted multi-mode waveguides showed a propagation loss as low as 0.8 dB/cm at 1550 nm wavelength. The micro-ring resonators exhibited a high quality-factor of 4 x 105 near 1550 nm wavelength, which represents the highest value reported in ChG micro-ring resonators. Furthermore, sub-micron nanoimprinted patterning of ChG films on non-planar plastic substrates was demonstrated, which establishes the method as a facile route for monolithic fabrication of high-index-contrast devices on a wide array of unconventional substrates.

8988-6, Session 1

Optical loss and crosstalk in multimode photolithographically-fabricated polyacrylate polymer waveguide crossings

Hadi Baghsiahi, David Selviah, Univ. College London (United Kingdom); Kai Wang, Xyratex Technology Ltd. (United Kingdom)

Complex interconnection patterns in electrical PCBs have to use multiple layers of copper tracks. However, the same interconnections can be made in a single layer using optical waveguides as they cross on the same layer. Waveguide crossings where two waveguides intersect in the same optical layer are particularly important components as they offer OPCB layout designers additional flexibility to solve layout problems such as routing around cutout areas, electrical components and other obstacles on an OPCB. Use of waveguide crossings can also help to avoid sharp bends in the design as these are an important cause of optical loss. Despite all of the advantages of waveguide crossings, and although most of the light travels along the intended waveguide, a proportion of the optical power in one waveguide will couple into the crossed waveguide after passing each intersect point or couple out of the original waveguide and into the cladding. This coupling phenomenon causes optical loss and crosstalk in the system.

In this paper, the results of an investigation of the optical loss due to the crossing of multimode polymer waveguide, fabricated on FR4 printed circuit boards, PCBs, are presented theoretically and experimentally. The optical loss due to crossing waveguides was calculated for different crossing angles. For the first time the results from two different simulation approaches, beam propagation and ray tracing were compared with the experiment results.

8988-7, Session 2

Recent progress in continuous-wave Ti:sapphire waveguide lasers *(Invited Paper)*

Christos Grivas, Univ. of Southampton (United Kingdom); Costantino Corbari, Gilberto Brambilla, Optoelectronics Research Centre, University of Southampton (United Kingdom)

Ti:sapphire (Al2O3:Ti3+) is a benchmark gain medium for development of wavelength tunable lasers and generation of ultra-short laser pulses, exhibiting a remarkable combination of spectroscopic and material characteristics, which partly originate from the sapphire host. The latter has excellent thermo-mechanical properties, a wide transmission window, high third-order and nonlinearity and is suitable as a substrate for epitaxial growth of various semiconductor-based integrated optical devices. Ti:sapphire crystals are characterized by a broadband emission, stretching from 650 to 1100 nm, which is responsible for the low emission cross section and short fluorescence lifetime of the Ti3+ ions, imposing a requirement for high pump powers for continuous-wave operation of bulk lasers. One way towards lower pump power thresholds and smaller source footprints is to adopt waveguide geometries.

Here, the various fabrication methods implemented for development of Ti:sapphire waveguide lasers to date will be briefly reviewed together with the results on the performance of the corresponding sources. Channel waveguides lasers produced recently by writing with femtosecond and picosecond laser pulsed in bulk Ti:sapphire crystals will be discussed in detail as the performance was by far superior to those of their counterparts fabricated by other methods. Continuous-wave laser operation at 798.25 nm was achieved above a threshold of 84 mW with output powers and slope efficiencies up to 143 mW and 23.5%, respectively, while wavelength tunable emission was demonstrated over a range of 170 nm. Furthermore, stable, mode-locked operation using graphene layers as saturable absorbers was realized, producing pulses of sub-picosecond duration and up to ~2-GHz repetition rates.

8988-8, Session 2

Er-doped tellurite waveguides for power amplifier applications *(Invited Paper)*

Jacob I. Mackenzie, Ganapathy S. Murugan, Univ. of Southampton (United Kingdom); Anthony W. Yu, James B. Abshire, NASA Goddard Space Flight Ctr. (United States)

Tellurite waveguides are promising candidates for high gain with broad-bandwidth, especially with Er-doping, which covers the telecommunications band and important spectral absorption features of atmospheric CO2. A relatively high index material tellurite is also strongly non-linear opening various possibilities for chip-based super-continuum or mode-locked lasers. In this presentation, we concentrate on the fabrication of new Er,Yb-doped tellurite waveguide films in a study aimed at developing power amplifier modules suited to LIDAR measurements from space that will enable improved mapping of the concentration and distribution of CO2 in our atmosphere.

Comparing the optical properties of several compositions in bulk samples, we targeted ones that provided the best emission cross section characteristics around 1572 nm coincident with a strong CO2 absorption line. When pumped at 1480 nm with a pump irradiance of 6 kWcm-2, the respective gain around the peak emission wavelength of 1531 nm was > 2 dB/cm and ~0.7 dB/cm around 1572 nm, from a sample having an erbium and ytterbium doping concentration of only 1.5 x 1020 cm-3.

Doped and undoped planar waveguides subsequently fabricated via RF magnetron sputtering onto oxidised silicon wafers have been characterized. Waveguide losses of single films of 2-4 micron thickness were found to be as good as 1.2dB/cm as deposited. Multilayer waveguides, that is effectively double-clad structure for high-power pump guiding have been realised, leading to slightly multi-mode ~4 micron thick core waveguides with an NA of 0.28, with a 14 micron pump guide and an NA>1. Spectroscopic and gain measurement characterisation of the doped films will be presented.

8988-9, Session 2

All-optical high-speed pulsed generation in SOAs *(Invited Paper)*

Amr S. Helmy, Fangxin Li, Univ. of Toronto (Canada)

Pulsed sources based on approaches that employ only photonic components and no RF components will be discussed in this talk. Several technologies have been explored to generate actively mode-locked pulse trains using electronic drives fiber ring cavities. However, for these sources the pulse repetition rate is usually limited by the bandwidth of the intra-cavity modulator. Filtering of highly-stable low repetition rate optical combs utilizing cavities such as Fabry-Perot etalons can be used to overcome this limitation. This scheme is not flexible as it requires highly precise control of ultrahigh finesse etalons which limits the repetition rate to the free spectral range of the filter. Pulsed sources based on semiconductor devices offer many advantages, including large gain bandwidth, rapid tunability, long-term stability.

In this talk we introduce a novel, simple method to generate optical clock with wavelength tunability using two continuous wave (CW) lasers. The lasers are injected into a conventional SOAs-based fiber ring laser. The beating signal generated by these two lasers causes the modulation of the SOA gain saturation inside the cavity. Thus, the SOA provides gain and functions as the modulator. When the lasing mode inside the cavity is amplified, it also results in gain-induced Four wave mixing. The proposed technique is particularly versatile, overcoming the bandwidth limitation of other techniques, which require RF sources.

Moreover, this technique provides the possibility for hybrid integration as it is comprised of semiconductor chips that can be heterogeneously integrated on a Si platform.

8988-10, Session 2

Electro-optic polymer/silicon hybrid slow light modulator based on photonic crystal nanobeam waveguides

Shin-ichiro Inoue, Akira Otomo, National Institute of Information and Communications Technology (Japan)

Silicon-based optical modulators fabricated using CMOS compatible nanofabrication technology are critical components to enable high-speed optical transceivers and optical interconnects for intra- and inter-chip networks. However, the bandwidths of these Si modulators are usually limited by the free carrier dynamics. Moreover, it is known that these modulation characteristics strongly depend on temperature owing to the high thermo-optic (TO) coefficient of Si. In this study, we report on the design and experimental demonstration of a Mach-Zehnder modulator based on electro-optic (EO) polymer/silicon hybrid one-dimensional (1D) photonic crystal (PhC) nanobeam waveguides. Organic EO polymers can provide extremely high modulation speeds in excess of 100 GHz, and very high EO coefficients that are much higher than that of lithium niobate (r33 = 30 pm/V). The optical field in the 1D PhC nanobeam is designed to be concentrated in the low index EO polymer clad and to compensate the positive TO coefficient of Si by using the negative TO coefficient of EO polymer. We have successfully demonstrated enhancement of the EO modulation efficiencies as a result of the slower group velocity in an MZI modulator that incorporates 0.1-mm-long PhC nanobeam phase-shifters. The observed in-device effective EO coefficient (r33 = 343 pm/V) is about 10 times larger than that of lithium niobate. Good agreement was obtained between the enhanced modulation efficiency and the photonic band structure, indicating that our EO polymer/silicon hybrid PhC nanobeam platform effectively enables temperature-independent EO modulation using a simple geometry and an extremely small device footprint at potentially ultrafast modulation speeds.

8988-11, Session 3

Silicon waveguide optical nonreciprocal devices based on magneto-optical phase shift *(Invited Paper)*

Tetsuya Mizumoto, Yuya Shoji, Kota Mitsuya, Tokyo Institute of Technology (Japan)

Optical nonreciprocal devices play unique roles in photonic circuits. An optical isolator allows light waves to propagate in a pre-determined direction, and prevents unwanted light waves from launching into optically active devices. An optical circulator enables us to construct highly functional photonic circuits.

A nonreciprocal rotation of polarization in a magneto-optical Faraday rotator is used to build bulk optical nonreciprocal devices. The same scheme, i.e. a magneto-optical TE-TM mode conversion, is hard to apply to waveguide devices, since waveguide dimensions as well as refractive indices must be controlled stringently to realize the TE-TM mode phase matching. In order to overcome this difficulty, it is effective to use the phase shift induced by the first order magneto-optical effect. Optical isolators and circulators have been demonstrated by employing magneto-optical phase shifters in silicon waveguide Mach-Zehnder interferometers. Phase differences of $-\pi/2$ and $\pi/2$ are provided between two interferometer arms by the magneto-optical effect depending on the light propagation directions. The optical isolator and circulator functions can be achieved by combining the magneto-optical phase shift with direction-independent phase difference of $\pi/2$.

An optical isolation of 30 dB has been achieved in a silicon waveguide optical isolator. An isolation of >20 dB is obtained in a wavelength range of 8 nm. Also, a four-port optical circulator is demonstrated with a maximum isolation of 30 dB. The magneto-optical phase shifter is realized by directly bonding 1.5X1.5 mm2 Ce:YIG dies to silicon wire waveguides in both devices.

8988-12, Session 3

Femtosecond laser processing in magneto-optical glasses

Qiang Liu, Simon Gross, Michael Withford, Michael Steel, Macquarie Univ. (Australia)

Femtosecond laser direct writing (FLDW) is developing rapidly but to date, there is no native optical isolator (needed to mitigate reflections in any optical system) for the platform. As a step towards integrated glass isolators, we have investigated FLDW in kHz and MHz pulse rate regimes to two magneto-optical glasses (TG20 and MR3-2) to ultimately create one-way structures based on the Faraday effect.

Previously, we fabricated basic waveguides obtaining single-mode guidance at 632 nm (the Faraday effect is strongest near the Tb^{3+} resonance at 485 nm) in both regimes. kHz regime waveguides were isotropic but had high propagation loss due to associated photodarkening (which could be post-annealed). The propagation loss of the MHz regime waveguides was acceptable due to lower photodarkening, but the waveguides were too narrow to confine light properly because of the very strong focus of the writing beam.

To try to combine the lower loss with larger waveguide width, we created overlapping structures using a series of superposed waveguides arranged in rings in MHz regime. The confinement in these multi-ring structures was indeed improved and the structure propagation loss was intermediate between that of one-path waveguides created in kHz and MHz regimes. For most other glasses, MHz FLDW systems operate in a heat-accumulation regime, producing waveguide diameters much larger than the writing laser spot size and superposed waveguides that merge into one by melting. Here, the sub-unit waveguides maintained their individual identity indicating that the heat-accumulation effect was absent. The annealed simple waveguides may be ultimately preferred.

8988-13, Session 3

Experimental demonstration of anomalous nonreciprocal optical response of 1D periodic magnetoplasmonic nanostructures

Lukas Halagacka, Technical Univ. of Ostrava (Czech Republic) and Institut d'Électronique Fondamentale (France); Mathias Vanwolleghem, Francois Vaurette, Institut d'Électronique Fondamentale (France); Jamal Ben-Youssef, Univ. de Bretagne Occidentale (France); Philippe Gogol, Navy Yam, Institut d'Électronique Fondamentale (France); Kamil Postava, Technical Univ. of Ostrava (Czech Republic); Beatrice Dagens, Institut d'Électronique Fondamentale (France); Jaromír Pi?tora, Technical Univ. of Ostrava (Czech Republic)

In this paper we analyze the optical and transversal magnetooptical (MO) response of a magnetoplasmonic (MP) nanostructure. The MP structure is a 1D periodic gold grating fabricated by lift-off technique on a MO dielectric substrate (Bi-substituted yttrium iron garnet $Bi_xY_{3-x}Fe_5O_{12}$). An enhanced MO activity of the structure is observed. Its origin is related to the the excitation of spectrally sharp surface plasmon polariton (SPP) resonances and their nonreciprocal shift by the transverse MO effect at the grating/garnet interface [1,2]. Following our recent theoretical work [3,4], we confirm here experimentally the predicted dependence of the MO response on the geometry of the grating, that is directly attributed to an anticrossing behaviour of a Fabry-Perot resonance in the grating's slits and the SPP resonances at its interfaces. Measuring the dispersion of the resonances by varying the incidence angle of the spectroscopic magnetooptical ellipsometer, has allowed us to determine precisely the operation point to observe this anticrossing. In this way we demonstrate that at optimal angle of incidence the sign of the transverse MO effect can be switched by the geometry of the grating without change of the orientation of the external magnetic field. The observed transverse magneto-optic Kerr amplitude of the order of 50% for near infrared frequencies (around 1eV) strongly outperforms what can be obtained on uniform ferromagnetic metallic films. Moreover, the sign change of TMOKE without switching the magnetization opens up new possibilities for the design of compact nonreciprocal devices.

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8988-14, Session 3

Efficient magneto-optical mode converter on glass

Jean Philippe Garayt, Univ. Jean Monnet Saint-Etienne (France); François Parsy, IMEP-LAHC (France); Damien Jamon, Univ. Jean Monnet Saint-Etienne (France); Sophie Neveu, Univ. Pierre et Marie Curie (France); François Royer, Univ. Jean Monnet Saint-Etienne (France); Elise Ghibaudo, Jean-Emmanuel Broquin, IMEP-LAHC (France)

The integration of magneto-optical materials to realize non-reciprocal functions is still a difficult problem, because classical magneto-optical materials require an annealing temperature as high as 700°C. In this framework, this study shows how it is possible to realize efficient magneto-optical mode converter using the association of a magnetic nanoparticles silica/zirconia composite with an ion exchanged glass waveguide.

Using a sol gel process, a silica/zirconia matrix is doped by magnetic nanoparticles ($CoFe_2O_4$) and coated on a glass substrate containing straight channel waveguides made by a silver/sodium ion exchange. The extremities of the guides were previously buried using field-assisted burial in order to facilitate light injection. Soft annealing (90°C) and UV treatment, both compatible with the ion exchange process, have been implemented to finalize the magneto-optical film.

Depending on the amount of nanoparticles in the composite, on the spatial distribution of the field in the guide and on the modal birefringence of the hybrid structure, the TE-TM conversion varies from several degrees to several tens of degrees. It can even reach the 45° required for the realization of an optical isolator, with a 100 nm bandwidth around 1550 nm.

These results fit well with the behavior of a polarization splitter recently realized on glass [1], and are promising in view of the realization of an integrated optical isolator on glass.

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8988-15, Session 4

Polarization-insensitive silicon immersion grating for telecom applications *(Invited Paper)*

Yuichi Higuchi, Yuzo Ishii, Koichi Hadama, Joji Yamaguchi, Tsuyoshi Yamamoto, Nippon Telegraph and Telephone Corp. (Japan)

In optical devices, including optical channel monitors and wavelength selective switches for telecommunications networks based on wavelength-division-multiplexing, the dispersion element is a key component for multiplexing and demultiplexing the signal for each wavelength channel.

A high-dispersion element is necessary for downsizing the devices, and an arrayed waveguide grating based on the planar devices structure is a solid solution. However, a grating is used in free-space optics so that the requirement for multiple ports or functional integration in some telecommunications devices can be met. A silicon immersion grating (IG) is attracting much attention as a high-dispersion grating for free-space optics.

In this paper, we propose a new silicon IG structure based on TIR to achieve both low polarization-dependent loss (PDL) and high diffraction efficiency.

Our IG consists of a silicon prism and a silicon grating coated with dielectric film. We analyze the effect of the refractive index of dielectric film on PDL and clarify the optimal refractive index ratio between a silicon grating and dielectric film. Selecting an adequate material for the dielectric film, we design the diffraction efficiency of TM polarization without changing that of TE polarization. The simulation results for the optimized IG show a PDL of 0.2 dB and diffraction efficiency of -0.4 dB. A prototype with high dispersion power provides a low PDL of 0.6 dB while maintaining a high diffraction efficiency of -0.4 dB in the C band. The differences between the measured and the designed PDL are due to error in the depth of the grating. By optimizing the etching condition, the PDL can be reduced.

8988-16, Session 4

Photonic integrated spectrometer-on-chip based on digital planar holograms

Giuseppe Calafiore, abeam Technologies, Inc. (United States); Alexander Koshelevc, Nano-Optic Devices (United States); Scott Dhuey, Lawrence Berkeley National Lab. (United States); Alxander Goltsov, Pavel Sasorov, Nano-Optic Devices (United States); Sergey Babin, abeam Technologies, Inc. (United States); Stefano Cabrini, The Molecular Foundry (United States); Vladimir Yankov, Nano-Optic Devices (United States); Christophe Peroz, abeam Technologies, Inc. (United States)

Computer-generated planar holograms offer a powerful alternative to control and manipulate the light onto planar lightwave circuits. In particular, digital planar holograms (DPH) represent a unique approach to encode almost any specific optical transfer function manipulating the light in the spectral and spatial domain with high flexibility [1]. Holographic elements are made of digitalized gratings that separate the spectral components of an incoming light beam and reflect them to a variety of different focal points corresponding to output channels. We have recently reported the fabrication of miniaturized spectrometer on chip based on planar hologram working in 160 nm bandwidth, with 1084 channels, a spectral channel spacing of 0.015 nm [2] and working in multiple customized bandwidths [3]. We extend here these results and demonstrate for the first time the monolithic integration of DPH elements connected with a full optical circuitry. The light propagates into ridge waveguides (RWG) and is efficiently separated and directed by a light splitter (directional coupler) to the input of each hologram (Fig. 1). Each DPH works in one specific spectral bandwidth and the light is reflected to the output plane. Nano-spectrometers are fabricated by electron beam lithography for prototyping and can be mass-produced at low cost by nanoimprint lithography. This work defines the state of the art for spectrometer on chip and demonstrates the high potential of our approach for developing a novel class of ultra-compact and low cost spectrometer for numerous applications.

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8988-17, Session 4

Extraordinary capabilities of optical devices incorporating guided-mode resonance gratings

Robert Magnusson, The Univ. of Texas at Arlington (United States)

Guided-mode resonance (GMR) effects arise via quasi-guided, or leaky, waveguide modes induced on patterned films with subwavelength periods. Materials including dielectrics, semiconductors, and metals can be used to build GMR elements patterned in one or two dimensions. These nanopatterned resonant elements yield versatile spectra with a rich variety of possible surface-localized photonic states. On account of advances in design and fabrication, new aspects, attributes, and application possibilities continue to appear. The parametric design space allows control of light amplitude, phase, polarization, near-field intensity, and light distribution on surfaces and within the device volume. The desired spectra are available in either transmission or reflection mode. For example, a simple resonance layer with one-dimensional periodicity enables narrow-line bandpass and bandstop filters, polarizers operating at normal incidence, wideband reflectors, and polarization-independent filters. Applications such as laser mirrors, ultrasensitive biosensors, solar-cell absorption enhancement, tunable filters, narrow-band nanoelectromechanical display pixels, nonlinear conversion, surface-enhanced Raman spectroscopy, slow-light control, and leaky-mode nanoplasmonics have been suggested. We summarize past accomplishments in this field and provide new and emerging aspects. These include new devices enabled by GMRs coexisting with the Rayleigh anomaly where, in one case, the Rayleigh anomaly provides wideband reflectors with extraordinarily sharp angular cutoff, and in the other, it yields effective transmission filters. Efficient omnidirectional absorbers and reflectors are shown to be possible. Ultracompact biosensors with multiparametric detection capability via polarization and modal diversity are explained and their application in biomedical systems presented. For each device type, we present both computed and experimental results.

8988-18, Session 4

Metamaterial Lüneburg lens for Fourier optics on-a-chip

Hamdam Nikkhah, Trevor J. Hall, Univ. of Ottawa (Canada)

A planar metamaterial Lüneburg lens that enables Fourier optics on-a-chip can be implemented in an SOI slab waveguide structure by patterning the silicon core with variable sized holes. The subwavelength patterning of binary nanocomposite material to form the metamaterial offers the major advantage of fabrication by a single etch step while demanding feature sizes that can be accessed by deep UV lithography in addition to e-beam lithography. A numerical calibration procedure has been described that is used to find the relation between fill factor and local homogenised effective refractive index which improves upon the predictions of analytic effective media theory used by other researchers. The concept and designs were verified by the 2D FDTD simulation of a two lens telescope system with waveguide feeds implemented in a metamaterial that shown a low insertion loss of -0.45 dB with a reliable field profile at exit. A 3D FDTD simulation of the same two lens telescope system that takes full account of the SOI layers, their finite thickness, and the ridge waveguide feeds also predicts a low loss of -0.83 dB. Less reliance however can be placed on this result due to the coarseness of

the computational grid that was necessary. Nevertheless both results are encouraging for planned fabrication trials. This structure can be used in optical transpose interconnection systems in optical switching architectures with the advantage of avoiding large number crossover waveguides in optical communication systems.

8988-19, Session 4

Numerical simulation of grating couplers for mode multiplexed systems

Benjamin Wohlfeil, Technische Univ. Berlin (Germany); Sven Burger, JCMwave GmbH (Germany); Christos Stamatiadis, Technische Univ. Berlin (Germany); Jan Pomplun, JCMwave GmbH (Germany); Frank Schmidt, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Lars Zimmermann, IHP GmbH (Germany); Klaus Petermann, Technische Univ. Berlin (Germany)

Due to the approaching capacity crunch in fiber optical communication systems spatial division multiplexing (SDM) has become a very active research field. Silicon photonics can provide solutions to generating, receiving and processing SDM signals. We present numerical investigations of a photonic integrated grating coupler for the excitation and detection of four LP fiber modes in both TE and TM polarization [1]. A high numerical accuracy is needed for optimizing the functionality of the device. We utilize a fully vectorial 3D Finite Element Method (FEM) for simulation of the grating coupler.

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8988-20, Session 5

Silicon-based packaged products and solutions *(Invited Paper)*

Yves Painchaud, Michel Poulin, Martin Pelletier, François Pelletier, Carl Paquet, Michel Cyr, Martin Guy, TeraXion Inc. (Canada); Christine Latrasse, Jean-Frédéric Gagné, Simon Savard, Guillaumne Robidoux, Marie-Josée Picard, Stéphane Paquet, Charles-André Davidson, TeraXion Inc (Canada); Mohamed Morsy-Osman, Mathieu Chagnon, David V Plant, Dept. Electrical Eng., McGill University (Canada)

TeraXion started silicon photonics activities aiming at developing new products and customized solutions. As a first product, a compact packaged coherent receiver based on silicon photonics has been developed. Optical characterization shows good optical performance including a quadrature error of less than 2 degrees and a common mode rejection ratio lower than -20 dB. System tests show error-free transmission up to 4800 km assuming forward error correction is used. We show that the package size is limited by the electrical interface. Migrating to more compact RF interface would allow to take the full benefit of this technology. Integration of high responsivity photodetectors represents a possible next step. We have obtained a responsivity better than 0.95 A/W up to 1568 nm while maintaining a 3dB bandwidth better than 20 GHz. Several customized solutions for specific applications have also been developed including an integrated circuit for optical phase-locked loop, a packaged modulator demonstrator and a laser-chip coupling assembly. Finally, we discuss the potential of phase-shifted integrated Bragg filters for laser frequency locking. These filters show a transmission notch having a width lower than 500 MHz thus allowing for precise frequency discrimination.

8988-21, Session 5

Photonic integration in indium-phosphide membranes on silicon (IMOS) *(Invited Paper)*

Huub P.M. M. Ambrosius, Jos J.G. M. van der Tol, Josselin Pello, Rui Zhang, Shrivatsa P. Bhat, Gunther Roelkens, Meint K. Smit, Technische Univ. Eindhoven (Netherlands)

Abstract: A new photonic integration technique is presented, which enables the use of indium phosphide based membranes on top of silicon chips. This can provide the electronic chips (CMOS) with an added optical layer (IMOS) for resolving the communication bottleneck. Very small passive devices have been realized, with performances comparable to other membrane devices (propagation loss 7 dB/cm, negligible bending loss for micron size radii, 3 dB splitter with 0.6 dB excess loss, resonator with Q-factor of 15.500). Also a new passive device is demonstrated, a <10 micron long polarization converter which shows broadband performance and tolerant fabrication. Furthermore, several active/passive integration techniques are investigated for realizing lasers within an otherwise passive membrane. For a technique based on regrowth a good morphology is obtained around the interfaces between the active and passive regions. The processing induced damage to the materials could be controlled, so that light emission in micro-PL measurements was found. However, an increasing blue shift with decreasing size occurred, due to quantum well intermixing. Optimizing the design and the processing can take care of this. A second active passive integration technique is based on polarization manipulation, and initial results show clear emission from cavities here, although the laser threshold has not yet been reached. Finally a technique base on twin guide structures is under development. Taken together, the results presented here show that it is feasible to realize extremely small passive and active devices in a photonic circuit in an InP membrane.

8988-22, Session 5

Hybrid photonic chip interferometer for embedded metrology

Prashant Kumar, Haydn Martin, Univ. of Huddersfield (United Kingdom); Graeme Maxwell, CIP Technologies (United Kingdom); Xiangqian Jiang, Univ. of Huddersfield (United Kingdom)

Embedded metrology is the provision of metrology on the manufacturing platform, enabling measurement without the removal of the workpiece. Providing closer integration of metrology upon the manufacturing platform can lead to the better control and increased throughput. In this work we present the development of a high precision hybrid optical chip interferometer metrology device. The complete metrology sensor system is structured into two parts; optical chip and optical probe. The hybrid optical chip interferometer is based on a silica-on-silicon etched integrated-optic motherboard containing waveguide structures and evanescent couplers. Upon the motherboard, electro-optic components such as photodiodes and a semiconductor gain block are mounted and bonded to provide the required functionality. The key structure in the device is a tuneable laser module based upon an external-cavity diode laser (ECDL). Within the cavity is a multi-layer thin film filter which is rotated to select the longitudinal mode at which the laser operates. An optical probe, which uses a blazed diffracting grating and collimating objective lens, focuses light of different wavelengths laterally over the measurand. Incident laser light is then tuned in wavelength time to effectively sweep an 'optical stylus' over the surface. Wavelength scanning and rapid phase shifting can then retrieve the path length change and thus the surface height. We give an overview of the overall design of the final hybrid photonic chip interferometer, constituent components, device integration and packaging as well as experimental test results from the current version now under evaluation.

8988-23, Session 5

Introducing photonic devices for wavelength division multiplexing transceivers on 300-mm SOI wafers using CMOS processes

Charles Baudot, STMicroelectronics (France); Jean-Marc Fédéli, CEA-LETI (France); Delphine Marris-Morini, Institut d'Électronique Fondamentale (France); Gilles Grand, CEA-LETI (France); Boris Caire-Remonnay, STMicroelectronics (France); Sylvie Menezo, CEA-LETI (France); Laurent Vivien, Institut d'Électronique Fondamentale (France); Frédéric Boeuf, STMicroelectronics (France); Ian O'Connor, Ecole Centrale de Lyon (France)

We introduce a device library aimed at producing opto-electrical transceivers. The device performances are targeted to address data transmissions of 25 Gbps per channel and above. The library includes silicon modulators, integrated germanium photo-detectors and silicon passive structures. Various solutions are also explored to support the design of wavelength division multiplexing (WDM) transceivers. The devices are fabricated on 300mm Silicon On Insulator (SOI) wafers using CMOS compatible processes. We demonstrate that the tools and methods used to fabricate the devices are well-suited for high-volume production of silicon photonic WDM transceivers in a CMOS wafer foundry.

8988-24, Session 6

Mid-Infrared AWG based on new low loss silicon/germanium waveguides *(Invited Paper)*

Pierre R. Labeye, Mickael Brun, Pierre Barritault, CEA-LETI-Minatec (France); Fahem Boulila, Mathieu Carras, III-V Lab. (France); Sergio Nicoletti, CEA-LETI-Minatec (France)

With the recent progress in integrated silicon photonics technology and the recent development of efficient quantum cascade laser technology (QCL), there is now a very good opportunity to investigate new gas sensors offering both very high sensitivity, high selectivity (multi-gas sensing, atmosphere analysis) and low cost thanks to the integration on planar substrate. In this context, we currently develop singlemode optical waveguides in the mid-infrared based on Silicon/Germanium alloy integrated on silicon. These waveguides, compatible with standard microelectronic technologies present very low loss in the [3300 – 1300 cm-1] range.

This paper will present the design, technological realization, and characterization of array waveguide grating devices specifically developed for the simultaneous detection of CO, CO2 and N2O using a single array of QCL sources. Gas sensing generally require a tunable source continuously covering the whole operational range of the QCL stack. With this objective, specific design has been adopted to flatten the optical transfer function of the whole multiplexer. In good agreement with the modeling, flat transmission over the full 100 cm-1 operational range around 2235 cm-1 were obtained with a peak-to-valley modulation of -5dB were experimentally measured. These devices will be soon associated with QCL arrays in order to provide integrated, powerful, multi wavelength, laser sources in the 2235 cm-1 region.

8988-25, Session 6

Photonic-integrated circuit on InP for millimeter-wave generation *(Invited Paper)*

Frederic van Dijk, Marco Lamponi, III-V Lab. (France); Mourad Chtioui, Thales Air Systems S.A. (France); François Lelarge, Gaël Kervella, III-V Lab. (France); Cyril C. Renaud, Martyn Fice, Univ. College London (United Kingdom); Guillermo Carpintero del Barrio, Univ. Carlos III de Madrid (Spain)

Indium phosphide and associated epitaxially grown alloys is a material system of choice to make photonic integrated circuits for microwave to terahertz signal generation, processing and detection. Fabrication of laser emitters, high speed electro-optical modulators, passive waveguides and couplers, optical filters and high speed photodetectors is well mastered for discrete devices. But monolithic integration of them while maintaining good performances is a big challenge.

We have demonstrated a fully integrated tunable heterodyne source designed for the generation and modulation of sub-Terahertz signals. This device is to be used for high data-rate wireless transmissions. DFB lasers, SOA amplifiers, passive waveguides, beam combiners, electro-optic modulators and high speed photodetectors have been integrated on the same InP-based platform. Millimeter wave generation at up to 120 GHz based on heterodyning the optical tones from two integrated lasers in an also integrated high bandwidth photodetector has been obtained.

8988-26, Session 6

SiGe-based platform for mid-IR integrated optics

Mickael Brun, Jean-Michel Hartmann, Sophie Ortiz, Pierre R. Labeye, Pierre Barritault, Salim Boutami, CEA-LETI-Minatec (France); Fahem Boulila, Mathieu Carras, III-V Lab. (France); Sergio Nicoletti, CEA-LETI-Minatec (France)

The interest of silicon photonics for integrated optics in data-com applications (i.e. 1.3 – 1.55 µm) is now well established. However, the absorption of the SiO2 cladding layers may limit the usefulness of Si waveguides in the mid IR range. Switching from Si to SiGe is very promising as this alloy is compatible with standard CMOS foundries; it is otherwise transparent over a large portion of the mid IR spectrum and exhibits intrinsic linear and nonlinear properties with improved performances. Furthermore, the optical properties can be tuned by continuously changing the Ge content in the alloy.

Using our 200 mm Si manufacturing facilities we have developed a SiGe/Si mid-IR photonics platform with different waveguides structures to investigate the potential of this material. To cover all applications beyond the usability of std. Si/SiO2 technology, we have investigated 3 kinds of heterostructures: a wide band graded index SiGe/Si stack to cover the whole 3-8 µm range, a step index SiGe/Si stack to cover applications below 3 µm and a step index Ge/SiGe stack to address applications up to 10 µm and beyond. The waveguides fabricated with those technological platforms present low losses spanning from 0.5 dB/cm to 2 dB/cm at ?= 4.5 µm and ?= 7.6 µm respectively.

Details about the devices' (i) fabrication, (ii) test and (iii) the library of basic and complex functions already available within this platform will be presented during the conference.

8988-27, Session 6

ZrO2-TiO2 thin films and resonators for mid-infrared integrated photonics

Feipeng Jiang, University of Electronic Science and Technology of China (China); Ningyuan Duan, Univ. of Electronic Science and Technology of China (China); Hongtao Lin, Lan Li, Univ. of Delaware (United States); Lei Bi, Univ. of Electronic Science and Technology of China (China); Juejun Hu, Univ. of Delaware (United States); Haipeng Lu, Xiaolong Weng, Jianliang Xie, Longjiang Deng, Univ. of Electronic Science and Technology of China (China)

Mid-infrared (MIR, 2-6 um wavelength) transparent metal oxides are attractive materials for planar integrated MIR photonic devices and sensing applications. In this study, we present reactive sputtering deposited ZrO2-TiO2 (ZTO) thin films as a new material candidate for integrated MIR photonics. We demonstrate that amorphous ZTO thin films can be achieved with Ti concentration of 40 at.% on various substrates. With increasing Ti concentration, the optical band gap decreases monotonically from 4.34 eV to 4.11 eV, while the index of refraction increases from 2.14 to 2.24 at 1 um wavelength. MIR micro-disk resonators on MgO substrates are demonstrated using Ge23/Sb7S70/Zr0.6Ti0.4O2 strip-loaded waveguides with a loaded quality factor of ~11,000 at 5.2 um wavelength. By comparing with a reference device of Ge23/Sb7S70 resonator on MgO and simulating the optical confinement factors, the ZTO thin film loss is estimated to be below 10 dB/cm. Single mode shallow ridge waveguides with a ridge height of 200 nm and a slab height of 1.2 um are also demonstrated using ZTO thin films on MgO substrates. The low loss, relatively high index of refraction, superior stability and proven CMOS compatibility of ZTO thin films make them highly attractive for MIR integrated photonics.

8988-28, Session 7

Bloch mode spatial harmonic decomposition in integrated localized surface plasmon chain

Mickael Février, Philippe Gogol, Navy Yam, Robert Megy, Beatrice Dagens, Institut d'Électronique Fondamentale (France)

The electromagnetic excitation of metallic nanoparticles (MNP) has attracted a great interest in the past decade due to the ability of surface plasmons to surpass the diffraction limit of conventional optics [1]. Chains of coupled resonant MNP have been proposed to allow transfer of electromagnetic energy from particle to particle at nanometer scales [2]. We consider here a sub-wavelength period gold nanoparticle chain. With appropriate geometrical parameters, such a chain behaves as a waveguide [3]. We show that spatial harmonics generated in such a sub-wavelength periodic structure can be locally separated or extracted. This is done by playing with the phase matching condition with another adjacent structure, especially another (dielectric) waveguide. The fundamental component can be locally cancelled in the periodic structure, resulting in a non-monotone phase evolution along the structure. Additionally we show that the analysis of the spatial harmonics allows extracting more information on the localized surface plasmon mode generation.

Such properties are of particular interest for periodic dielectric or metallic periodic structure which can be inserted in interferometers, in order to control with more freedom degree or in more compact device the interference state, for example to increase biosensor [4] sensitivity.

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8988-29, Session 7

Ultra-compact and Ultra-broadband TE-pass Polarizer with a Silicon Hybrid Plasmonic Waveguide

Xiaowei Guan, Peipeng Xu, Zhejiang Univ. (China); Xiaowei Guan, Zhejiang University (China); Yaocheng Shi, Daoxin Dai, Zhejiang Univ. (China)

An ultra-compact TE-pass polarizer with an ultra-broad band is proposed theoretically and demonstrated experimentally by utilizing silicon hybrid plasmonic waveguides. For silicon hybrid plasmonic waveguides, the TE-polarized light mainly propagates along the silicon core and is hardly influenced by the metal structure on the top. In contrast, for TM polarization, light is dramatically influenced by the metal structure due to the plasmonic effect. In this paper, the metal layer is designed to have an F-P cavity as well as Bragg grating so that TM-polarized light is reflected efficiently while TE-polarized light goes through with very low loss. The design and simulation of the present TE-pass polarizer is given. By utilizing a Bragg grating metal structure, the TE-pass polarizer is with a size of as compact as 0.5 ? 3.1 ?m2. The present ultra-compact polarizer has a theoretical extinction ratio as high as 15 dB in a broad band of >220 nm and the loss for the passed TE polarization mode is lower than 2 dB over a broad band. The novel ultra-compact and ultra-broadband TE-pass polarizer is realized with a simple fabrication process. The measurement result agrees well with the theoretical prediction.

8988-30, Session 7

Slow-light enhanced nanoscale plasmonic waveguide sensors and switches

Yin Huang, Pouya Dastmalchi, Georgios Veronis, Louisiana State Univ. (United States)

In this paper, we introduce slow-light enhanced nanoscale plasmonic waveguide devices for manipulating light at the nanoscale. In particular, we investigate nanoplasmonic metal-dielectric-metal (MDM) waveguide structures for high-sensitivity sensors and low-power optical switches. Such plasmonic waveguide systems can be engineered to support slow-light modes. We find that, as the slowdown factor increases, the sensitivity of the effective index of the mode to variations of the refractive index of the material filling the structures increases. Such slow-light enhancements of the sensitivity to refractive index variations lead to enhanced performance of active plasmonic devices such as sensors and switches. We first consider Mach-Zehnder interferometer (MZI) sensors in which the sensing arm consists of a slow-light waveguide based on a plasmonic analogue of electromagnetically induced transparency (EIT). We show that a MZI sensor using such a waveguide leads to approximately an order of magnitude enhancement in the refractive index sensitivity, and therefore in the minimum detectable refractive index change, compared to a MZI sensor using a conventional MDM waveguide. We also consider plasmonic switches consisting of a MDM waveguide side-coupled to arrays of MDM stub resonators. The MDM waveguide and stubs are filled with an active material with tunable absorption coefficient. We optimize the geometry of the structures to maximize the modulation depth when the insertion loss is constrained to be less than an acceptable threshold. We find that, when compared to conventional MDM absorption switches, such slow-light enhanced switches achieve significantly higher modulation depth with moderate insertion loss.

8988-31, Session 7

Integrated power divider/combiner at hybrid orthogonal junctions

Mohamed H. El Sherif, Osman S. Ahmed, Mohamed H. Bakr, McMaster Univ. (Canada)

Nano-plasmonic devices have been recently integrated with a silicon nanowire which is utilized to guide light in/out from the optical circuit. Silicon nanowire has limited propagation losses compared to the conventional plasmonic waveguides. Light can propagate relatively long distances on-chip with negligible losses. Light coupling at the silicon nanowire and plasmonic circuit interface is a challenge due to the large resonant reflections introduced. Compact nano-plasmonic devices have been recently proposed for directly coupling to the silicon nanowire with minimal non-idealities.

We propose an integrated power divider/combiner at the interface between silicon nanowire and plasmonic slot waveguide (PSW). The proposed configuration facilitates light access and manipulation in planar nano-plasmonic circuits. The light is incident from a standard silicon nanowire to be accessed by a nano-plasmonic circuit providing subwavelength confinement. The structure overcomes the losses associated with long distance light propagation in nano-plasmonic splitters as coupling and splitting are performed at the same interface with minimal losses. Two PSWs placed orthogonally to the silicon nanowire, forming hybrid junctions, are exploited for the power division/combining functionality. The power splitter has been analyzed using the finite difference time domain (FDTD) numerical method. The ultra-compact proposed device provides wide-band power splitting functionality. A splitting of 34%, over most of the wavelength spectrum from 0.8 µm – 2.5 µm, is demonstrated.

8988-32, Session 7

Optically-readable plasmonic resistive random-access memory integrated with an SOI waveguide

Alexandros Emboras, The Hebrew Univ. of Jerusalem (Israel)

Resistive random access memory (RRAM) devices are simple metal-insulator-metal (MIM) structures with at least two resistive states: low and high. These devices can offer both outstanding performances (i.e. low switching electrical power, endurance, retention and high speed) and easy CMOS integration (simple materials and structure). To that respect, they are considered as a potential candidate for the next generation non-volatile memories. Here, we propose and demonstrate a new concept in which the resistance changes of the RRAM device can be monitored optically. This approach is expected to improve the speed processing and the power consumption as compared to the electronic methods, since no electrical parasitic effects (e.g. resistance loss) are involved.

The scope of this work is to integrate an optical RRAM device with an SOI waveguide. The investigated device rely on the variations in absorption of the fundamental plasmonic mode supported in the RRAM switching stack, caused by voltage induce changes of the insulator resistivity. Fabrication of our device is based on CMOS compatible approach of local-oxidation of silicon, which enables the realization of RRAM and low optical loss channel photonic waveguide at the same fabrication step. The RRAM consists of a Ag/a-Si/Si with an active area of 0.350 x 2 µm2.

Electro-optical characterization of the device is ongoing. We show reproducible nanoscale electrical resistance switching behaviour with switching current and voltage of 1nA and 4 V respectively. Finally, we demonstrate an optical hysteresis with an off/on optical transmission ratio of few percent.

8988-33, Session 7

Submicron-integrated plasmonic power splitter

Mohamed A. Swillam, Marina Ayad, The American Univ. in Cairo (Egypt)

Using plasmonic waveguide for interconnects application is very promising direction to achieve high density integration a good size compatibility with electronic devices. Thus, proposing compact and efficient functional plasmonic devices is or prime essential to achieve the required system functionalities. Power splitters are widely used as one of the important component of the optical interconnects and integrated photonic and plasmonics devices. We propose a simple, ultra compact and wideband balanced power divider. The advantage of this device is compactness and ability to split the power over wideband with negligible imbalance. The device is based on plasmonic slot waveguide configuration and has submicron total foot print. To achieve the proposed optimized design, a simple and novel analytical model is utilized for modelling the behavior or any plasmonic structure using circuit model.

8988-34, Session 8

Application of atomic layer deposition in nanophotonics *(Invited Paper)*

Seppo Honkanen, Univ. of Eastern Finland (Finland)

We review our recent results on using Atomic Layer Deposition (ALD) in fabrication of nanophotonic devices. ALD is a unique thin film deposition method providing several unparalleled advantages: atomic level control of film composition and thickness, perfect step coverage, and large-area uniformity. We employ the advantages of ALD in connection with Si-nanophotonics and with replicated polymer based resonance waveguide gratings.

Si-nanowaveguides are gaining significant importance and they are expected to play a crucial role in the new generation of photonic devices. The functionality of silicon nanophotonic devices can be dramatically increased by taking advantage of thin film materials that have superior optical properties compared to silicon. For example, integration of silicon nanowaveguides with materials featuring very large third-order nonlinearity would be attractive. In our research we investigate the use of thin films grown by ALD in nonlinear silicon nanophotonics. Here we present several new structures based on filling the so-called slotted Si-nanowaveguides with ALD-grown materials.

We also present our recent results on polymer based Guided-Mode Resonance Filters (GMRFs). In our approach the GMRFs are fabricated by combining replicated polymer materials and ALD-grown thin films. GMRFs are diffraction gratings with spectrally narrow reflectance peaks due to resonance anomalies. A unique feature in our replicated gratings is the use of ALD in producing uniform and conformal high-index films on the corrugated grating structures. Our approach of combining replication techniques with ALD can lead to low-cost and sensitive sensor devices, e.g., for medical diagnostics.

8988-35, Session 8

Integrated lithium niobate photonic crystals *(Invited Paper)*

Nadège Courjal, Clément Guyot, Gwenn Ulliac, Arnaud Gerthoffer, Fabien Henrot, Wentao Qiu, Jean-Yves Rauch, Maria-Pilar Bernal, Fadi I. Baida, FEMTO-ST (France); Sylvain Ballandras, Frequency Components and Systems (France)

The development of all-optical, acousto-optical or electro-optical photonic crystals (PhCs) represents a stimulating challenge for the production of advanced functionalities in compact optical devices. LiNbO3 appears as an excellent candidate for such realizations, due to its well-known nonlinear, piezoelectric and electro-optic properties. Two main challenges need however to be overcome before LiNbO3 PhCs can be integrated in photonic circuits. The first one is related to the weak confinement of light in LiNbO3 waveguides: the maximum index change produced by standard techniques is quite small (<0.01), resulting in a broadly distributed optical mode. Thin films of LiNbO3 enabling tight light confinement are now available, but they involve high integration losses and difficult-to-implement technologies. Secondly, the production of high aspect ratio LiNbO3 PhCs is severely hindered by the LiF re-deposition occurring during the dry etching processes.

We present easy-to-implement technologies to produce high aspect ratio LiNbO3 PhCs in confined optical waveguides. Ti-indiffusion is combined with optical grade dicing to fabricate confined ridge waveguides with low propagation losses (<1 dB/cm). Additional solutions are provided to minimize coupling losses with standard fibers. LiNbO3 PhCs with extremely high aspect ratio (>15) are also demonstrated. This is achieved by properly tilting the ridge before patterning its walls by Focused Ion Beam (FIB). Finally, we show how optical coherence tomography can be exploited to fully characterize the waveguides and nanostructures. These developments open the way to the dense integration of compact optical devices such as modulators, spectral filters or electric field sensors.

8988-36, Session 8

Chemical inertness of UV-cured optical elastomers within the printed circuit board manufacturing process for embedded waveguide applications

Kevin L. Kruse, Karl A. Walczak, Michigan Technological Univ. (United States); Nicholas Thomas, Calumet Electronics Corp. (United States); Brandon W. Swatowski, Michigan Technological Univ. (United States); Casey D. Demars, Calumet Electronics Corp. (United States); Christopher T. Middlebrook, Michigan Technological Univ. (United States)

Embedding polymer optical waveguides into Printed Circuit Boards (PCBs) for intra-board or board-to-board high speed data communications require polymer materials that are compatible and inert when exposed to the common PCB manufacturing processes. This is done not only to ensure that waveguide functionality doesn't degrade after chemical exposure, but to make sure that the PCB manufacturing integrities and standards are not corrupted by the introduction of polymers into the production process. The PCB manufacturing flow is laid out to expose major requirements that would be required for the successful implementation of polymer materials for embedded waveguide development. Chemical testing and analysis were performed on Dow Corning© UV-Cured Optical Elastomers designed for low loss embedded optical waveguides. Two main types of testing were conducted to show polymer compatibility in both monomer and polymer form. Various chemical baths treated with raw polymer material were tested for effective contamination. Fully polymerized multimode waveguides were fabricated and exposed to PCB chemicals at temperatures and durations comparable to PCB manufacturing conditions. Chemical analysis shows that the chosen polymer is compatible and inert with standard PCB manufacturing processes.

8988-37, Session 8

Observation of Raman scattering in glass integrated waveguides: a route towards supercontinuum generation

Fabien Geoffray, Lionel Bastard, Jean-Emmanuel Broquin, Grégory Grosa, IMEP-LAHC (France)

Integrated optics allows realizing a great variety of optical components from sensors to light sources. Especially, laser sources, from continuous wave DFB lasers to Q-switched pulsed laser, are made by glass integrated optics. Actually, the development of pulsed lasers allowed increasing the power density into the integrated waveguides to a level compatible with the generation of nonlinear phenomena. Indeed nonlinear mechanisms such as Raman scattering, four-wave mixing or self-phase modulation can now be obtained in integrated waveguide opening the route to the realization of integrated supercontinuum sources.

In this paper we investigate the nonlinear response of integrated waveguides made by ion-exchange in glass. In particular we study the Raman scattering processes in normal dispersion regime with nanosecond pumping, which is recognized as an essential mechanism of spectral broadening towards supercontinuum generation. The design and characterization of integrated waveguides in order to achieve a high power density without reaching the damage threshold of the glass is first presented. The focus is put on the trade-off between the effective mode area, its loss and the coupling efficiency. In a second part our work focuses on the observation and modeling of the Raman response of these waveguides through spontaneous Raman scattering, line broadening and stimulated effects measurements. We also put in evidence the stimulated Raman scattering and measure the Raman gain. Finally, the obtained experimental results are compared to the numerical simulations and perspectives of this work in terms of integrated broadband sources are presented.

8988-38, Session 8

Precision dicing of optical materials

Lewis G. Carpenter, Christopher H. Holmes, Peter A. Cooper, James C. Gates, Peter G. R. Smith, Univ. of Southampton (United Kingdom)

Physical micromachining of optical materials via precision dicing, where blades with diamond grit remove material, has been recently shown to be a promising technology in the machining of optical materials. Many useful optical materials when machined with conventional etchants achieve results that can have poor form and high surface roughness, especially in crystalline materials such as YAG, sapphire and lithium niobate.

Dicing has been recently used to produces ridge waveguides in lithium niobate and Nd:YAG to enhance nonlinearity and produce waveguide lasers. However, most of these publications only provide qualitative description of the surfaces generated after dicing, via either SEM or microscope images. In order to understand the effects of dicing and to interpret the machining results in a comparable manor, quantitative analysis is needed.

Within this work quantitative surface metrology has been used, enabling the optimization of the dicing procedure, allowing the machinability of optical materials to be examined. The authors have already demonstrated that precision dicing, in a ductile regime of material removal, can achieve structures in silica that are highly vertical (<0.2° from vertical), with average surface roughnesses of 4.9 nm (Sa) and with depths of cut of ~60 ?m in a single pass.

Other optical materials to be investigated include germanium, YAG, lithium niobate and silicon. The authors will present quantitative surface metrology on a variety of diced optical materials. These optimized dicing produces will then be used to make an optical device, such as waveguides, to interrogate losses caused by surface roughness.

8988-39, Session 8

Ion beam irradiated optical channel waveguides

István Bányász, Wigner Research Ctr. for Physics of the H.A.S. (Hungary); Miklós Fried, Zsolt Zolnai, István Rajta, Research Institute for Technical Physics and Materials Science (Hungary); Gyula Nagy, Hungarian Academy of Sciences (Hungary); Vladimír Havránek, Nuclear Physics Institute of the ASCR, v.v.i. (Czech Republic); Miklós Veres, László Himics, Wigner Research Ctr. for Physics of the H.A.S. (Hungary); Simone Berneschi, Stefano Pelli, Gualtiero Nunzi Conti, Giancarlo C. Righini, Istituto di Fisica Applicata Nello Carrara (Italy)

Active and passive optical waveguides are fundamental elements in modern telecommunications systems. A great number of optical crystals and glasses were identified and are used as good optoelectronic materials. However, fabrication of waveguides in some of those materials remains still a challenging task due to their susceptibility to mechanical or chemical damages during processing. Researches were initiated on ion beam fabrication of optical waveguides in tellurite glasses.

Channel waveguides were written in Er:TeO2-WO2 glass through a special silicon mask using 1.5 MeV N+ irradiation [1]. This method was improved by increasing N+ energy to 3.5 MeV to achieve confinement at the 1550 nm wavelength, too. An alternative method, direct writing of the channel waveguides in the tellurite glass using focussed beams of 7 – 12 MeV C3+ and C5+ and 6 MeV N2+, has also been developed. Channel waveguides were fabricated in undoped eulytine (Bi4Ge3O12) and sillenite type (Bi12GeO20) bismuth germanate crystals using both a special silicon mask and a thick SU8 photoresist mask and 3.5 MeV N+ irradiation. The waveguides were studied by phase contrast and interference microscopy and micro Raman spectroscopy. Guiding properties were checked by the end fire method. Losses of channel waveguides written in Er:tellurite glasses were reduced by moderate thermal annealing (up to 260 Cº)

[1] S. Berneschi, G. Nunzi Conti, I. Bányász, A. Watterich, N. Q. Khanh, M. Fried, F. Pászti, M. Brenci, S. Pelli, G. C. Righini “Ion beam irradiated channel waveguides in Er3+-doped tellurite glass”, Applied Physics Letters, 90, 121136, (2007)

8988-40, Session 9

Integrated optofluidics for on-chip biological sample preparation and analysis *(Invited Paper)*

Hong Cai, Joshua W. Parks, Univ. of California, Santa Cruz (United States); Tomas Wall, Brigham Young Univ. (United States); Kaelyn D. Leake, Tomas Yuzvinsky, Univ. of California, Santa Cruz (United States); Jungkyu Kim, Texas Tech Univ. (United States); Ricardo Carrion Jr., Jean L. Patterson, Texas Biomedical Research Institute (United States); Richard A. Mathies, Univ. of California, Berkeley (United States); Aaron R. Hawkins, Brigham Young Univ. (United States); Holger Schmidt, Univ. of California, Santa Cruz (United States)

Optofluidic devices based on liquid-core ARROW waveguides have been shown to provide single molecule and single bioparticle fluorescence detection sensitivity using a fully planar, waveguide-based silicon chip and fiber-optic readout. Here, we describe the vertical integration of this optofluidic detection layer with a variety of microfluidic layers for adding sample preparation steps to form a single analysis system. We will present both passive and actively controlled microfluidic layers, implementation of essential sample preparation functions, and subsequent optical analysis of single micro- and nanoparticles on the optofluidic chip. Applications to detection of infectious disease and cancer biomarkers will be discussed.

8988-41, Session 9

Optofluidic hybrid platform with integrated solid core waveguides

Romeo Bernini, Genni Testa, Gianluca Persichetti, Istituto per il Rilevamento Elettromagnetico dell’Ambiente (Italy); Pasqualina M Sarro, DIMES-ECTM TUDelft (Netherlands)

This paper reports an optofluidic hybrid platform based on hybrid liquid core ARROW waveguides. Multimodal liquid core hybrid PDMS-silicon ARROW (h-ARROW) was used for sample flowing and solid core hybrid PDMS-ARROW (solid h-ARROW) was integrated in a self-aligned optical configuration with the ARROW optofluidic channel. In comparison to full silicon ARROW, in a h-ARROW the top silicon part is replaced by a single layer of PDMS. The platform is composed by a modular structure with different functionalities on the same chip, toward a fully integrated optofluidic device. The microfluidic system was completely realised with PDMS using a layered structure while the optical part was realized developing a hybrid silicon/PDMS solution. The combination of different materials and fabrication processes permits to take the advantages of the high optical quality achievable using silicon processes and of the low cost and simplified fabrication stages involved in the polymer processing. The coupling of light from off-chip optical fiber with the optofluidic channel is obtained through self-aligned solid core h-ARROWs integrated in the platform. Solid h-ARROW differ from h-ARROW only of core material, which is fabricated with higher refractive index PDMS. Optofluidic channel dimension was chosen in order to allow an easy insertion of standard optical fiber. Thanks to this configuration, an automatic optical alignment is assured between the h-ARROW waveguides, the solid h-ARROW and the off-chip collecting optical fibers. The sensing performance of the proposed device was tested by performing fluorescence measurements on liquid sample flowing in the ARROW optofluidic channel.

8988-42, Session 9

Graphene functionalized leaky cavity mode biosensor based on silicon nanowire array

Qiushi Guo, Hai Zhu, Univ. of Pennsylvania (United States); Feng Liu, Shanghai Normal Univ. (China); Alexander Y. Zhu, Jason C. Reed, Fei Yi, Ertugrul Cubukcu, Univ. of Pennsylvania (United States)

Subwavelength high-index dielectric structures are able to support highly localized and geometrically tunable strong optical resonances. These resonances can be manipulated to dramatically improve light concentration, and in turn, enable a myriad of exciting chip-scale photonic elements. Here, we report that the leaky cavity mode resonance (LCMR) excited in periodic silicon nanowire (SiNW) arrays can be utilized to serve as a novel paradigm for low cost, label-free and highly sensitive biosensing. The resonances, ranging from 500 to 900 nm, possess a narrow bandwidth with a transverse electromagnetic field that extends deeply into the surrounding medium. The devices exhibit bulk refractive index sensitivities up to 222 nm/RIU. Moreover, we demonstrate that the silicon nanostructures can be functionalized with a graphene monolayer by taking advantage of graphene’s ability to adsorb biomolecules. This sensing platform has far-reaching implications for unraveling protein-protein interactions and offers unique opportunities for low cost point-of-care diagnostics on a single silicon photonic chip.

8988-43, Session 9

Sensitivity of Mach-Zehnder interferometer for dissolved gas monitoring

Susan Lindecrantz, Univ. of Tromsø (Norway); Firehun T. Dullo, Northern Research Institute, Tromsø (Norway); Balpreet S. Ahluwalia, Olav G. Hellesø, Univ. of Tromsø (Norway)

An integrated optical sensor is developed for measuring gas concentration for subsea and atmospheric application. The optical sensor is based on waveguide Mach-Zehnder interferometer (MZI). In MZI, the light is spilt into a sensing and a reference arm, and after a certain distance the branches are recombined. The sensing branch is covered with a sensitive doped layer that has high affinity towards a specific gas. The presence of the gas brings a change in the refractive index on the sensing arm, which is translated into a change in the output signal. With a prior calibration the change in the output signal is correlated to the gas concentration. The waveguide should be single mode and it is desirable to have high intensity in the evanescent field. The light can be tightly confined inside the waveguide using a high refractive index material and by using thin waveguides, the intensity of the evanescent field can be enhanced. Simulations are performed to obtain waveguide parameters with low losses and high sensitivity. It was found that the sensitivity depends on the core height of the waveguide

and on the input polarization. The maximum sensitivity at wavelength 785 nm was obtained for a waveguide of core thickness 150 nm and 5 nm rib height and 1 µm width with TM polarization. Two designs of the MZI are studied, normal and the tapered MZI.

Results of the simulation for optimal waveguide parameters for high sensitivity, single-mode behavior and the first experimental measurements will be demonstrated.

8988-44, Session 10

Design and simulation of a semiconductor chip-based visible NIR spectrometer for Earth observation

Joanna Coote, ZiNIR Ltd. (United Kingdom); Emma R. Woolliams, Nigel Fox, National Physical Lab. (United Kingdom); Ian D. Goodyer, Stephen J. Sweeney, ZiNIR Ltd. (United Kingdom)

We are developing a new semiconductor chip-based visible-NIR spectrometer chip for Earth observation applications. Spectroscopic measurements of sunlight reflected from the Earth allow remote diagnosis of bio/geophysical parameters e.g. land use, pollution, mineral exploration, carbon cycle etc. The spectrometer chip offers the potential both for deployment in space, and for small, low cost, high performance sensors being widely (geographically) distributed in deserts, oceans and forests, enabling ground based calibration and validation.

The chip features a series of high-Q microdisk resonators evanescently coupled to a central waveguide. Each resonator resonates at a different wavelength, so selects-out a part of the incoming spectrum. The semiconductor layers are designed to form a p-i-n junction in each resonator, allowing a photo-generated current to flow when photons are absorbed [1]. This approach overcomes some difficulties faced by spectrometers based on gratings or interferometers, such as loss of resolution when miniaturised, fragility of moving components, stray light and alignment issues.

The main design aspects are choice of semiconductor materials, for which we choose industry standard substrates such as GaAs; design of quantum well heterostructures to provide appropriate optical properties; modelling of the central waveguide to provide high optical confinement while minimising loss, and FDTD simulations to determine the resonance wavelengths of the microdisks in the array. Our latest simulation results will be discussed along with expected performance characteristics and future prospects for the spectrometer chip.

1. Sweeney, S.J., Zhang, Y., Goodyer, I.D., "The development of a novel monolithic spectrometer chip concept", Proc. SPIE 8264, (2012)

8988-47, Session 10

Refractive index sensing utilizing photonic crystal nano-beam cavity with slotted stack

Peipeng Xu, Zhejiang Univ. (China); Kaiyuan Yao, Univ. of California, Los Angeles (United States); Jiajiu Zheng, Xiaowei Guan, Yaocheng Shi, Zhejiang Univ. (China)

We present the design, fabrication, and the characterization of a high-Q slotted one dimensional photonic crystal nano-beam cavity with parabolic-width stack.

Their peculiar geometry enables the resonating mode locates close to the air-band. This also indicates that the majority of electric field is distributed in the slotted low-index area.Therefore, the detection of refractive index changes in a given analyte with high sensitivity because of the large overlap between the optical mode and the analyte. Furthermore, the Q-factor maintains a high value over a wide range of background refractive index, indicating a very large sensing range of the device. This is especially advantageous compared to the microring based sensors whose sensing range is inevitably limited by the free spectrum range (FSR).

The fabricated device shows a Q-factor up to 9000 which can be improved by further optimizing the fabrication processes since the calculated Q-factor is ~106. The refractive index sensing for NaCl solutions with different concentrations gives a sensitivity around 410 which shows good agreement to the simulations (~430).

8988-55, Session 10

High-contrast GeTe4 waveguides for mid-infrared biomedical sensing applications

Vinita Mittal, James S. Wilkinson, Ganapathy Senthil Murugan, Univ. of Southampton (United Kingdom)

The ideal molecular "fingerprint" region for biochemical analysis is dominated by the Mid-IR spectral region from 2µm to 13µm. Realisation of single mode waveguides optimised for evanescent field based sensing is essential to detect analytes of very low concentration using their fingerprint molecular vibrations. Since commonly used silicate glasses do not transmit at wavelengths beyond 3µm and some Mid-IR transmitting glasses such as the fluorides degrade when in contact with water, novel materials are required to cover this range. Germanium telluride is a promising material which has a broad IR transparency in the region of 2µm - 20µm. We demonstrate a "high contrast" ($\Delta n \approx 1$), GeTe4 single mode rib waveguide on ZnSe. GeTe4 thin films were deposited on ZnSe substrates by RF sputtering at room temperature. Deposition parameters such as sputtering pressure, power, and argon flow rate were varied to optimise the deposition conditions and to study their effect on the resulting films. The deposited films were amorphous as confirmed by XRD and the average roughness of the films was between 4 and 11nm as measured by AFM. The films transmitted over the full spectral range from 2µm - 20µm as measured by FTIR. Photolithography followed by reactive-ion etching was carried out to etch the film to produce a rib waveguide structure with low surface roughness and vertical sidewalls, using an optimised mixture of CHF3 and O2. Further optical characterization of these waveguides including propagation loss and mode profile will be presented.

8988-68, Session 10

Rigorous coupled wave analysis model for a fiber Bragg grating strain sensor in polarization maintaining single-mode optical fiber

Joel Quintana, Raymond C. Rumpf, Virgilio Gonzalez, The Univ. of Texas at El Paso (United States)

Fiber-Bragg Gratings (FBG) for Structural Health Monitoring (SHM) have been studied extensively as they offer electrically passive operation, EMI immunity, high sensitivity, and multiple multiplexing schemes, as compared to conventional electricity based strain sensors. FBG sensors written in Polarization Maintaining (PM) optical fiber offer an additional dimension of strain measurement simplifying sensor implementation within a structure. This simplification however, adds complexity to the detection of the sensor's optical response to its corresponding applied strain. We propose a rigorous coupled wave analysis (RCWA) model modified to simulate a fiber Bragg grating (FBG) in a polarization maintaining optical fiber. We study the effects of the reflected Bragg wavelength to the changes in shape of the optical fiber core waveguide and compare the results to the existing literature.

8988-48, Session 11

Heterogeneous photonic integrated circuits and their applications in computing, networking, and imaging *(Invited Paper)*

S. J. Ben Yoo, Univ. of California Davis (United States)

We discuss progress, challenges, and future prospects of heterogeneous integration for future information systems. Semiconductor and dielectric materials including silicon, InP, GaAs, GaN, Si3N4, SiO2, TiO2, LiNbO3, YIG, BIG, and Al2O3 offer variety of optical, electrical, and magnetic properties. Integration such heterogeneous materials can bring new functionality to integrated systems. We will discuss several examples. The first example pursues a fully-reconfigurable multi-stage optical lattice filter built by cascading identical unit cells consisting of a Mach-Zehnder interferometer (MZI), a ring resonator, and optical amplifiers using silicon CMOS, dielectric, and InP processing technologies. The experimental results of silicon photonic optical lattice filters show full control over the single unit cell pole and zero, switching the unit cell transfer function between a notch filter and a bandpass filter, narrowing the notch width down to 400 MHz, and tuning the center wavelength over the full free spectral range (FSR) of 10 GHz. The second example pursues 3D integrated circuits consisting of processor-memory-photonic interconnects. By combining the state-of-the-art silicon CMOS technologies, the new silicon photonic technologies, and hybrid 3D integration technologies, we pursue a new 3D integrated circuit consisting of a processor plane, a memory plane, and a silicon-photonic interconnect plane. Through-silicon-via electrical interconnects together with a new photonic-via interconnects can play an important role in 3D interconnects. The third example exploits coherent optical signal generation in optical arbitrary waveform generation and coherent optical signal detection in optical arbitrary waveform measurement scalable to THz bandwidth and beyond. Realizing such systems on hybrid integrated circuits will be discussed. The fourth example explores the concept of interferomic telescopes realized on silica and silicon photonic integrated circuits. We will summarize the impacts of such integrated systems on computing, networking, and imaging systems, and discuss future prospects and challenges.

8988-49, Session 11

Investigation of temperature dependence on optical current transducers consisting of a polymeric photonic IC and a high birefringence spun fiber

Woo-Sung Chu, Sung-Moon Kim, Min-Cheol Oh, Pusan National Univ. (Korea, Republic of)

Optical current transducers (CTs) are indispensable devices for the accurate monitoring of large electrical currents in environments suffering from severe electromagnetic interference. Temperature dependence of optical CTs has given a large influence on accuracy and linearity. Temperature dependence of optical CTs is occurred by incomplete annealing cause remained residual birefringence on the coiled fiber, quarter wave plate (QWP) and Verdet constant. For reduce temperature dependence of optical CTs, fiber coil was made of high birefringence spun fiber (HBSF) instead of annealed fiber coil and quarter wave plate was made of photonic crystal polarization maintaining fiber (PCPMF) that has extremely low temperature dependence. Various functional optical devices are integrated on a single chip in order to construct optical current transducers based on polarization rotated reflection interferometry, which consists of polarization maintaining 3-dB couplers, TE-pass polarizers, TE/TM polarization converters, and thermo-optic phase modulators. The polarization dependent output response phase modulation optical CTs module incorporating the integrated–optic device to measure the optical phase retardation exhibited good linearity with deviation less than 0.5%. Long term stability of optical CTs is well within 0.5%. In the experiment of electrical current measurement, the optical signal exactly followed the 6 kA, 60 Hz sinusoidal waveform source current. Single chip integration reduces the complexity of the interferometry, and enables mass-production of low-cost high performance optical CT.

8988-50, Session 11

Enabling all-optical logic gates through inverse design in passive photonic crystal structures

Imanol Andonegui, Angel J. Garcia-Adeva, Univ. del País Vasco (Spain)

We report on the design of ultracompact all-optical passive logic gates based on disordered photonic crystal topologies. We used an inverse design approach, provided by various heuristic optimization methods as well as a genetic algorithm as an engine for achieving these apparently counter-intuitive structures. The resulting set of logic gates yield to a meaningful compactness that combined with their all-optical being, could provide a significant enhancement of optical circuitry. PC topologies proposed throughout this work are constrained in order to satisfy the limitations imposed by lithographic manufacturing techniques. Therefore, these designs are not only interesting from a theoretical point of view but also of great practical importance, since they can be readily manufactured.

8988-51, Session 11

Stable planar microcavities based on mesoscopic photonic crystals

Giovanni Magno, Lab. d'Analyse et d'Architecture des Systèmes (France) and Politecnico di Bari (Italy); Antoine Monmayrant, Lab. d'Analyse et d'Architecture des Systèmes (France) and Univ. de Toulouse (France); Marco Grande, Politecnico di Bari (Italy); Françoise Lozes-Dupuy, Olivier Gauthier-Lafaye, Lab. d'Analyse et d'Architecture des Systèmes (France) and Univ. de Toulouse (France); Giovanna Calò, Vincenzo Petruzzelli, Politecnico di Bari (Italy)

Self-Collimation (SC) is an interesting property of photonic crystals (PhC). This phenomenon happens when for a given wavelength the related isofrequency curve shows a quasi-flat section in a certain direction. This allows light propagation in self-guided beams without any lateral spreading. Mesoscopic Photonic Crystals (MPhCs) are novel structures constituted by alternating slabs of bulk material with slabs of PhC. In MPhCs the self-collimation condition relies on the curvature index nc and on the idea of null accumulated curvature over a mesoscopic period. These new concepts are extremely flexible allowing the coexistence of other useful properties as slow light, low or high filling factor and a precise control on the reflectivity. The latter allows designing AR and HR structures with high transmission (>99 %) and reflection (>99 %), respectively, without any additional adaptation of the interface (as graded or half-holed PhC) that makes both design and fabrication more difficult. An accurate design of these structures can be easily achieved by simple planar wave expansion method (PWEM) calculation (to determine the curvature index) and by solving simple algebraic linear equations that control the whole reflectivity. Therefore, a novel class of devices could be conceived starting by the AR and HR. For example, combining two HR structures it is possible to design mesoscopic self-collimation planar microcavities with high Q factors, allowing a high concentration of energy. Design method and physical principles of these microcavities will be detailed.

8988-52, Session 11

A polarization modulation in monolithically-integrated devices at 300 mbps

Muhammad Azhar Naeem, Univ. of the Punjab (Pakistan); Mohsin Haji, Barry M. Holmes, David C. Hutchings, John H. Marsh, Anthony E. Kelly, Univ. of Glasgow (United Kingdom)

A polarisation modulation with 300 Mbps in integrated devices, fabricated monolithically on strained InP/AlGaInAs material, is reported. The device consists of a semiconductor hetero-structure laser section, a polarisation mode convertor (PMC) section, and an active differential phase shifter (DPS) section.

To control the state of polarisation (SOP) in the optical signals has an immense importance as the optical communication systems carry the information with higher data rates. Photonic integrated circuits (PICs) help to fabricate the devices with minimum cost, high efficiency and with low losses. The miniaturisation of the devices is also possible by PICs. The most important component in polarisation modulation is the PMC, which can be introduced in the integrated devices as mode beating or mode evolution element. The PMCs were fabricated using various material systems including GaAs/AlGaAs and LiNbO3. The reported device in this paper is realised using standard fabrication procedures. Initially, these devices were characterised for the TM purity. The dynamic polarization control was also investigated by injecting the current on the DPS section of the integrated device. Thereafter, high speed radio frequency (RF) probes were used for characterisation of the devices. The output optical signals using high speed probes were obtained at 300 Mbps, using the polarisation analyser set at +45°,-45°, 0° (TE) and 90° (TM). The signals were complement to each other at +45° and -45°, whereas at 0° (TE) and 90° (TM), there was no signal. Although there was a little bit signal, which was attributed to the noise generated by the measurement components.

8988-53, Session PWed

Monolithically integrated DWDM DFB laser array fabricated by a modified SAG technique

Can Zhang, Song Liang, Liangshun Han, Baojun Wang, Hongliang Zhu, Wei Wang, Institute of Semiconductors (China)

A modified selective area growth (SAG) technique, in which the effective index of only the upper separate confinement heterostructure (SCH) layer are modulated to obtain different emission wavelengths, is demonstrated to fabricate the dense wavelength division multiplexing (DWDM) multi-wavelength laser arrays (MWLAs). Here, the 20-channel DFB laser arrays with 0.22nm and 0.44nm channel spacings are respectively obtained, all showing highly uniform wavelength spacings, which is promising for fabrication of low cost MWLAs.

8988-54, Session PWed

Numerical analysis of optical resonances in 3D nanoresonators

Sven Burger, JCMwave GmbH (Germany) and Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); Lin Zschiedrich, Jan Pomplun, JCMwave GmbH (Germany); Frank Schmidt, JCMwave GmbH (Germany) and Konrad-Zuse-Zentrum (Germany)

For various technological applications it is desired to strongly confine light to very small ivolumes.

High resonance Q-factors of optical microcavities can be attained using the high reflectivity of multi-layer Fabry-Perot resonators, of total internal reflection and/or of photonic bandgap materials.

For an efficient design of microcavities and other integrated photonic components 3D simulations of Maxwell's equations are needed. For this purpose we use finite-element method (FEM) based solvers for the Maxwell eigenvalue and for the Maxwell scattering problems (JCMsuite).

The method is based on higher order vectorial elements on adaptive unstructured grids.

In this contribution we present FEM convergence results from a recent study of high-Q resonances in a hybrid material system [1].

In the numerical study, a 3D lossy high-index-constrast structure defines a challenging modeling benchmark.

Results from four different methods (FEM, finite-difference time-domain method, FDTD, rigorous coupled wave analysis, RCWA, bidirectional eigenmode propagation, BEP) have been compared.

Qualitative agreement and quantitative discrepancies are discussed [1].

[1] B. Maes, J. Petracek, S. Burger, P. Kwiecien, J. Luksch, I. Richter. Opt. Express, 21, 6794 (2013).

8988-56, Session PWed

Waveguide sensors for liquid using gapped optical fibers

Kazutaka Baba, Keita Chiba, Sendai National College of Technology (Japan)

A waveguide sensor for measurements of refractive index and absorptance of liquid has been theoretically investigated. We use a gapped optical fiber as the sensor. The gap is filled with the liquid whose optical characteristics are to be measured. A light beam gradually expands as the beam propagates in the gap because of diffraction An optical loss of the gapped optical fiber depends on the refractive index and absorptance of the liquid in the gap. That is, the optical loss becomes smaller with the refractive index of the liquid as the light beam greatly expands in the media with smaller refractive index. The optical loss becomes larger with the absorptance of the liquid. Therefore, the refractive index and absorptance can be measured by using two waveguide sensors with different gap width. In the previous work, we investigated the theoretical characteristics of the sensors by using the two-dimensional slab waveguide for simplification. In this work, we have derived an equation for evaluation of the optical losses by approximating the fundamental mode in the optical fiber by a Gaussian function for practical use. And we clearly show the relationship between the optical loss and the refractive index of liquid filled into the gap for various gapped optical waveguides. The optical loss more greatly changes in the gaped optical fiber in comparison with the gaped slab waveguide. We have also designed a saccharimeter for the liquid with Brix scale 0–20% by using the gapped waveguide. For example, the optimum gap widths are evaluated as 1.8 mm for the spot sizes of 0.01 mm.

8988-57, Session PWed

Plasmonic slot nano-waveguides with flattened Luneburg lens-based optical couplers

Bayaner Arigong, Rongguo Zhou, HyoungSoo Kim, Yuankun Lin, Hualiang Zhang, Univ. of North Texas (United States)

In the last few years, compact nano-scale device¬¬s such as plasmonic waveguides have attracted a lot of research interests, since they can be applied in front-end building blocks of future optical communication systems. Until now, different kinds of plasmonic slot waveguides have been studied by many researchers. However, the corresponding challenges such as propagation loss, field diffusion, and unable to couple the light from free space to waveguides have prevented plasmonic waveguides from being widely used in highly integrated photonic circuits. Luneburg lens as a perfect imaging lens has excellent performance in manipulating the light to focus at diffusion free point. Therefore, Gabrielli et al. proposed a fiber-to-chip coupler based on integrated Luneburg lens manipulating the light to silicon waveguide. The resulting fiber-to-waveguide coupler mediated by a Luneburg lens will not suffer from total insertion losses and it can reduce the losses introduced by misalignment. However, due to the spherical shape of conventional Luneburg lens, the performance of this device will be greatly limited by the incident angle of incoming optical signals. Meanwhile, transformation optics (TO) technique has been applied extensively in the field of microwave engineering since it is a powerful tool that can be used to design functional electromagnetic device to transform the curved surface into flattened shape without changing the properties. In this paper, by applying the transformation optics technique to the Luneburg lens, for the first time in this field, we design a plasmonic slot-waveguide with flattened Luneburg lens based optical coupler. The full wave EM simulation results prove that the proposed structure can efficiently couple the wide angle and broadband optical signals into the plasmonic slot-waveguide. It is expected that the new optical couplers can help to build robust on-chip photonic circuits for next-generation optical communication systems.

8988-59, Session PWed

A broadband silicon electro-absorption modulator (EAM) using Schottky diode

Uiseok Jeong, Korea Univ. (Korea, Republic of); Dong Chul Han, Korea Univ. (Korea, Republic of) and SAMSUNG Electronics Co. (Korea, Republic of); Dong Ho Lee, Kyungwoon Lee, J Kim, Jung Ho Park, Korea Univ. (Korea, Republic of)

A silicon optical modulator operating at high speed and low voltage was accomplished using a Schottky diode. The optical modulation of this device is achieved by the change of guiding light intensity due to free-carrier absorption, not conventional interference effects.

The rib waveguide structure of the modulator with a height of 340 nm, a etch depth of 140 nm, a width of 4.8 um, and a modulation length of a 200 ?m. It was designed to maximize the free carrier injection by a Schottky contact on the rib waveguide center. The center of the rib waveguide is lightly doped with boron in 10e16 cm-3, and the sides are heavily doped with boron in 10e20 cm-3 to improve modulation depth by injecting free carriers into the center of the rib waveguide. This design allowed a high overlap between the optical mode and carrier density variations in the center of the waveguide compared to conventional silicon P-N diode electro-optical modulators. To achieve high speed, travelling-wave type electrode is designed to allow co-propagation of electrical and optical signals along the waveguide.

The device results demonstrated beyond a 4dB modulation depth at 10Gpbs with 3 Vpp driving voltage.

8988-60, Session PWed

Optical isolation for optical ICs using a self-assembled scattering monolayer

Guang-Hao Huang, Jun-Whee Kim, Min-Cheol Oh, Pusan National Univ. (Korea, Republic of)

In modern optical communication systems, data traffic over the internet is daily growing, so the WDM optical communication system is used for improving signaling speed. There are strong demands on highly integrated optical components. Variable optical attenuator (VOA) arrays are used with optical switches in cascaded form in ROADM system. Though the two devices based on polymer waveguide technology are commercialized in these days, it is still not viable to integrate the two array devices on a single chip due to the significant crosstalk between them. The light radiated from VOA is guided in the planar waveguide and it hardly escapes from the planar waveguide structure, so they could be coupled into the adjacent channels and forms crosstalk to deteriorate the transmission capability. Self-assembled scattering monolayer (SASM) is imbedded in a cladding layer in this work in order to reduce the crosstalk. Because of the large index contrast in the polymer waveguide, causing strong diffraction of the planar guided modes toward the surface normal directions. Depending on the size and period of the microsphere, the diffraction efficiency is simulated based on 2D FDTD method. The PLC waveguide is fabricated by using a conventional lithography, a dry etching for controlling the size of microsphere, and an UV curing process. By measuring the diffraction efficiency of the sample with different lengths of microsphere area, we found cladding mode attenuation efficiency is as high as 23 dB/cm. Consequently by using the SASM, the crosstalk between adjacent channels could be decreased to -50 dB.

8988-61, Session PWed

1300-nm thermo-optic tunable lasers based on polymeric Bragg reflection waveguide devices for low-cost OCT

Chi-Hun Sung, Jun-Whee Kim, Min-Cheol Oh, Pusan National Univ. (Korea, Republic of)

Wavelength tunable lasers are demonstrated in terms of the thermo-optic (TO) refractive index tuning of polymer waveguide Bragg reflectors. The polymer waveguide device has superior TO efficiency for substantially changing the refractive index. The Bragg grating and oversized rip waveguide structure was designed by using the effective index method and the transmission matrix method. The polymer waveguide is fabricated using low-loss fluorinated polymer materials with refractive indices of 1.392 and 1.372 for the core and the cladding layers, respectively. The Bragg reflection grating imbedded in a polymer waveguide is optimized to produce an appropriate reflection spectrum for external cavity lasers. The spectral response of the fabricated tunable Bragg reflector device was characterized by using an SLD with a single side high-reflection coating. The output spectrum of the external cavity laser exhibited a side mode suppression ratio of 35 dB. For the wavelength tuning experiment, electrical heating power was applied on the thin film heater. The peak-wavelength change was linearly proportional to the applied heating power. The laser exhibited an SMSR of 35 dB, and a tuning range of 20 nm. 1300-nm thermo-optic tunable lasers will be useful for implementing low-cost OCT system.

8988-62, Session PWed

Orthogonal solutions for asymmetric-coupled waveguide arrays: an elegant, analytical approach

Niharika Kohli, Univ. of Delhi South Campus (India); Sangeeta Srivastava, Univ. of Delhi (India); Enakshi K. Sharma, Univ. of Delhi South Campus (India)

Silicon on Insulator (SOI) waveguides are the focus of present day nanophotonics due to their smaller device footprint and compatibility with CMOS technology. Coupled waveguide arrays have been widely analysed by the simple yet intuitive coupled mode theory. However, for asymmetric strongly coupled waveguide arrays, the supermodes obtained by coupled mode theory are not orthogonal solutions and hence, fail to satisfy the conservation of power. We present an elegant, three step analytical methodology for obtaining accurate orthogonal solutions for asymmetric waveguide arrays. First, the propagation characteristics of the individual waveguides are obtained. Next, an orthogonal basis set, which is formed by a linear combination of the modal fields of the individual waveguides, is generated using the Gram Schmidt orthogonalization procedure. The Ritz Galerkin Variational method, with the trial field as an expansion in

terms of the newly formed orthogonal basis set, is then used to obtain the modes of the coupled waveguide array. The procedure is illustrated by use on strongly coupled SOI waveguide arrays. The modal solutions obtained for the waveguide arrays are exactly orthogonal to one another. Since the new orthogonal basis set is essentially a linear combination of the modal solutions of the individual waveguides, the quantities involved in the analysis are analytically identical to those defined as coupling coefficients and overlap integrals in the conventional coupled mode theory. The theory presents itself as a strong alternative to numerically intensive and time consuming techniques that are frequently employed for the analysis of such structures.

8988-63, Session PWed

On the resonance frequency of an integrated optical ring resonator with low radius of curvature

Diaa Khalil, Si-Ware Systems (Egypt) and Ain Shams Univ. (Egypt); Amr Wageeh, Salwa El-Sabban, Gamal A. F. M. Khalaf, Helwan Univ. (Egypt)

Ring resonators are key elements in new integrated optical circuits for many applications including optical filters, optical modulators, and add/drop multiplexers. For wide free spectral range FSR resonators suitable for telecommunication applications, the ring dimensions are critically small and the waveguide dispersion is usually strong enough to perturb the calculation of the resonance frequency and FSR. In such situation, the conventional technique to correct the FSR calculation is to use the group refractive index in place of the refractive index. However, the comparison with the FDTD calculations shows that even with the group index calculation, a relatively big error is obtained at very small radius. In this work we propose a new simple formulation for estimation of the resonance frequency and FSR calculation in dispersive ring resonators. The new formulation depends on the expansion of the effective refractive index as a function of the wavelength and then solving the resonance equation to get the resonance wavelengths and consequently the FSR. Using our formula we get an error in the resonance wavelength estimation less than 0.2% when compared with the FDTD and considering it as a reference, in comparison to an error in the order of 5-6% when using the conventional formula based on the group index calculation. The formula estimates also an oscillatory behavior in the FSR with the inverse of the ring radius exactly as observed in the FDTD which cannot be predicted by the use of the group index calculation.

8988-64, Session PWed

Piezoforce and contact resonance microscopy correlated with Raman spectroscopy applied to a non-linear optical material and to a lithium battery material

Rimma Dekhter, Gabi Zeltzer, Oleg Zinoviev, Nanonics Imaging Ltd. (Israel); Michael Roth, The Hebrew Univ. of Jerusalem (Israel); Bernhard Roling, Philipps-Univ. Marburg (Germany); Aaron Lewis, The Hebrew Univ. of Jerusalem (Israel)

A non-linear optical material (KTP) and a lithium-ion conductive glass ceramic (LICGC) for lithium batteries have been studied with Raman Spectroscopy on-line with Piezo Force and Contact Resonance Microscopies. This is allowed by a unique design of the scanned probe microscopy platform used in these studies and the electrical probes that have been developed that keep the optical axis completely free from above so that such combinations are feasible. The integration allows the investigation of alterations in the strain induced in the chemical structure of the materials as a result of the induction of piezo force. The combination of chemical characterization with both piezo force and contact resonance [1] microscopy allows for the monitoring of structural and ionic changes using Raman scattering correlated with these modalities. In KTP, it has been seen that the largest changes take place in TiO6 octahedral structure symmetric and antisymmetric stretch in the interfaces between the regions of the poling of the structure. In the LICGC, defined Raman changes are observed that are related to the contact resonance frequency. The combination adds considerable insight into both the techniques of Piezo Force Microscopy and Contact Resonance Microscopy.

1. Balke et al, Nature Nanotechnology DOI: 10.1038/NNANO.2010.174 92010)

8988-65, Session PWed

Inverse scattering designs of dispersion-engineered single-mode planar waveguides

Alexander R. May, Francesco Poletti, Michalis N. Zervas, Univ. of Southampton (United Kingdom)

Dispersion-engineered waveguides, such as dispersion shifted, dispersion flattened and dispersion compensating fibers, continue to constitute important elements in advanced photonic systems for telecommunication and nonlinear applications. Traditionally such waveguides have been optimised by using ad-hoc designs with apriori defined complex refractive index profiles. In this work, we use for the first time an inverse-scattering (IS) approach to design single-mode waveguides with controlled linear and higher-order dispersion coefficients. The technique is based on a numerical solution to the Gelfand-Levitan-Marchenko (GLM) integral equation, for the inversion of rational reflection coefficients with arbitrarily large number of leaky poles. Using Sturm's theorem we obtain the allowable domain for the leaky-pole positions and calculate the resulting dispersion maps and corresponding refractive index distributions. We show that common features of dispersion-engineered waveguides such as trenches, rings and oscillations in the refractive index profile come naturally from the inverse scattering algorithm without any apriori assumptions. Increasing the leaky-pole number is shown to increase the granularity in the dispersion map, as well as, allows design of waveguides with identical low order and differing higher order dispersion coefficients. Previous work on waveguide design employed analytical solutions to GLM equation, limited to only three poles, and was restricted to mode size calculation only. This new powerful design algorithm is expected to be useful in designing a new generation of dispersion engineered fibers with superior performance.

8988-66, Session PWed

Temperature sensitivity of waveguide Mach-Zehnder interferometer

Firehun T. Dullo, Norut Tromsø (Norway); Viktor Sokolov, Cyprien Chauvet, Susan Lindecrantz, Univ. of Tromsø (Norway); Stian A. Solbø, Norut Teknologi (Norway); Olav G. Hellesø, Univ. of Tromsø (Norway)

Waveguide Mach-Zehnder interferometers (MZI) are finding increased application due to their high sensitivity. The MZI possess two arms, sensing and reference arms. We want to use waveguide MZI for field measurement, i.e. sensing of methane for subsea and atmospheric applications, it is thus important to study the temperature dependence of the sensor. An experimental study of temperature sensitivity of waveguide MZI is presented. When a temperature of a waveguide chip is changed, there is a change in the phase due to the temperature coefficient of thermal expansion and refractive index of the waveguide material and the surrounding media. Three designs, balanced MZI, unbalanced MZI and tapered MZI under balanced configuration are studied. For tapered MZI, the two arms at the output were tapered

and combined to generate the inference fringes. To investigate the temperature sensitivity of the interferometer, we measure the phase shift at the output of the interferometer as function of temperature. For normal MZI design a photodetector at the output was used to record the output power, whereas for a tapered MZI a CCD camera at the output was used to directly image the fringe pattern. It was found that the balanced MZI is very stable with temperature. However, for an unbalanced MZI with a difference of 1 mm between two arms, a small phase shift was observed. The phase shift was less than one period with a change of 10o C. The comparison of temperature sensitivity of normal and tapered MZI under balanced configuration is also presented.

8988-67, Session PWed

High-efficient and broadband nanoabsorbers and nanoreflectors based on metallic dielectric periodical structures

Joaquim Isidio Lima Jr., Juarez Caetano da Silva, Vitaly Felix Rodriguez-Esquerre, Univ. Federal da Bahia (Brazil); Cosme Eustaquio Rubio Mercedes, Univ. Estadual de mato Grosso do Sul (Brazil)

Broadband nanostructured metallic and dielectric absorbers and reflectors are of great interest in integrated optics. They shown strongly sensitive to the polarization modes and they have a great potential for applications like polarizers, detectors of polarization or reflector for nanoantennas applications, operating in optical frequencies covering the interval of the O-E-S-C-L-U bands. In this work, novel geometric and optical configurations are numerically analyzed by an efficient finite element formulation. Depending on their geometries they can act as absorbers or reflectors. The absorber or reflected central frequencies of the analyzed devices can be easily tuned over the entire communications wavelength band by varying their geometrics and optical parameters In our numerical simulations we obtained peaks of absorption larger than 80% in optical wavelengths, by using metals like silver and gold in combination with silica substrates. We are now working towards absorbers and reflectors insensitive to the polarization of the incident waves.

8988-69, Session PWed

Electric field sensors consisting of polymeric photonic integrated chips

Sung-Wook Heo, Woo-Sung Chu, Min-Cheol Oh, Pusan National Univ. (Korea, Republic of)

Optical electric field sensors are indispensable devices for the accurate monitoring of high electric voltages in the environment suffering from severe electromagnetic interference. This paper reports on the study of an optical electric field sensors based on the EO crystal (z-cut $LiTaO_3$). Electric field sensing part consists of polarization maintaining collimator, faraday rotator, $LiTaO_3$ and dielectric mirror. $LiTaO_3$ has different size by dicing in the experiment, dielectric mirror used for the reflective type that placed at the end of crystal. $LiTaO_3$ voltage applied to the way used electrodes that the deposited Au on glass using a photo-mask lithography, and it's located crystal above and below to applied voltage. And the incident light was 45 degree linearly polarization for the optical axis of EO crystal using the faraday rotator. The reason of the 45 degree linealy polarization incident to EO crystal is electro-optic effect to take the maximum due to the most sensitive at the 45 degree. Electric field sensing signals are analyzed by polarization rotated reflection interferometry (PRRI). The PRRI is integrated on a single chip, which consists of polarization maintaining 3-dB couplers, TE-pass polarizers, TE/TM polarization converters, and thermo-optic phase modulators. Single chip integration reduces the complexity of the interferometry, and enables mass-production of low-cost high performance electric field sensors.

8988-70, Session PWed

The performance analysis of an electro-optic polymer modulator

Guofang Fan, Technical Institute of Physics and Chemistry (China); Yuan Li, lihua lei, Shanghai Institute of Measurement and Testing Technology, National Center of Measurement and Testing (China); qi wang, Guangming Xu, Haohui Ren, Technical Institute of Physics and Chemistry (China); hongyu li, College of Mechanical and Electronic Engineering, Shandong University of Science and Technology (China)

In this paper, we present a detailed analysis about the electro-optic (EO) polymer modulators using a full vectorial finite difference (FVFD) mode solver for an optical waveguide and a finite-element method (FEM) for a microwave electrode. A detailed discussion has been presented to describe a modulator about performance parameters: VL, ΔfL with the design parameters, where VL is the product of the half-wave voltage V and the electrode interaction length L, the parameter ΔfL is the product of the 3 dB optical bandwidth Δf and the electrode interaction length L.

8988-71, Session PWed

Towards an optical biosensor based on WGM microbubble resonators

Ambra Giannetti, Sara Tombelli, Cosimo Trono, Simone Berneschi, Istituto di Fisica Applicata Nello Carrara (Italy); Daniele Farnesi, Ctr. Studi e Ricerche Enrico Fermi (Italy) and Istituto di Fisica Applicata Nello Carrara (Italy) and UNIPRESS (Italy); Andrea Barucci, Silvia Soria, Gualtiero Nunzi Conti, Francesco Baldini, Istituto di Fisica Applicata Nello Carrara (Italy)

Recently, for their particular properties, optical microbubble resonators (OMBRs) have gained an increasing interest in many fields of photonics. They are obtained starting from a microcapillary preform by means of a particular fabrication process, which increases its radial dimension along the axial direction. In our laboratories, we fabricated OMBRs by heating a slightly pressurized capillary with a rotating arc discharge. High quality factors Q (>10^7) were obtained for these microresonators and their working as refractometers was demonstrated. These hollow microstructures may be suitable for the realisation of label-free optical biosensors because they combine the whispering gallery mode (WGM) resonator properties with the intrinsic capability of integrated microfluidics. In fact, the sensitivity of an OMBR increases, well over that of the other microresonator based biosensors, by reducing the wall thickness of the bubble microcavity – in a way that the peak of the electric field emerges at the interface between the inner and the internal medium. Nevertheless, a crucial step for the development of an OMBR based biosensor is its inner surface functionalization, which requires a precise local spatial selectivity in order to implement the biosensing layer only in correspondence of the microbubble. For this purpose, we have studied the possibility to locally functionalize – by a suitable physical and chemical process – the inner wall of the starting microcapillaries in a single spot having a size comparable with that of the microbubble. An overview of the preliminary results achieved in our laboratories about the OMBRs and their possible functionalization will be presented.

8988-72, Session PWed

Portable dual-beam generator using a hybrid integrated guided-wave beam aligner

Hong-Shik Lee, Korea Institute of Lighting Technology (Korea, Republic of); Vivek Raj Shrestha, Sang-Shin Lee, Kwangwoon Univ. (Korea, Republic of)

A portable dual beam generator has been realized tapping into an ultra compact guided-wave beam aligner, fed with infrared (IR) and visible laser sources. The beam aligner is composed of a straight and a 90° bent waveguides for the IR and visible channels, which are hybrid integrated with two different laser diodes operating at ? = 905 nm and 605 nm, respectively, at their input facets; and highly aligned IR and visible beams are emanating from the same output facet of the aligner device. The proposed dual beam generator is created by appending a collimating lens to the prepared aligner. The beam aligner was rigorously designed and analyzed using beam propagation method while the beam generator has been designed and analyzed using a ray tracing tool. The aligner was produced in silica waveguides, and it was active aligned and hybrid integrated with an IR and visible LD chips. The optical coupling efficiency for the IR and visible channel was observed to be 26 and 15%, respectively providing a well defined IR and visible mode profiles at the output of the aligner, with the light sources integrated. Finally, the aligner was combined with a collimating lens giving rise to a 35 mm compact size of the embodiment, providing a highly collimated IR and visible beam featuring Gaussian-like profiles with divergence angles of 0.1o and 0.08o, respectively, and propagating almost collinearly with an angular alignment of 0.13o, thereby making it applicable to the fields of laser surgery and biomedical applications.

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8989-1,

III-V semiconductor optoelectronic devices from UV to THz: recent advances and future trends *(Keynote Presentation)*

Manijeh Razeghi, Northwestern Univ. (United States)

Nature offers us different kinds of atoms, but it takes human intelligence to put them together in an elegant way in order to realize functional structures not found in nature. The so-called III-V semiconductors are made of atoms from columns III (B, Al, Ga, In. Tl) and columns V(N, As, P, Sb,Bi) of the periodic table, and constitute a particularly rich variety of compounds with many useful optical and electronic properties. Guided by highly accurate simulations of the electronic structure, modern semiconductor optoelectronic devices are literally made atom by atom using advanced growth technology such as Molecular Beam Epitaxy (MBE) and Metal Organic Chemical Vapor Deposition (MOCVD). Recent breakthroughs have brought quantum engineering to an unprecedented level, creating light detectors and emitters over an extremely wide spectral range from 0.2 um to 300 um. Nitrogen serves as the best column V element for the short wavelength side of the electromagnetic spectrum, where we have demonstrated III-nitride light emitting diodes and photo detectors in the deep ultraviolet to visible wavelengths. In the infrared, III-V compounds using phosphorus ,arsenic and antimony from column V ,and indium, gallium, aluminum, ,and thallium from column III elements can create interband and intrsuband lasers and detectors based on quantum-dot (QD) or type-II superlattice (T2SL). These are fast becoming the choice of technology in crucial applications such as environmental monitoring and space exploration. Last but not the least, on the far-infrared end of the electromagnetic spectrum, also known as the terahertz (THz) region, III-V semiconductors offer a unique solution of generating THz waves in a compact device at room temperature. Continued effort is being devoted to all of the above mentioned areas with the intention to develop smart technologies that meet the current challenges in environment, health, security, and energy. This talk will highlight my contributions to the world of III-V semiconductor Nano scale optoelectronics, devices from deep-UV to THz.

8989-2, Session 1

Output power enhancement in microlasers by selective pumping *(Invited Paper)*

Hakan E. Tureci, Li Ge, Omer Malik, Princeton Univ. (United States)

Optical microcavities can be designed to take advantage of total internal reflection to provide ultralow-threshold microlasers. One crucial problem of these devices for applications is their low power efficiency due to poor outcoupling. Various strategies, including waveguide coupling and cavity deformation, have been pursued in the past to increase the output power of microcavity lasers. Little is known, however, about the effect of mode competition on the overall power-efficiency of devices, limiting proposed solutions for high-performance devices. Here, we treat spatial hole-burning interactions exactly and show how the output power delivered by a microlaser in the multimode lasing regime depends on properties of the resonator. Subsequently, using a spatially tailored pump profile, we demonstrate a general method to suppress multi-mode lasing and enhance the output power of a microlaser by orders of magnitude, exemplifying it for the cases of microdisk and stadium-shaped lasers.

8989-3, Session 1

High-quality large-area ELOG InP on silicon for photonic integration using conventional optical lithography *(Invited Paper)*

Himanshu Kataria, Wondwosen T. Metaferia, Carl Junesand, KTH Royal Institute of Technology (Sweden); Chong Zhang, John E. Bowers, Univ. of California, Santa Barbara (United States); Sebastian Lourdudoss, KTH Royal Institute of Technology (Sweden)

We present a simple method of growing large areas of InP on Si through Epitaxial Lateral Overgrowth (ELOG) from the isolated single openings. These openings are defined in deeply etched SiO_2 mask fabricated using conventional optical lithography and reactive ion etching. Normally an aspect ratio (mask thickness/opening width) > 1 is required to hinder the infiltration of the threading dislocations from the seed layer into the ELOG layer. Since in conventional optical lithography, minimum feature size is limited to ~1 μm due to diffraction limit, optimization of etching a rather thick (2 μm) SiO_2 mask is indispensable. According to our previous studies, mask with this thickness can eventually be used as a cladding layer for a buried Si waveguide to form a true monolithically integrated photonic device on Si. We examine this method and assess the quality of the ELOG InP on Si thus obtained using μ-photoluminescence (μ-PL) and transmission electron microscope (TEM). We also compare its quality and defect filtering with those of the ELOG layers obtained from lower aspect ratios (< 1). The high optical quality of multi quantum well (MQW) layers grown on the ELOG layer is promisingly supportive of the feasibility of this method for mass production.

8989-4, Session 1

Photonic Mach-Zehnder modulators driven by surface acoustic waves in AlGaAs technology

Antonio Crespo-Poveda, Andrés Cantarero, Mauricio M. de Lima Jr., Univ. de València (Spain); Rudolf Hey, Klaus Biermann, Paulo V. Santos, Abbes Tahraoui, Paul-Drude-Institut für Festkörperelektronik (Germany); Bernardo Gargallo, Univ. Politécnica de Valencia (Spain); Iñigo Artundo, VLC Photonics (Spain); Pascual Muñoz, Univ Politécnica de Valencia (Spain) and VLC Photonics (Spain)

We have designed, fabricated, and characterized a tunable photonic Mach-Zehnder modulator consisting of two 180? -dephased output waveguide channels, driven by a surface acoustic wave in the GHz frequency range built on (Al,Ga)As material system. Odd multiples of the fundamental driving frequency are enabled by adjusting the applied acoustic power, allowing for the modulation of the optical signals at higher frequencies using modest (lower) frequency generators. A good agreement between theory and experimental results is achieved.

8989-5, Session 2

Very large-scale silicon photonics *(Invited Paper)*

Michael Watts, Massachusetts Institute of Technology (United States)

We report on the development of the first 300mm silicon photonics process flow and its application to a very large scale nanophotonic phased array. The silicon photonics process flow, developed over the past couple of years, provides a complete set of photonic devices, from silicon modulators, tuners, and phase shifters, to germanium detectors and even on-chip lasers. By coupling compact emitters to phase shifters employing adiabatic bends to enable direct and efficient heating of the silicon and therein maximally compact phase shifters, a "unit-cell" with one phase shifter and one emitter, was created only a few wavelengths in extent. With such a compact "unit-cell", we created, for the first time, a large-scale, two- dimensional active nanophotonic phased array. In the largest demonstration of its kind, we passively phased-up 4096 nanoemitters to produce the MIT-logo in the far-field, and actively steered a smaller array along both the horizontal and vertical axis as well as created dynamic and arbitrary patterns in the far-field. Already, these results have received considerable interest in the use of these phased arrays for LADAR-based accident avoidance technologies, spatial division multiplexed communications, and biomedical imaging applications. Moreover, the phased arrays are truly holographic, and if pushed into the visible would enable true three-dimensional holographic displays. More generally, this demonstration represents the first very large-scale integrated photonic demonstration of any kind, with over 12,000 optical elements and reveals Moore's Law-like growth rates in circuit complexity, opening up the possibility for mega-scale microphotonic circuits in the near future.

8989-6, Session 2

Fully-integrated hybrid silicon free-space beam steering source with 32-channel phased array *(Invited Paper)*

Jared C. Hulme, Jonathan K. Doylend, Martijn J. Heck, Jock T. Bovington, Michael L. Davenport, Univ. of California, Santa Barbara (United States); Jon D Peters, Larry A Coldren, University of California, Santa Barbara (United States); John E. Bowers, Univ. of California, Santa Barbara (United States)

Free-space beam steering using optical phased arrays is a promising method for implementing free-space communication links and Light Detection and Ranging (LIDAR) without the sensitivity to inertial forces and long latencies which characterize moving parts. Implementing this approach on a silicon-based photonic integrated circuit adds the additional advantage of working with highly developed CMOS processing techniques. In this work we discuss our progress in the development of a fully integrated 32 channel PIC with a widely tunable diode laser, a waveguide phased array, an array of fast phase modulators, an array of hybrid III-V/silicon amplifiers, surface gratings, and a graded index lens (GRIN) feeding an array of photodiodes for feedback control. The PIC has been designed to provide beam steering across a 15°x5° field of view with 0.6°x0.6° beam width and background peaks suppressed 15 dB relative to the main lobe within the field of view for arbitrarily chosen beam directions. Fabrication follows the hybrid silicon process developed at UCSB with modifications to incorporate silicon diodes and a GRIN lens. We also discuss the electronic system developed to drive this device.

8989-7, Session 3

Silicon nanophotonics integration for chip-scale optical communication *(Invited Paper)*

Andrew Grieco, Univ. of California, San Diego (United States); Dawn T. Tan, Singapore Univ. of Technology & Design (Singapore); Kazuhiro Ikeda, Nara Institute of Science and Technology (Japan); Maziar P. Nezhad, Univ. of California, San Diego (United States) and RWTH Aachen (Germany); Matthew Puckett, Yeshaiahu Fainman, Univ. of California, San Diego (United States)

We will describe recent work in the area of integrated nanophotonics that have applications to on chip communication. In this context we will present passive filters and resonators produced through periodic waveguide modulation. We will also demonstrate nonlinear optical pulse compression in a monolithic device that integrates self phase-modulation and dispersion compensation. We also discuss wavemixing applications.

8989-8, Session 3

Optical transceiver ICs based on 3D die-stacking of optoelectronic devices *(Invited Paper)*

Harmen J. S. Dorren, Technische Univ. Eindhoven (Netherlands)

We demonstrate a wafer scale fabrication process of the 3D stacked transceivers which leads to very high bandwidth density as well as potential low cost. A receiver chip based on 3D stacking a photodiode chip directly on top of TIA CMOS IC is demonstrated. Uniform open eye patterns at 10 Gbps/channel are demonstrated for both 3D stacked receiver and transmitter chips and BER measurements of the transmitter show penalty free operation under uniform biasing conditions proving that the interconnecting technology is robust.

8989-9, Session 4

2D and 3D heterogeneous photonic integrated circuits *(Invited Paper)*

S. J. Ben Yoo, Univ. of California, Davis (United States)

We discuss new progress in 2D and 3D photonic integration technologies aimed at realizing future computing, communication, and imaging systems. Silicon photonics offers high density integration of nano-scale and submicron-scale photonic and electronic devices on possibly the same silicon CMOS fabrication platform. Hybrid or hetero integration technologies can allow various semiconductor and dielectric materials offering a variety of optical, electrical, and magnetic properties. The new femto-second laser inscribing technology allows us to form arbitrarily shaped 3D waveguides and optical interconnects on variety of materials. In this talk, we discuss new 2D and 3D integrated systems realized on heterogeneous material platforms.

8989-10, Session 4

Hybrid integration of RF photonic devices *(Invited Paper)*

Lute Maleki, Vladimir S. Ilchenko, Andrey B. Matsko, OEwaves, Inc. (United States)

This is to replace incomplete submission PW14O- OE110-18

We demonstrate tightly packaged (1 cc form factor) low-noise RF photonic oscillators including self-injection-locked semiconductor laser chips and ultrahigh Q crystalline microresonators as well as reconfigurable RF photonic filters. The microresonators characterized with quality factors exceeding a billion are in the heart of the fully-operational photonic systems. We figured out how to package the resonators without Q-factor degradation. The integration is achieved at a free-beam optical micro-bench. Usage of the free beam optics removes the problems related to the conventional on-chip integration of optical components that usually results in excessive scattering and loss inappropriate for the systems characterized with extremely low attenuations. The demonstrated devices have extremely low acceleration sensitivity and are operational in the broad frequency range.

Low phase noise in RF oscillators, a sought-after property to enable e.g. sensitive radar applications, is driven by low Leeson frequency that is one half of the operational bandwidth in delay line, or a filter, being an integral part of the oscillator loop. In our devices, it coincides with the loaded passband of the optical resonance that ranges between 100 kHz (in resonators made of calcium and magnesium fluoride) and 1 MHz (in resonators made of electro-optic crystals such as lithium tantalate and lithium niobate). It should be emphasized that this bandwidth is realized in packaged devices, with evanescent couplers attached and critically coupled to mode-matched beams from a laser of choice. We achieve this through 1) maintaining highest possible unloaded Q factor from fabrication through integration; 2) executing high tolerance of resonator geometry to facilitate mode matching to the laser, and eliminating mode scrambling and crosstalk.

The values of the routinely obtained unloaded optical bandwidth are < 30 kHz in fluorite resonators, and < 300 kHz in lithium tantalate resonators, giving ample room for one or two critically coupled mode matched evanescent ports for device integration. The operational microwave frequency in our microresonator based oscillators coincides with the free spectral range determined by round-trip of light within the microresonators and scales from 5 to 40 GHz, depending on the resonator size and host material. Unlike single-mode microtoroidal resonators utilized in high-repetition-rate high-power-pumped optical comb generators, our resonators possess much larger mode volume and may exhibit dense spectrum unless the resonator geometry is properly selected, and resonator and the pumping optical beam are properly matched.

8989-11, Session 4

Observation of optically induced transparency effect in silicon nanophotonic wires with graphene

Longhai Yu, Jiajiu Zheng, Daoxin Dai, Sailing He, Zhejiang Univ. (China)

Graphene, a well-known two-dimensional sheet of carbon atoms in a honeycomb structure, has many unique and fascinating properties in optoelectronics and photonics. Integration of graphene on silicon nanophotonic wires is a promise approach to enhance light-graphene interactions. In this paper, we demonstrate on-chip silicon nanophotonic wires covered by graphene with CMOS-compatible fabrication processes. Under the illumination of pump light on the graphene sheet, a loss reduction of silicon nanophotonic wires, which is called optically induced transparency (OIT) effect, is observed over a broad wavelength range for the first time. The pump power required to generate the OIT effect is as low as ~0.1mW and the corresponding power density is about 2x103mW/cm2, which is significantly different from the saturated absorption effect of graphene reported previously. This implies a new mechanism for the present OIT effect, which will be beneficial to realize silicon on-chip all-optical controlling in the future. It also suggests a new and efficient approach to tune the carrier concentration (doping level) in graphene optically.

8989-29, Session PWed

Plastic and atmosphere two medium Infrared photonic detector switch

Tao Yang, Jilin Electric Power Survey & Design Institute (China); Yujing Yang, Jilin Teacher's Institute of Engineering & Technology (China)

In the past year, photonic switch usually used only atmosphere medium, and if Infrared light goes a long way such as 9cm, the photonic switch will does not work. But now we have a new method and circuits to solve the problem. Infrared light now can goes through atmosphere and plastic two medium and a long distance above 9cm. The products will be used on the much more application field such as the elevator and industry control system and etc..

8989-30, Session PWed

Low-loss and low-crosstalk graded-index polymer optical waveguide circuit fabricated using an imprint method

Yohei Yamashita, Takaaki Ishigure, Keio Univ. (Japan)

To sustain the growth of computing performances, high bandwidth data throughput between the nodes are required for high-performance computers maintaining low power consumption. Hence, optical interconnection technologies are regarded as one of the feasible solutions, and multimode polymer parallel optical waveguides have been anticipated for realizing high-bandwidth-density on-board optical interconnects. In particular, for the chip-to-chip interconnects on a board, polymer waveguide circuits comprised of curved and crossed waveguides in addition to straight one would be key components.

We have demonstrated that low loss and low inter-channel crosstalk are achieved by graded-index (GI)-core polymer waveguides compared to conventional step-index (SI) waveguides. Then, we found that the imprint method was capable of fabricating GI-core waveguide circuits with a simplicity and low cost. However, anticipated low-loss and low-crosstalk have not yet experimentally obtained. One of the causes of high loss could be a bridged structure over the cores due to a residual core layer: sometimes observed in polymer waveguides fabricated using the imprint method.

In this paper, we improve the fabrication procedure of the imprint method to obtain low-loss and low-crosstalk GI-core waveguides: particularly focus on eliminating the bridged structure. We experimentally demonstrate that the GI-core waveguides fabricated using the modified imprinting method show lower loss and lower crosstalk than SI-core waveguide fabricated using the same material by the same method, even if a slight bridged structure remains. Furthermore, by applying this method to fabricate perpendicularly crossed waveguides, we also demonstrate that GI-core waveguides significantly reduce the loss due to the crossings.

8989-31, Session PWed

Inter-channel crosstalk in densely aligned multimode polymer parallel optical waveguides

Takuya Kudo, Takaaki Ishigure, Keio Univ. (Japan)

In accordance with the rapid performance increase of high-performance computers, optical printed circuit boards (O-PCBs) incorporated with multimode polymer optical waveguides are highly expected for realizing board-level optical interconnects. In these days, narrower channel-pitch has been strongly anticipated for polymer waveguides, and thus the inter-channel crosstalk in optical waveguides is of concern. We have proposed to apply graded-index (GI) core multimode polymer optical waveguides to O-PCBs, and have demonstrated the capabilities of high-bandwidth-density board-level optical interconnect by the GI-core waveguides .

In terms of the fabrication method of polymer optical waveguides, the imprinting method is a well-known inexpensive candidate. However, the "residual layer" after removing the stamp has been a key issue, because the residual layer could form a bridge between the cores parallel aligned, which could increase the inter-channel crosstalk.

Hence, in this paper, we theoretically estimate the inter-channel crosstalk in densely aligned multimode parallel waveguides using a beam propagation method (BPM). Then, we compare the results of GI-core waveguide with those of conventional step-index (SI)-core counterpart.

We simulate the crosstalk in bridged core waveguides by varying the bridge thickness from 1 ?m to 5 ?m. The inter-channel crosstalk in SI-core waveguide increases from -25 dB to -4 dB with increasing the bridge thickness. Contrastingly, the worst inter-channel crosstalk in GI-core is as low as -15 dB when the bridge has a 5-?m thickness. Thus, the imprinting method should be utilized for fabricating GI-core waveguides, because the inter-channel crosstalk is un-problematic even if a residual layer remains.

8989-12, Session 5

Recent results in silicon photonics at the University of Southampton *(Invited Paper)*

Graham T. Reed, Goran Z. Mashanovich, Frederic Y. Gardes, David J. Thomson, Youfang Hu, Jordi Soler Penades, Milos Nedeljkovic, A. Khokar, P. Thomas, Callum Littlejohns, A. Ahmad, Scott Reynolds, Rob P. Topley, C. Mitchell, S. Stankovic, Nathan Owens, Xia Chen, P. R. Wilson, L. Ke, Taha M. Ben Masaud, A. Tarazona, Harold M. H. Chong, Univ. of Southampton (United Kingdom)

In this paper we will discuss recent results in our work on Silicon Photonics. This will include active and passive devices for a range of applications. Specifically we will include work on Mid IR silicon photonics, modulators and drivers, deposited waveguides, multiplexers and device integration. These devices and technologies are important both for established applications such as integrated transceivers for short reach interconnect, as well as emerging applications such as disposable sensors and mass market photonics.

8989-13, Session 5

Silicon photonic modulators and receivers for short reach optical interconnects *(Invited Paper)*

David V. Plant, McGill Univ. (Canada)

We review silicon photonic based modulators (Mach-Zhender and ring based devices) and receivers (direct detection and coherent) applicable in short reach optical interconnects. Novel device designs and experimental results will be presented.

8989-14, Session 5

Electronic interfaces to silicon photonics *(Invited Paper)*

Anthony L. Lentine, Jonathan A. Cox, William A. Zortman, Daniel J. Savignon, Sandia National Labs. (United States)

No Abstract Available

8989-15, Session 5

Design methodologies for silicon photonic integrated circuits *(Invited Paper)*

Lukas Chrostowski, The Univ. of British Columbia (Canada)

No Abstract Available

8989-16, Session 5

Traveling wave electrode design for ultra-compact carrier-injection HBT-based electroabsorption modulator in a 130nm BiCMOS process

Enjin Fu, Valencia M. J. Koomson, Tufts Univ. (United States); Pengfei Wu, Z. Rena Huang, Rensselaer Polytechnic Institute (United States)

Silicon photonic system, integrating photonic and electronic signal processing circuits in low-cost silicon CMOS processes, is a rapidly evolving area of research. The silicon electroabsorption modulator (EAM) is a key photonic device for emerging high capacity telecommunication networks to meet ever growing computing demands. To replace traditional large footprint Mach-Zehnder Interferometer (MZI) type modulators several small footprint modulators are being researched. Carrier-injection modulators can provide large free carrier density change, high modulation efficiency, and compact footprint. The large optical bandwidth and ultra-fast transit time of 130nm HBT device make the carrier-injection HBT-based EAM (HBT-EAM) a good candidate for ultra high-speed optical networks.

This paper presents the design and 3D full-wave simulation results of a traveling wave electrode (TWE) structure to increase the modulation speed of a carrier-injection HBT-EAM device. A monolithic TWE design for an 180um ultra compact carrier-injection-based HBT-EAM implemented in a commercial 130nm SiGe BiCMOS process is discussed. The modulator is electrically modeled at the desired bias voltage and included in a 3D full-wave simulation using CST software. The simulation shows the TWE has a S11 lower than -17.8dB and a S21 better than -1.22dB covering a bandwidth from DC-60GHz. The electrical wave phase velocity is designed close to the optical wave phase velocity for optimal modulation speed. The 3D TWE design conforms to the design rules of the BiCMOS process. Simulation results show an overall increase in modulator data rate from 10Gbps to 60Gbps using the TWE structure.

8989-17, Session 5

An integrated CMOS detection system for optical short-pulse

Chang-Gun Kim, Young-Wan Choi, Nam-Pyo Hong, Chung-Ang Univ. (Korea, Republic of)

Recently, a number of devices using nuclear in medical industry has been increased. Among nuclear sources, gamma ray (?-ray) emitted by a radioactive isotope can be used to find position of cancer cell based on Compton Effect. When gamma ray reflected by cancer cell hits multi-channel double sided silicon detector (DSSD), electron and hole pairs corresponding charge signal are generated abruptly. To process this short-pulse signal in DSSD, existing systems are expense and also hard to manage due to their large size and huge power consumption. Hence, an integration of front-end readout electronics for bulky system is required. In other words, We need signal processing that can detect low-level signals under noisy environments with low energy consumption. In this work, we design a CMOS charge sensitive amplifier (CSA) and shapers for pulse signal detection. Each channel of the DSSD includes a CSA followed by two parallel CR-RC Gaussian pulse shapers. Here, the CSA is used to convert charge signal to voltage signal. Slow and fast shapers are used to measure the energy and to prevent pile-up distortion. The proposed CSA presents an open loop gain of 100 dB, phase margin of 68 degrees and gain bandwidth of 9.7 MHz assuring a high stability, and that is composed of negative feedback schematic using pseudo-resistor to reduce chip area. The shaping times of fast and slow shapers are 500 ns and 8 ?s, respectively. More detailed experimental results and discussions on CSA and shapers will be presented.

8989-18, Session 6

Local slow-light engineering: a strategic way to use slow light *(Invited Paper)*

Khaled Mnaymneh, Univ. of Michigan (United States)

Creating optical signals in nanostructured materials (like photonic crystals) at room-temperature for integrated optics with extraordinary small group velocities has the desired advantage of increasing light-matter interactions so that non-linear effects, such as switching and frequency conversion, can be harnessed for next-generation information processing. However, the great promise that makes slow-light possible is also it's greatest threat - large interactions also means large scattering losses. In this talk, I review the concepts of slow-light in structured media and its pitfalls but at the same time I demonstrate a strategic, smarter way to use slow-light. As an example, I will focus on a slow-light biosensor.

8989-19, Session 6

Towards optoelectronic architectures for integrated neuromorphic processors

Romain Martinenghi, Antonio Baylón Fuentes, Maxime Jacquot, Yanne K. Chembo, Laurent Larger, FEMTO-ST (France)

We investigate theoretically and experimentally the computational properties of an optoelectronic neuromorphic processor based on a complex nonlinear dynamics. This neuromorphic approach is based on a new paradigm of or reservoir computing, which is intrinsically different from the concept of Turing machines. It essentially consists in expanding the input information to be processed into a higher dimensional phase space, through the nonlinear transient response of a complex dynamics excited by the input information. The computed output is then extracted via a linear separation of the transient trajectory in the complex phase space, performed through a learning phase consisting of the resolution of a regression problem. We here investigate two architectures for photonic neuromorphic computing via these complex nonlinear dynamical transients. First, a versatile photonic nonlinear transient computer based on a multiple-delay is reported. Its hybrid analogue and digital architecture allows for an easy reconfiguration, and for direct implementation of in-line processing. Its computational efficiency in parameter space is also reported. Secondly, a processor based on electro-optic nonlinear delay phase dynamics is designed with Telecom grade devices, allowing up to 10GHz bandwidth for information processing according to Reservoir Computing concepts. In both cases, the computational performance is successfully evaluated on a standard spoken digit recognition task. We then discuss the pathways that can lead to the effective integration of such systems.

8989-20, Session 6

Precision alignment of integrated optics in surface electrode ion traps for quantum information processing

Amber L. Young, Jeffrey D. Hunker, A. Robert Ellis, Daniel L. Stick, Sally Samora, Joel R. Wendt, Sandia National Labs. (United States)

The integration of optics for efficient light delivery and the collection of fluorescence from trapped ions in surface electrode ion traps is a key component to achieving scalability for quantum information processing. Diffractive optical elements (DOEs) present a promising approach as compared to bulk optics because of their small physical profile and their flexibility in tailoring the optical wavefront. The precise alignment of the optics for coupling fluorescence to and from the ions, however, poses a particular challenge. Excitation and manipulation of the ions requires a high degree of optical access, significantly restricting the area available for mounting components. The ion traps, DOEs, and other components are compact, constraining the manipulation of various elements.
For efficient fluorescence collection from the ions the DOE must be have a large numerical aperture, which results in greater sensitivity to misalignment. The ion traps are sensitive devices, a mechanical approach to alignment such as contacting the trap and using precision motors to back-off a set distance not only cannot achieve the desired alignment precision, but risks damage to the ion trap.

We have developed a non-contact precision optical alignment technique that uses line foci produced by off-axis linear Fresnel zone plates (FZPs) projected on alignment targets etched in the top metal layer of the ion trap to demonstrate micron-level alignment accuracy.

8989-21, Session 7

LiDAR sensors for real-time high-accuracy 3D mapping and object detection, tracking, identification, and classification

Louay A. Eldada, Quanergy, Inc. (United States)

We present advanced designs and fabrication technologies used for the production of light detection and ranging (LiDAR) sensors that enable real-time high-accuracy 3D mapping and object detection, tracking, identification and classification. We also describe sensor data fusion between 3D point clouds generated by LiDAR sensors and color images captured by video cameras to generate color point clouds or RGBD (Red, Green, Blue, Depth) data.

8989-22, Session 7

Monolithic device for on-chip fast optical phase conjugation integrating an image sensor and a spatial light modulator

Timothe LaForest, Antoine Dupret, Arnaud Verdant, CEA-LETI-Minatec (France); François Ramaz, Ecole Supérieure de Physique et de Chimie Industrielles (France); Sylvain Gigan, Institut Langevin (France); Gilles Tessier, Ecole Supérieure de Physique et de Chimie Industrielles (France); Emilie Benoit à la Guillaume, Institut Langevin, ESPCI ParisTech, CNRS UMR 7587 (France)

Optical phase conjugation finds many applications in various fields, such as medical imaging, optical data storage, endoscopy, etc… Digital optical phase conjugation (DOPC), i.e. using pixilated devices, is a technique in progress but suffers from several bottlenecks compared to techniques based on holography in photorefractive crystals or dynamic holography in a gain medium. In fact, the use electronic devices for optical phase conjugation means that the electronic delays must be compliant with the optical response of the setup. This is the main problem when in vivo image are considered because the correlation time of a tissue imaging in vivo is no longer than few milliseconds. Another issue with optical imaging in biological imaging is the light scattering. Acousto-optic imaging is a technique to obtain optical information of a tissue with a millimetric resolution. This technique is based on heterodyne detection of a holographic signal. Indeed, in order to get phase and amplitude information of the acousto-optic signal, the acquisition of 4 holograms is necessary. These 4 holograms must be recorded before the transmitted intensity through the sample decorrelates.

In that scope, we propose a new device for the acquisition of 4 images at 4 kHz, and on-chip DOPC. The pixel device is made of a liquid crystals layer over CMOS photodiodes array. Thus, the measured signal in the photodiode can be processed at pixel-level, in order to control the liquid crystals cell without sending the image out of the sensor and without an external addressing of the SLM. We show that the device will be

compliant with correlation time of biological tissues, i.e. the loop time between intensity measurement of interference and addressing of the liquid crystals layer is about few milliseconds, including response time of the liquid crystals molecules. Finally, the 16 µm pixels pitch array of our device allows a good sampling of holographic images.

8989-23, Session 7

Integrated ridge waveguides in germanium on gallium arsenide for long wavelength infrared detection of chemical warfare simulant triethylphosphate

Parker Wray, Yi Zou, The Univ. of Texas at Austin (United States); Swapnajit Chakravarty, Omega Optics, Inc. (United States); Dakota Crisp, Southeast Missouri State Univ. (United States); Ray T. Chen, The Univ. of Texas at Austin (United States)

Terrorists' use of nerve agents causes a deep concern for the United States and its soldiers. Infrared spectroscopy has proven an effective way of detecting such rogue chemicals. However, the equipment is bulky and cannot be used dynamically. Lab-on-chip sensors using guided wave devices, for diode laser absorption spectroscopy, provides an effective solution to address the need for portable chemical detectors. Guided wave absorption spectroscopy devices have been demonstrated in the near-infrared for the detection of volatile organic compounds and greenhouse gases. However, the absorbance signatures of chemical warfare simulants are weaker in the near-infrared than at the longer wavelengths in the mid- and far-infrared. Unfortunately, long wavelength guided wave devices for absorption spectroscopyare unavailable due to the lack of appropriate core and cladding materials. These materials need to provide the ability to guide light with sufficient optical confinement at the wavelength of 9.5 micron for instance, which is a peak absorbance of the chemical warfare simulant triethylphosphate.We have experimentally demonstrated ridge waveguides in single crystal germanium on lattice-matched gallium arsenide substrates guiding light at 9.5 micron. A glass cell is mounted on the device within which the triethylphosphate vapors from an adjacent vapor generation apparatus, interacts with the optical waveguide. In this paper,we describe optical measurements to measure guided wave propagation using end-fire coupling into and out of the optical waveguides. Methods to measure propagation loss of the 9.5 micron waveguide will be presented. Finally, sensing of triethylphosphate in liquid and vapor form will be demonstrated.

8989-24, Session 7

Glucose sensing by means of silicon photonics *(Invited Paper)*

Ronny Bockstaele, Ghent University (Belgium); Eva Ryckeboer, Nannicha Hattasan, Yannick De Koninck, Muhammad Muneeb, Steven Verstuyft, Danaë G. Delbeke, Wim Bogaerts, Gunther Roelkens, Roel G. Baets, Univ. Gent (Belgium)

No Abstract Available

8989-25, Session 7

A novel phase-sensitive SPR biosensor array based on prism phase modulator

Gaoao Ye, Wei Yang, Li Jiang, Jun Qian, Zhejiang University, China (China); Sailing He, KTH Royal Institute of Technology (Sweden)

No Abstract Available

8989-26, Session 8

Highly-efficient nanofocusing for integrated on-chip nanophotonics *(Invited Paper)*

Hyuck Choo, California Institute of Technology (United States)

The development of techniques for confining photons efficiently on the deep sub-wavelength spatial scale will revolutionize scientific research and engineering practices. The efficient coupling of light into extremely small nanoscale spaces has posed a major challenge in on-chip nanophotonics due to the need to overcome various loss mechanisms and the on-chip nanofabrication challenges. Here, we present the experimentally demonstrated achievement of highly efficient nanofocusing in an Au-SiO2-Au gap plasmon waveguide using a carefully engineered 3D taper. The dimensions of the SiO2 layer, perpendicular to the direction of wave propagation, tapered linearly below 100 nm. In simulation, the 3D linear-tapering approach could focus 830 nm light into a 2-by-5 nm2 area with ≤3 dB loss and an intensity enhancement of 3.0 x 104. In a two-photon luminescence measurement, the device achieved an intensity enhancement of 400 within a 14-by-80 nm2 area and transmittance of 74%.

Taking a step further, we propose an integration of the 3D linearly tapered gap plasmon waveguide and impedance-tuning plasmonic crystals to achieve even more efficient nanoscale on-chip light confinement and manipulation. The proposed nanoplasmonic structure could achieve an unprecedented maximum intensity enhancement of ~104 within a 103-nm3 volume, with coupling efficiency exceeding 70%. Because of its noticeably high degree of light confinement and throughput, the integrated device could potentially be used to implement nanoscale on-chip terahertz light sources and detectors for next-generation computing and communication applications.

8989-27, Session 8

Mode conversion/coupling in submicron SOI (silicon-on-insulator) waveguides and the applications *(Invited Paper)*

Daoxin Dai, Zhejiang Univ. (China)

Submicron silicon-on-insulator (SOI) optical waveguides, which has ultra-high index contrast and ultra-small cross section, provide a very promising way to realize nano-photonic integrated circuits (PICs) with high integration density. For the functionality elements realized with submicron SOI optical waveguides, mode conversion and mode coupling play an important role. In this paper, we give a review for our recent work including the following parts. First, the polarization-dependent mode conversion happening in a tapered submicron SOI optical waveguides is demonstrated experimentally as well as analyzed theoretically. Such a kind of mode conversion is applied to realize polarization rotation with simple fabrication processes. Second, the mode coupling/conversion between two optical waveguides forming an asymmetrical directional coupler (ADC) is also summarized. Such an ADC has been used to realize ultrasmall polarization-beam splitters (PBS) as well as a seamless integration between different types of optical waveguides. ADCs have been also developed to realize ultra-compact, ultra-broadband mode multiplexers, which is very important to enable ultra-high speed optical interconnects with a multimode optical waveguide. Our recent theoretical and experimental work on mode multiplexers is reviewed finally.

8989-28, Session 8

Metal membrane with dimer slots as a universal polarizer

Sergej V. Zhukovsky, DTU Fotonik (Denmark); Maksim Zalkovskij, Radu Malureanu, Technical Univ. of Denmark (Denmark); Christian Kremers, Bergische Univ. Wuppertal (Germany); Dmitry N. Chigrin, Bergische Univ. Wuppertal (Germany) and RWTH Aachen (Germany); Peter T. Tang, IPU (Denmark); Peter U. Jepsen, DTU Fotonik (Denmark); Andrei V. Lavrinenko, Technical Univ. of Denmark (Denmark)

In this work, we show theoretically and confirm experimentally that thin metal membranes patterned with an array of slot dimers (or their Babinet analogue with metal rods) can function as a versatile spectral and polarization filter. We present a detailed covariant multipole theory for the electromagnetic response of an arbitrary dimer based on the Green functions approach. The theory confirms that a great variety of polarization properties, such as birefringence, chirality and elliptical dichroism, can be achieved in a metal layer with such slot-dimer patterning (i.e. in a metasurface). Optical properties of the metasurface can be extensively tuned by varying the geometry (shape and dimensions) of the dimer, for example, by adjusting the sizes and mutual placement of the slots (e.g. inter-slot distance and alignment angle). Three basic shapes of dimers are analyzed: II-shaped (parallel slots), V-shaped, and T-shaped. The T-shaped dimer is found to be so sensitive to the variations of the slots lengths that all possible polarization states on any trajectory from one pole of the Poincare sphere to its equator can be produced. Theoretical results are well supported by full-wave three-dimensional simulations. Our findings were verified experimentally on the metal membranes fabricated using UV lithography with subsequent Ni growth. Such metasurfaces were characterized using time-domain THz spectroscopy. The samples exhibit pronounced optical activity (500 degrees per wavelength) and high transmission: even though the slots cover only 4.3 % of the total membrane area the amplitude transmission reaches 0.67 at the resonance frequency 0.56 THz.

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8990-1, Session 1

A compact and low-loss silicon waveguide crossing for O-band optical interconnect

Yi Zhang, Univ. of Delaware (United States); Matthew Streshinsky, Ari Novack, A*STAR Institute of Microelectronics (Singapore) and National Univ. of Singapore (Singapore); Yangjin Ma, Shuyu Yang, Univ. of Delaware (United States); Andy E. J. Lim, Guo-Qiang Lo, A*STAR Institute of Microelectronics (Singapore); Tom W. Baehr-Jones, Univ. of Delaware (United States); Michael Hochberg, A*STAR Institute of Microelectronics (Singapore) and Univ. of Delaware (United States) and National Univ. of Singapore (Singapore)

Silicon photonics attracts extensive attention in recent years as a promising solution for next generation high-speed, low energy consumption, and low lost data transmission system. Although a few experiments indicated board-level and long haul communication capability is possible, major and near-future application of silicon photonics is commonly seen as Ethernet at 100Gb/s and beyond, such as interconnect in data centers, where O-Band has been standardized for its low fiber dispersion. However, almost all silicon photonics devices demonstrated up to date operate at C band, the fiber loss and erbium amplification window, probably due to the wider availability of lasers and testing apparatus at this wavelength. C-Band devices cannot operate at O-Band, despite the fact they share similar physics. A C-band single mode waveguide starts to support higher order modes at O-Band, let alone differences devices like multiplexer, modulator, and photodetector. Thus whole device library need to be redesigned and recalibrated for O-Band application. In this paper, we present an ultra compact, low loss, and low cross-talk waveguide crossing operating at O-Band. It is designed using finite difference time domain (FDTD) method coupled with particle swarm optimization (PSO). Device footprint is only 6um x 6um. Measured insertion loss is 0.19+/-0.02 dB, uniform across an 8-inch wafer. Cross talk is better than -35 dB, limited by testing. Waveguide crossing is an essential component for complex photonic integrated circuit, since optical signal cannot be routed using multiple-layer topology as electrical signal does. Characterization of the rest of device library is undergoing.

8990-2, Session 1

Launching of multi-project wafer runs in ePIXfab with micron-scale silicon rib waveguide technology

Timo Aalto, Matteo Cherchi, Mikko Harjanne, Sami Ylinen, Markku Kapulainen, Tapani Vehmas, VTT Technical Research Ctr. of Finland (Finland)

For several years the silicon photonics community has been able to benefit from significant cost sharing in the form of multi-project wafer (MPW) runs that were first introduced by ePIXfab and later offered by others too. The MPW service offering has expanded from passive devices to various active devices, and even to electronics integration with the optics. So far this has been exclusively based on submicron silicon-on-insulator (SOI) waveguides with 220 nm as the most common SOI thickness.

In this paper we introduce new MPW offering that is launched by VTT through ePIXfab. It is based on micron-scale SOI rib waveguides with 3 µm as the baseline SOI thickness. This technology offers a unique combination of single-mode and ultra-broadband operation, low coupling and propagation losses, small polarisation dependency, and small footprint. Together these characteristics provide complementarity to the existing MPW services and open up new application opportunities for silicon photonics.

In addition to an overview of our SOI platform and the new MPW offering we present some recent device and application highlights. While micron-scale waveguides typically require mm or cm-scale bends, bending radii of a few µm are now possible in 3 µm SOI with negligible losses. We also demonstrate crossings with negligible loss and cross-talk, as well as functional components for filtering, tuning, switching etc. Also the ongoing development of monolithically integrated active components, novel low-temperature flip-chip concepts and low-loss packaging will be described. Some example applications for this generic technology will be presented, including optical communication and sensing.

8990-3, Session 1

The Euler bend: paving the way for high-density integration on micron-scale semiconductor platforms

Matteo Cherchi, Sami Ylinen, Mikko Harjanne, Markku Kapulainen, Tapani Vehmas, Timo Aalto, VTT Technical Research Ctr. of Finland (Finland)

We present our recent breakthrough for high density integration in micron-scale thick semiconductor platform. The novel bend concept is presented from a theoretical and simulation point of view Experimental results are shown based on silicon strip waveguides fabricated on 4 ?m thick Silicon on Insulator wafers. The high confinement of micron-scale strip waveguides completely suppresses radiation losses, while coupling to higher order modes is suitably suppressed by a suitable bend shape design based on the Euler spiral. The design method is presented and supported by the experimental results. The proposed approach enabled for example the realization of 180° bends with 1.27 µm effective radii and 0.09 dB loss, which are the smallest low-loss bends ever reported for an optical waveguide. Bends with larger bending radii have been shown to have losses smaller than 0.01 dB per turn on a very broad wavelength range. Some experimental applications to resonators, spirals, and Mach-Zehnder interferometers are also presented, along with envisaged applications to other semiconductor platforms. A special focus will be dedicated to potential applications in III-V platforms. In fact the novel bend could lead to unprecedented dense integration of active devices as well as to novel concepts for active components, including lasers and semiconductor optical amplifiers.

8990-4, Session 1

Low-loss spiral waveguides with ultra-small footprint on a micron scale SOI platform

Matteo Cherchi, Sami Ylinen, Markku Kapulainen, Mikko Harjanne, Tapani Vehmas, Timo Aalto, VTT Technical Research Ctr. of Finland (Finland)

We have recently characterized spirals waveguides fabricated on 4 ?m thick Silicon on Insulator (SOI) wafers. They are based on low-loss strip waveguides and suitably designed low-loss micron scale bends. Spirals with different bends (bending radii ranging from 8.6 µm to 184.5 µm) and different lengths (from 0.38 cm to 146.24 cm) have been tested to extrapolate propagation losses and bending losses. In particular lowest bending losses have been found to be smaller than 0.01 dB per turn, while propagation losses are about 0.15 dB/cm, i.e. one order of magnitude smaller than typical losses of submicron silicon waveguides. The spirals can also have very small footprint, thanks to the novel micron-

scale bends that we have recently developed. For example a 52.57 cm long spiral based on a bend with 69 µm effective bending radius has a foot print of just 2.3 mm2 and an overall 12 dB propagation loss, which means an effective combined propagation loss of about 0.23 dB/cm. This was obtained with a non-optimal bend and a 2 µm gap between adjacent waveguides. In the sake for a smaller footprint, the gap could also be shrinked down to about 1 µm, since coupling between the highly confined modes of our waveguides is almost negligible. The unique combination of low propagation losses, low loss micron-scale bends and waveguide pitches of a few microns, makes our silicon photonics platform the ideal one for low loss long spiral waveguides with very small footprint.

8990-5, Session 1

A new generation of ultra-dense optical I/O for silicon photonics *(Invited Paper)*

Mitchell S. Wlodawski, Victor I. Kopp, Jongchul Park, Jonathan Singer, Eric E. Hubner, Daniel Neugroschl, Norman Chao, Azriel Z. Genack, Chiral Photonics, Inc. (United States)

Responding to the optical packaging needs of a rapidly growing silicon photonics market, we have developed a new generation of ultra-dense-channel, all-optical, input/output (I/O) couplers that bridge the gap between standard optical fibers and photonic integrated circuits. These couplers, or Pitch Reducing Optical Fiber Arrays (PROFAs), provide a means to simultaneously match both the mode field and channel spacing, or pitch, in an optical fiber array and a photonic integrated circuit (PIC) I/O. Both primary methods for optically interfacing with PICs, via vertical coupled gratings and edge couplers, can be addressed with PROFAs. PROFAs bring the signal-carrying cores, either multimode or singlemode, of many optical fibers into close proximity within a device that can couple, with low insertion loss, into on-chip components, including waveguides, gratings, detectors and emitters. Two-dimensional (2D) PROFAs offer more than an order of magnitude enhancement in channel density compared to conventional one-dimensional (1D) fiber arrays. PROFAs also offer low vertical profile solutions with integrated optical fibers that simplify optoelectronic packaging while reducing PIC I/O real estate requirements.

1D and 2D arrayed packaged solutions for both die edge and face coupling are presented along with corresponding PIC design considerations regarding waveguide and vertically coupled gratings.

8990-6, Session 1

A high-performance SOI grating coupler with completely vertical emission

Hsin-Lun Tseng, Chih-Wei Tseng, National Tsing Hua Univ. (Taiwan); Neil Na, National Tsing Hua Univ. (Taiwan); Erik Chen, Forelux Inc. (Taiwan)

Silicon-on-insulator grating coupler is a crucial passive device that enables the coupling of light into and out of a sub-micron, silicon-based photonic integrated circuit. In particular, a grating coupler with completely vertical emission is vital for interfacing surface-emitting/receiving optoelectronic devices, and can largely reduce the packaging cost and complexity due to off-normal configuration. Unfortunately, for a grating coupler with completely vertical emission, it inevitably induces the second-order diffraction that significantly degrades the coupling efficiency and enhances the backreflection. In this work, we propose and study a new concept for making a high-performance grating coupler with completely vertical emission. Following our design strategy, we numerically show that a total coupling loss ~ 1 dB, a backreflection < -20 dB, and a spectral linewidth > 20 nm can be achieved at the same time (without full optimization), when our grating coupler is butt-coupled to a standard single-mode fiber operating at 1310 nm wavelength.

Compared to the previous proposals such as slant grating, polymer wedge, and entrance mirror made by slit or chirped grating, our approach requires only a simple uniform grating and two etch steps to achieve the desired high performances. The full optimization algorithms and possible fabrication procedures will also be presented.

8990-7, Session 2

Erasable diffractive grating couplers for wafer scale testing in silicon-on-insulator

Rob P. Topley, Gregorio Martinez-Jimenez, Univ. of Southampton (United Kingdom); Liam O'Faolain, Univ. of St. Andrews (United Kingdom); Noel Healy, Sakellaris Mailis, David J. Thompson, Frederic Y. Gardes, Anna C. Peacock, David N. Payne, Goran Z. Mashanovich, Graham T. Reed, Univ. of Southampton (United Kingdom)

Test points are essential in allowing optical circuits on a wafer to be autonomously tested after selected manufacturing steps, hence allowing poor performance or device failures to be detected early and to be either repaired using direct write methods or a cessation of further processing to reduce fabrication costs.

Grating couplers are a commonly used method for efficiently coupling light from an optical fiber to a silicon waveguide, they are relatively easy to fabricate and they allow light to be coupled out from any location on the device without the need for polishing , making them the perfect candidate for an optical test point.

A fixed test point can be added for this purpose, traditionally however these devices are fabricated by etching the silicon waveguide, and hence this permanently adds loss and leads to a poor performing device when placed into use.

We demonstrate a similar device utilising a refractive index change induced by lattice disorder. Lattice disorder can later be removed using localised laser annealing methods once the testing has been completed, rendering the final device operation as a working, high performance device, unimpaired by the testing process. This technology has the potential to improve yield and reduce manufacturing costs of silicon photonics integrated circuits.

8990-8, Session 2

Cost-effective single-etched TM-mode SOI grating couplers for broadband perfectly vertical coupling

George Dabos, Aristotle Univ. of Thessaloniki (Greece); Dimitrios Kalavrouziotis, National Technical Univ. of Athens (Greece); Jens Bolten, Andreas Prinzen, AMO GmbH (Germany); Nikos Pleros, Aristotle Univ. of Thessaloniki (Greece); Dimitris M. Tsiokos, Aristotle Univ. of Thessaloniki (Greece) and Ctr. for Research and Technology Hellas (Greece)

Future mass deployment of affordable silicon-on-insulator (SOI)-based photonic integrated circuits will require ultra wide-band operation, low-cost CMOS compatible fabrication processes as well as simplified assembly and packaging techniques. In this context, the grating coupler demonstrating perfectly vertical source-to-chip coupling was introduced as the key enabling component tolerant to the fiber-to-silicon waveguide mode mismatch relaxing coupling alignment requirements. In addition, perfectly vertical incidence simplifies chip assembly allowing for simple vertical bonding techniques. However, vertical coupling structures so far proposed require two or more lithography/etching steps, use additional mirrors or deploy slotted waveguides significantly increasing fabrication complexity and cost or even disregarding CMOS compatibility. Motivated by the above rationale, we present two designs of broadband, fully etched TM-mode grating couplers for perfectly vertical coupling,

requiring one etching step during fabrication and maintaining CMOS compatibility. The first design refers to a uniform grating consisting of 22 periods with 670 nm period length, exhibiting 5.6 dB coupling losses at 1564 nm and a 3dB bandwidth of 32 nm. In addition, we show how the 3dB bandwidth is extended from 32 to 76 nm by adding a chirped section at the front end of the uniform section. The ultra-wideband coupler can be used across all C-band as well as in S and L bands, it is realized at no expense of fabrication complexity while coupling efficiency is maintained. The coupling efficiency can be improved if the grating gap is decreased below 80 nm yet increasing fabrication resolution requirements. The proposed structures are currently being fabricated.

8990-9, Session 2

Tolerance analysis for efficient MMI devices in silicon photonics

Carmen Vázquez García, Alberto Tapetado, Massachusetts Institute of Technology (United States) and Univ. Carlos III de Madrid (Spain); Jason S. Orcutt, Huaiyu C. Meng, Rajeev J. Ram, Massachusetts Institute of Technology (United States)

Silicon is considered a promising platform for photonic integrated circuits (PIC) as PICs can be fabricated in state-of-the-art electronics foundaries with integrated CMOS electronics [Orcutt et al, 2011], [Meade et al, 2013]. Besides, the high index contrast between silicon or polysilicon and silicon dioxide allows manufacturing waveguides with submicron cross sections and very small bending radii, leading to high integration density. While much of the existing work on CMOS photonics [Orcutt et al, 2011][Meade et al, 2013] has used directional couplers for power splitting, MMI devices may have relaxed fabrication requirements and smaller footprints [Besse et al, 1994] compared to other configurations based on coupling between parallel waveguides, potentially energy efficient designs. MMI devices have already been used as 1x2 splitters, 2x1 combiners in QPSK modulators [Dong et al, 2012], 3dB couplers in ring resonators [Xu et al, 2007] and cross couplers for switches [Leuthold et al, 2001] [Wang et al, 2006]. State-of-the-art CMOS manufacturing processes have sub-nanometer lithographic precision. In contrast, the lower resolution photolithography available for InP devices coupled with the precision of epitaxial growth results in the device width being the most variable dimension in InP, meanwhile CMOS layer thicknesses is less accurately controlled than InP epitaxial film thickness.

In this work, 3dB, butterfly and cross MMI couplers, based on silicon waveguides are realized on bulk CMOS technology [Meade et al, 2013]. Footprints around 60um2 are obtained. MMI tolerances to manufacturing process and bandwidth are analyzed and tested showing the robustness of the MMI devices. Due to the high contrast ratio of these waveguides 3D-FDTD simulations are performed to get accurate designs [Vazquez et al, 1994].

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8990-10, Session 2

Monolithic integration of micron to sub-micron waveguides with 2D mode-size converters in SOI platform *(Invited Paper)*

Sujith Chandran, Saket Kaushal, Bijoy K. Das, Indian Institute of Technology Madras (India)

CMOS compatible sub-micron photonic wire waveguides (PhWWs) in SOI platform are used for the realization of compact photonic devices. However, waveguides with larger cross-sections (~2 µm) are preferred for polarization independent and/or dispersion-free performance [1]. Besides, waveguides with lower cross-sections are tapered to a larger cross-section (>5 µm) to improve fiber-chip-fiber light coupling [2]. Therefore, integration of waveguides with varying cross-sections on the same substrate platform is highly demanding. We present here the experimental demonstration of 2D mode-size converter that is useful to couple light from large cross-section waveguide devices to smaller cross-section waveguide devices and vice versa. We have used SOI substrate with a device layer thickness of 5 µm to fabricate large cross-section rib waveguides (LCRWs: rib height = 5 µm, slab height = 4 µm and width = 5 µm), reduced cross-section rib waveguides (RCRWs: rib height = 2 µm, slab height = 1 µm and width = 1.5 µm) along with proposed 2D mode-size converter. The fabrication process consists of three photolithographic definitions and subsequent reactive ion etching steps. Fabricated waveguides and mode-size converters have been characterized to be nearly polarization independent. The waveguide loss is measured to be 0.1 dB/mm for LCRW and 0.07 dB/mm for RCRW, respectively. The observed mode size of an LCRW is 9 µmx4 µm and that for RCRW is 2.7 µmx2.3 µm. The measured insertion loss for an LCRW-RCRW mode-size converter is ~ 1 dB for a tapering length of 150 µm. Similar performance is expected for a scaled design of 2D mode-size converter between RCRW and sub-micron PhWW – details will be presented in the conference.

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8990-11, Session 3

Silicon photonic crystals *(Invited Paper)*

Liam O’Faolain, Univ. of St. Andrews (United Kingdom)

Integration density, channel scalability, low switching energy and low insertion loss are the major prerequisites for on-chip WDM systems. A number of device geometries have already been demonstrated that fulfill these criteria, at least in part, but combining all of the requirements is still a difficult challenge. Photonic crystal cavities provide the ultimate confinement of light in space and time, giving the potential to realise devices with the lowest energy consumption and highest integration densities.

Here, we demonstrate the use of photonic crystal cavities to enhance the light emission from Silicon defects [1], realise modulators with very low switching energies [2] and compact pure silicon photodiodes at the telecoms wavelengths [3]. These devices provide a platform of the realisation of compact all-silicon optical links.

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8990-12, Session 3

Design and fabrication of 8-channel AWGs with 2-µm-SOI for optical interconnects

Sidharth Ravindran, Bijoy K. Das, Indian Institute of Technology Madras (India)

Arrayed Waveguide Gratings (AWGs) are useful for WDM applications in SOI based optical interconnect technologies. The AWGs with submicron waveguide cross-sections are compact, but they are highly polarization dependent and intolerant to fabrication errors – obvious because of the close proximity of the waveguides near free propagation region [1]. Therefore, recent trend is to design interconnect devices with relatively larger waveguide cross-sections (~2-3 ?m) [2, 3]. However, the advantages of single-mode guiding properties and polarization independencies in such larger waveguide cross-sections have not been fully exploited.

In this work, we report an optimized design and fabrication of nearly polarization independent AWG in SOI substrate with 2-µm device layer thickness. The footprint of entire device is 15 mm x 7.5 mm which consists of input/output waveguides, input/output free propagation regions and an array of 40 waveguides with differential lengths [delta] L=109 µm. The birefringence (n_eff^TE-n_eff^TM) of the single-mode waveguides has been minimized to 3.4 x〖10〗^(-3) and group index dispersion has been found to be -1.2x〖10〗^(-4) nm^(-1) (-2.3x〖10〗^(-4) nm^(-1)) for TE (TM) polarization. The device can (de-)multiplex 8 channels with 100 GHz spacing and has a free spectral range of 800 GHz – uniform over a wide range of wavelengths encompassing C+L bands. It is found to have a channel cross talk of < -20 dB and polarization dependent peak shift of < 0.5 nm (62 GHz). The proposed AWG has been fabricated using conventional i-line lithography, followed by reactive ion etching process (SF_6: Ar:: 20:20 sccm, Pressure: 200 mTorr, RF power: 150 W). Detailed design and fabrication issues along with characterization results will be presented in the conference.

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8990-13, Session 3

The evolution of angled MMI structure on the SOI platform

Youfang Hu, David J. Thomson, Frederic Y. Gardes, Goran Z. Mashanovich, Graham T. Reed, Univ. of Southampton (United Kingdom)

The angled multimode interferometer (AMMI) was recently demonstrated as a wavelength division (de)multiplexing (WDM) structure employing the phenomenon of dispersive self-imaging in a multimode planar waveguide. We first demonstrated a single 4-channel AMMI on the silicon-on-insulator (SOI) platform showing WDM functionality with the distinct advantages of low insertion loss (1-2dB), low cross-talk (<-20dB), ease of fabrication (single lithography and etching steps) and good tolerance to fabrication error (10nm error in waveguide width corresponds to 1nm shift in wavelength). This structure is also applicable in various planar waveguide platforms and at different wavelength bands. However, a single AMMI is limited to have a relatively large channel spacing and a small number of channels in order to maintain high-performance WDM functionality. Here we report several structures derived from a single AMMI on the SOI platform in order to boost its WDM functionality. A bidirectional AMMI designed for channel matching operation in an optical transceiver was demonstrated using two identical AMMIs sharing the same multimode interference waveguide; an 8-channel WDM comprising of two 4-channel AMMIs interleaved by an imbalanced Mach-Zehnder interferometers (MZIs) was fabricated, and channel matching between the AMMIs and the MZI was achieved without an additional wavelength tuning structure; a 12- or 16-channel WDM based on AMMI interleaved with ring resonators (RRs) was also proposed, where channel matching between AMMIs and RRs is also achievable without a wavelength tuning structure.

8990-14, Session 3

Fabrication-tolerant optical filters for dense integration on a micron-scale SOI platform

Matteo Cherchi, Sami Ylinen, Mikko Harjanne, Markku Kapulainen, Tapani Vehmas, Timo Aalto, VTT Technical Research Ctr. of Finland (Finland); George T. Kanellos, Ctr. for Research and Technology Hellas (Greece); Dimitris Fitsios, Ctr. for Research and Technology Hellas (Greece) and Aristotle Univ. of Thessaloniki (Greece); Nikos Pleros, Aristotle Univ. of Thessaloniki (Greece)

We present the first characterization results of some cascaded interleavers that we have recently fabricated on 4 ?m thick Silicon on Insulator (SOI) wafers. The Mach-Zehnder inferferometer filters are based on strip waveguides, micron-scale bends and compact MMIs, all components with low loss and high tolerance to fabrication errors, due to the high mode confinement in the silicon region. Strip waveguides losses are about 0.15 dB/cm, typical bend losses are about 0.02 dB per turn, and losses of MMI splitters are about 0.15 dB. Three different filter layouts have been designed with 0.5 mm2, 0.3 mm2, and 0.2 mm2 footprint respectively. While the first two layouts match almost perfectly the theoretical design, the smallest one has relatively poorer performance. A clear explanation for this issue will be presented in terms of optical proximity problems in the fabrication process.

The fabricated filters have a FWHM of about 6 nm and a Free Spectral Range of about 45 nm and an overall loss of about 1 dB. They will be used as pass-band filters to suppress the Amplified Spontaneous Emission of Semiconductor Optical Amplifiers in the optical RAM circuits of the RAMPLAS project funded by the European Commission.

8990-15, Session 3

Apodized grating silicon waveguides for tunable optical delay lines

Saeed Khan, Sasan Fathpour, Univ. of Central Florida (United States)

Modern optical communication systems require tunable optical delay lines for synchronization of data packages. Chirped fiber grating are typically used as a dispersive element for this application. Fiber-based schemes, however, suffer from bulkiness, slow response and/or low time resolution. Integrated photonics on silicon is one alternative approach. Several more advanced device architectures have been subsequently demonstrated on silicon, including ring-resonator and photonic crystal (PhC) line-defect waveguide types.

The coauthors of this paper have recently proposed a novel class of tunable optical delay lines based on apodized gratings. In this paper, we have experimentally demonstrated our proposed approach and studied the performance of the fabricated delay lines for optical telecommunication applications.

The designed grating waveguides were fabricated using a complementary metal–oxide–semiconductor (CMOS)-compatible process using 193-nm deep ultraviolet (UV) lithography. Delay tuning was achieved by using the thermooptic effect via microheaters fabricated on top of grating waveguides.

The bit rate was extracted from broadening of transform-limited input pulses due to the fitted dispersion of the delay line. By varying the applied voltage from 0 V to 15 V, the time delay varies from ~ 132 ps to ~ 46 ps. Meanwhile, the maximum limit on bit rate varies from ~ 13 Gb/s to ~ 93 Gb/s. Hence, at this particular signal wavelength, the operating bit rate is at least 13 Gb/s, the attainable tunability is ~ 86 ps. Hence, the tunability-bit -rate product is 1.12, and the delay-bit-rate-product is 1.72.

8990-16, Session 3

Silicon nanomembrane-based compact true-time-delay module on unconventional substrates

Harish Subbaraman, Omega Optics, Inc. (United States); Xiaochuan Xu, Ray T. Chen, The Univ. of Texas at Austin (United States)

In this paper, we present the fabrication and demonstration of a silicon nanomembrane based true-time-delay line module on unconventional substrates, such as glass. Photonic crystal waveguides are designed in order to provide large time delay values within a short length. Continuously tunable time delay is achieved by wavelength tuning, which utilizes the strong dispersion of the photonic crystal waveguides. Photonic crystal tapers are implemented at the strip-photonic crystal waveguide interfaces, which lowers the coupling loss and enables operation closer to the band edge, thus providing larger time delay values. The true-time-delay module comprising of judiciously chosen lengths of PCW and strip waveguides in each arm are fabricated on an SOI wafer first, and then transferred onto a glass substrate with an SU-8 bottom cladding layer. Subwavelength grating (SWG) couplers are employed in order to enable device characterization. A large time delay > 55ps per millimeter length of the true-time-delay line is achievable within a wavelength tuning range of 20nm. Such a demonstration opens vast possibilities for a whole new range of high performance, light-weight and low power photonic components for conformal system applications.

8990-17, Session 3

Ge quantum-well optical interconnects on bulk silicon

Papichaya Chaisakul, Institut d'Électronique Fondamentale (France); Delphine Marris-Morini, Univ. Paris-Sud 11 (France); Jacopo Frigerio, Daniel Chrastina, Politecnico di Milano (Italy); Mohamed Said Rouifed, Univ. Paris-Sud 11 (France); Stefano C. Cecchi, Politecnico di Milano (Italy); Paul Crozat, Univ. Paris-Sud 11 (France); Giovanni Isella, Politecnico di Milano (Italy); Laurent Vivien, Univ. Paris-Sud 11 (France)

We present a new approach to monolithically integrate Ge quantum well optical interconnects on silicon substrates. We experimentally show that Ge-rich Si1-xGex virtual substrates (VS) can act as a passive optical waveguide on which a low temperature high quality epitaxial growth of Ge quantum wells can be performed, realizing active optical interconnects on bulk silicon. The photonic integration of a passive Si0.16Ge0.84 waveguide and two Ge/SiGe MQW active devices, an optical modulator and a photodetector, was realized by using a single epitaxial growth step. A Si0.16Ge0.84 VS was engineered to meet the two conflicting requirements of (1) being a waveguide with minimized optical loss at the operating wavelength of the quantum-confined Stark effect (QCSE) modulator based on Ge/Si0.16Ge0.84 multiple quantum wells (MQWs), and (2) forming a VS with minimized lattice mismatch to the MQW stack to ensure a high quality epitaxial growth. We will present low-voltage and broadband Ge quantum well interconnects integrated on bulk silicon chips.

8990-18, Session 4

Hybrid-integrated external cavity lasers for high-density Si-photonic WDM transceiver platform *(Invited Paper)*

Aaron J. Zilkie, Bhavin J. Bijlani, Pegah Seddighian, Saeed Fathololoumi, Daniel C. Lee, Wei Qian, Joan Fong, Roshanak Shafiiha, Dazeng Feng, B. Jonathan Luff, Mehdi Asghari, Kotura, Inc. (United States)

Silicon photonics is rapidly emerging as the next-generation technology for realizing low-cost, high speed, efficient interconnects in data center networks and high power computing. Wavelength-division-multiplexing (WDM) offers high-bandwidth, high-density, and inherent parallelism in these systems and therefore is of interest for scaling optical solutions for long-term band-width growth. Power efficiency is also a key requirement driving technology selection particularly as data rates increase. We will report on power-efficient multi-channel hybrid-integrated external-cavity DBR lasers, consisting of III-V reflective-SOAs (RSOAs) hybrid-integrated to our 3-μm-platform silicon-on-insulator (SOI) WDM transceiver platform. We will present details on the laser threshold, light-current behavior, spectra, and noise performance for 100 Gb/s WDM transmission.

8990-19, Session 4

Characteristics of avalanche electroluminescent nanoscale Si light sources in SOI technology

Christo Janse van Rensburg, INSiAVA (Pty) Ltd. (South Africa) and Univ. of Pretoria (South Africa); Monuko du Plessis, Petrus J. Venter, Univ. of Pretoria (South Africa) and INSiAVA (Pty) Ltd. (South Africa)

Silicon-on-insulator (SOI) is fast becoming a popular technology platform for silicon photonic devices as well as RF- and nanoelectronics, while the field of nanoscale silicon structures remains an active topic in optoelectronic research. Silicon light sources with an active material only a couple of nanometers in dimension has several distinct advantages for enhanced light emission due to carrier confinement and improved external light extraction efficiency when compared to bulk CMOS light sources. This work focuses on these inherent advantages, where the design of nanoscale silicon light source arrays is presented, implemented in a custom SOI process utilizing hot carrier luminescence generated by avalanching pn-junctions.

SOI light sources have shown an improvement in electroluminescent power emitted through various techniques inducing carrier confinement effects. These techniques are typically applied by either thinning the silicon active material in one or two dimensions. Conventional nanoscale SOI LEDs usually depend on recombination in forward-biased junctions. The wavelengths of interest are consequently in the near-infrared range around the band gap energy. In contrast, the device structures presented in this paper is based on hot carrier luminescence utilizing reach-through and punch-through techniques. We present the power spectral densities of the structures over a very wide spectral range also covering the visible wavelengths. The spectral characteristics of the SOI light sources were investigated and the dominant light generation mechanisms were identified.

This work compares the various device structures and light source architectures and reveals accurate device dimensions obtained via focused ion beam (FIB) and scanning electron microscope (SEM) imaging. Device simulations are also conducted to investigate the electrostatic behavior of junctions within the small active regions of the structures. The results presented exemplify the possibilities of SOI light sources for future applications.

8990-20, Session 4

High-intensity 100-nW 5GHz silicon avalanche LED utilizing carrier energy and momentum engineering

Lukas W. Snyman, Tshwane Univ. of Technology (South Africa) and Micro Systems SA (South Africa); Jean-Luc Polleux, Univ. Paris-Est Marne-la-Vallée (France); Kingsley A. Ogudo, Tshwane Univ. of Technology (South Africa) and Micro Systems SA (South Africa); Carlos Viana, Sebastain Wahl, Univ. Paris-Est Marne-la-Vallée (France)

Si Avalanche based LEDs have been developed that effectively emit up to 100nW / µm 2 in the 650 -850nm regime (Snyman et al, Japanese Journal Applied Physics, 2007; Snyman et al , Proc SPIE, 2008, 2009, 2010 ; Snyman et al , IEEE Journal of Quantum Electronics, June 2010, and SPIE JM3 article , Snyman et al on optical links, January 2013). Correspondingly, small micro-dimensioned detectors with pW/ µm 2 sensitivity (for the same wavelengths) can be realized also in CMOS integrated circuitry. Latest research results also show that specific Si CMOS Av LEDs can be developed that emit mainly in the 700-800nm regime. The technology is envisaged to particularly have wide scale application in futuristic all on chip optical link and on onchip micro-photonic systems. Higher intensities and energy outputs at lower frequencies can be applied such as on chip micro-photonic systems including absorbance , florescence imaging chemical spectroscopic analyses as well as a wide range of MOEMS sensor applications.

Because of there reverse biased nature and micron dimensioning capabilties as assocaited with this technology, the parasitics influencing high frequency performance can be considerably favourably designed. The energy of the multiplied carrirers can aslo be effectively minimised using carrier density engineering teniques.

The above technologies were now effectively realized by combining front end expertise in Si Av LED technology (Snyman et al) ; RF characterization technology (Polleux et al) and Si and Si -Ge bipolar technology as available at ESIEE Engineering School , Cedex Franc. It is believed that the micro dimensioning approach, carrier energy and momentum engineering , and application in new novel application field of bio sensors are all novel and front end contributions are all novel contributions in the international arena.The currentr emission intensities is the highest ever reported. Compare nearest technolgies, Xu et al , 2012 , In Si Ava technology, 2010, Snyman et al , 2011 and Spain Barcelona competitor technology, 2010 .

The technology as developed have been extensively patented in the form of USA patent applications US 2012 017 0942, US 2012 012 015 3864, US 2012 015 4812 ; as well as in Provisional RSA Patent Applications 2009/04162, 2009/04163 , 2009/04509 , 2009/04508 , 2010/00200, 2010/02021, 2013/5678 and three PCT patents filed by TUT, June 2010.

8990-21, Session 4

Enhanced infrared transmission from Er-doped SiO2/nc-Si multilayer waveguides under lateral electrical pumping

Halina Krzyzanowska, Vanderbilt Univ. (United States); Karl S. Ni, Yijing Fu, Univ. of Rochester (United States); Philippe M. Fauchet, Vanderbilt Univ. (United States)

Despite much research, highly efficient Si-based light sources - the missing link in an all-silicon on-chip optical interconnection system have not yet been achieved. One of the most promising ways for making efficient electrically pumped Si light sources at the standard telecommunication wavelength (1550 nm) is using Si nanostructures and erbium.

This work presents studies of enhanced transmission at the Er emission wavelength in a multilayer waveguide using an electric pump-optical probe configuration. Multilayer samples were fabricated by the sequential deposition of silicon and silicon dioxide co-sputtered with Er on Si substrates. Subsequently, a 300 nm thick SiO2 layer was deposited on the top of the multilayer by an E-beam evaporator and patterned to form a ridge waveguide. A prism coupling arrangement was used to launch the probe beam into the slab waveguide. p-i-n diodes with titanium electrodes were made for electrical pumping.

The multilayer structures acts as a multislot waveguide and provides a strong (~10) reduction of free carrier absorption for TM polarization by confining the photons in the SiO2 layers where the Er are located and away from the Si layers where carrier injection takes place. Here, the multilayer was pumped electrically and probed optically. In strong forward bias, enhancement of the transmitted probe intensity was observed for the TM mode but not the TE mode, for which free carrier absorption is not suppressed. These results can be explained by a model that takes into account carrier transport in the thin Si layers and subsequent excitation of the Er located in the adjacent SiO2 layers.

These results are promising for the development of on-chip silicon light sources.

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8990-22, Session 4

Dual-facet coupling of SOA array on 4-um silicon-on-Insulator implementing a hybrid integrated SOA-MZI wavelength converter

Theonitsa Alexoudi, Dimitris Fitsios, Ctr. for Research and Technology Hellas (Greece) and Aristotle Univ. of Thessaloniki (Greece); George T. Kanellos, Ctr. for Research and Technology Hellas (Greece); Nikos Pleros, Ctr. for Research and Technology Hellas (Greece) and Aristotle Univ. of Thessaloniki (Greece); Tolga Tekin, Technische Univ. Berlin (Germany); Matteo Cherchi, Sami Ylinen, Mikko Harjanne, Markku Kapulainen, Timo Aalto, VTT Technical Research Ctr. of Finland (Finland)

Hybrid integration on Silicon-on-Insulator (SOI) has emerged as a practical solution for compact and high-performance Photonic Integrated Circuits (PICs). It aims at combining the cost-effectiveness and CMOS-compatibility benefits of the low-loss SOI waveguide platform with the versatile active optical functions that can be realized by III-V photonic materials. The utilization of SOI, as an integration board, with ?m-scale dimensions allows for an excellent optical mode matching between silicon rib waveguides and active chips, allowing for minimal-loss coupling of the pre-fabricated III-V components. While dual-facet coupling as well as III-V multi-element array bonding should be employed to enable enhanced active on-chip functions, so far only single side SOA bonding has been reported. In the present communication, we present a novel integration scheme that flip-chip bonds a 6-SOA array on 4-µm thick SOI technology by coupling both lateral SOA facets to the waveguides, and report on the preliminary results of a SOA-MZI-on-SOI circuit operating as wavelength converter. Thermocompression bonding was applied to integrate the pre-fabricated SOAs on SOI, with vertical and horizontal alignment performed successfully at both SOA facets. The demonstrated device has a footprint of 8.2mm x 0.3mm while experimental evaluation for the SOA-MZI-on-SOI circuit revealed a 10Gb/s wavelength conversion operation capability with only 0.2dB power penalty. Our experiments show how dual facet integration can significantly increase the level of optical functionalities achievable by flip-chip hybrid technology and pave the way for more advanced and more densely PICs.

8990-23, Session 4

Mid-infrared nonlinear silicon photonics *(Invited Paper)*

Xiaoping Liu, OFS Labs. (United States); Bart Kuyken, Univ. Gent (Belgium); William M. J. Green, IBM Thomas J. Watson Research Ctr. (United States); Richard M. Osgood, Columbia Univ. (United States); Roel G. Baets, Gunther Roelkens, Univ. Gent (Belgium)

Recently there has been a growing interest in mid-infrared (mid-IR) photonic technology with a wavelength of operation approximately from 2-14 um. Among several established mid-IR photonic platforms, the silicon nanophotonic platform can potentially offer ultra-compact, and monolithically integrated mid-IR photonic devices and device arrays, which can have broad impact across mid-IR applications, such as molecular spectroscopy, and imaging. At room temperature, silicon has a bandgap ~ 1.12 eV resulting in vanishing two-photon absorption (TPA) for mid-IR wavelengths beyond 2.2 um, which, coupled with silicon's large nonlinear index of refraction and its strong waveguide optical confinement, enables efficient nonlinear processes in the mid-IR. By taking advantage of these nonlinear processes and judicious dispersion engineering in silicon waveguides, we have recently demonstrated several silicon mid-IR nonlinear components, including optical parametric amplifiers (OPA), broadband sources, and a wavelength translator. The silicon nanophotonic waveguide's anomalous dispersion design, providing four-wave-mixing (FWM) phase-matching, has enabled the first demonstration of silicon mid-IR optical parametric amplifier (OPA) with a net off-chip gain exceeding 13 dB. In addition, reduction of propagation losses and balanced second and fourth order waveguide dispersion design has led to an OPA with an extremely broadband gain spectrum from 1.9-2.5 um and >50 dB parametric gain, upon which several novel silicon mid-IR light sources were built, including a mid-IR optical parametric oscillator, and a supercontinuum source. Finally, a mid-IR wavelength translation device, capable of translating signals near 2.4 um to the telecom-band near 1.6 um with simultaneous 19dB gain, has been demonstrated.

8990-24, Session 4

Model of charge transport in Er-doped SiO2/nc-Si multilayers under lateral carrier injection

Halina Krzyzanowska, Vanderbilt Univ. (United States); Karl S. Ni, Yijing Fu, Univ. of Rochester (United States); Philippe M. Fauchet, Vanderbilt Univ. (United States)

In spite of intensive studies, highly efficient Si-based light emitting devices have not been demonstrated, in large part because carrier transport through Er-doped SiOx is difficult.

This work presents current-voltage relationships and efficient infrared electroluminescence (EL) from Er-doped SiO2/nc-Si multilayers with various layer thicknesses and shapes of electrodes. A space charge transport model is applied to elucidate carrier transport in the nm-thin Si multilayer structure.

Multilayer samples were fabricated by sequential magnetron sputtering of silicon and co-sputtering of silicon dioxide (SiO2) and Er on 5 µm thick thermally grown SiO2 layers on Si (100) wafers. Lateral p-i-n devices were fabricated by ion implantation. Our deposition procedure guarantees control of the distance between Er and silicon - a critical parameter for achieving efficient Er luminescence.

The current-voltage relationships for multilayers with different electrode spacings, from 40 ?m to 10 ?m, reveal good rectifying properties and demonstrate that charges flow through the nc-Si layers in the p-i-n structure under forward bias. Analysis of the I-V curves using the space charge transport model explains the nature of carrier transport in the thin nc-Si layers. We have found that the voltage threshold for EL takes place in the trap filled regime, when transfer of charges to Er is possible. Moreover, the similarity between the infrared EL and PL spectra demonstrates that in both cases Er is excited by the carriers injected in the nc-Si layers.

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8990-100,

Pushing the boundaries of silicon photonics

Michal F. Lipson, Cornell Univ. (United States)

Photonics on chip enables monolithic integration of optics and microelectronics for applications such as optical interconnects in which high data streams are required in a small footprint. I will provide an overview of recent advances and challenges in the field. As an example of silicon photonics unique capabilities, I will describe ultrahigh speed devices that enable one to change the structure's optical properties on a time scale that is shorter than the photonic time of flight, leading to novel applications such as optical isolators on a silicon chip.

8990-25, Session 5

Ultrasensitive optofluidic-nanoplasmonic BioMEMS for life sciences and point-of-care diagnostics *(Invited Paper)*

Ahmet A. Yanik, Univ. of California, Santa Cruz (United States)

Optofluidic-Nanoplasmonic devices, localizing light to the sub-wavelength dimensions, is opening a myriad of unprecedented opportunities for biomedical diagnosis and pharmaceutical applications. In this talk, I will introduce a number of advanced technologies based on nanoscale control of light and fluidics on a chip. I will show how to overcome some of the fundamental limitations of the state of art techniques used in vitro diagnostics, which makes up a $10 Billion global market. I will first introduce an ultrasensitive detection technology with detection limits surpassing the gold standard surface plasmon resonance (SPR) sensors while enabling million fold enhanced multiplexing capabilities with minute sample volumes. Using a bottom-up approach, I will merge nanofluidic and nanophotonic technologies at sub-wavelength dimensions to break the diffusion barrier. For point-of-care applications, I will introduce a novel sensing scheme enabling label-free detection of biomarker proteins “with the naked eye” using plasmonic analogs of Fano resonances. I will also demonstrate real world applications of optofluidic-plasmonic sensors for rapid and reliable detection of whole viruses from biological media at medically relevant concentrations. I will extend our nanofluidic approach to a micro-nano cross flow scheme for isolation of rare circulating tumor cells (CTCs). I will also discuss potential implications of this technique for the analysis of single tumor cells and their metastatic potential.

8990-26, Session 5

Methods to array photonic crystal microcavities for high-throughput high-sensitivity biosensing on a silicon-chip-based platform *(Invited Paper)*

Ray T. Chen, The Univ. of Texas at Austin (United States); Swapnajit Chakravarty, Omega Optics, Inc. (United States); Yi Zou, The Univ. of Texas at Austin (United States) and Univ. of Texas at Austin (United States); Wei-Cheng Lai, Liang Zhu, The Univ. of Texas at Austin (United States)

Chip-integrated label-free optical biosensing microarrays are extremely attractive in several applications ranging from detection of cancers and allergens, for drug discovery and biomarker discovery in medicine and life sciences, to food science and biodefense. A label-free platform further eliminates steric hindrance and simplifies the biochemistry. Till date, photonic crystal (PC) microcavity based biosensors have demonstrated highest sensitivities among all chip based optical technologies. Concentrations down to 50fM (3pg/ml) have been experimentally demonstrated. While there is obviously significant merit in detecting small and smaller concentrations from the perspective of early diagnosis of cancers, very often patient samples are not available in abundance. Consequently, a platform for multiplexed detection of several biomolecular events, simultaneously at the same instant of time, is highly desirable. Silicon Photonics is ideally suited for the above requirement. Our biosensor comprises a PC microcavity coupled to a PC waveguide. High sensitivities were achieved by slow light engineering which reduced the radiation loss and increased the stored energy in the photonic crystal microcavity resonance mode. Resonances with high quality factor Q~26,760 coupled with larger optical mode volumes allowed enhanced interaction with the analyte biomolecules which resulted in sensitivities down to 2 cells per micro-liter to lung cancer cell lysates. Detection specificity was ensured by multiplexed specific and control binding reactions in a sandwich assay format from multiple PC microcavities arrayed on a multimode interference power splitter. We have multiplexed up to 64 PC microcavities in series and parallel for high throughput multiplexing. We will review our recent work.

8990-27, Session 5

Silicon photomultipliers applications to biosensors

Maria Francesca Santangelo, Roberto Pagano, Consiglio Nazionale delle Ricerche (Italy); Salvatore A. Lombardo, Istituto per la Microelettronica e Microsistemi (Italy); Emanuele Luigi Sciuto, Fulvia Sinatra, Univ. degli Studi di Catania (Italy); Delfo N. Sanfilippo, Giorgio P. Fallica, STMicroelectronics (Italy); Sebania Libertino, Istituto per la Microelettronica e Microsistemi (Italy)

Biosensors importance, nowadays, is enhancing exponentially as well as their applications. Optical transduction is the most used method to recognize DNA hybridization with traditional markers, such as CY3 and CY5. In this work we used a novel Si-based detector, having a low noise and a high sensitivity, up to a single photon detection. It is a Silicon photomultiplier (SiPM), a device formed by avalanche diodes operating in Geiger mode, in parallel connections. Arrays with different dimensions were electro-optically characterized (5x5; 10x10 and 20x20 pixels) in order to identify the best in terms of signal-to-noise ratio, for our purposes. The SiPM array was used to study both traditional and innovative fluorophores. CY5 was chosen as "reference" marker. It has an absorption peak at 649 nm and an emission peak at 664 nm. Ru(bpy)3[PF6]2 was identified as innovative fluorophore, since it has absorption and emission peaks at 455 and 625 nm, respectively. Measurements were carried out in both functional regimes: continuous and pulsed. Emission spectra in the range 500–750 nm were measured with both traditional photomultipliers tubes (PMT) and SiPM operating at room temperature in continuous mode. More interestingly, fluorophore lifetimes were monitored showing that SiPM can measure lifetimes as short at 1 ns (CY5 lifetime), well below the lowest PMT limit (23 ns). Ru(bpy)3[PF6]2 lifetime characterization was performed with both PMT and SiPM (being in the hundreds of ns range), as a function of the solvent and after deposition and drying on glass substrates, revealing interesting results.

8990-28, Session 5

High-performance conformal sensors employing single-crystal silicon nanomembranes

Xiaochuan Xu, The Univ. of Texas at Austin (United States); Harish Subbaraman, Swapnajit Chakravarty, Omega Optics, Inc. (United States); Ray T. Chen, The Univ. of Texas at Austin (United States)

In this paper, we present the fabrication and demonstration of silicon nanomembrane (SiNM) based high-performance sensors on flexible substrates, such as Kapton. L13 photonic crystal microcavities are designed in order to provide high mode quality factors. The photonic crystal devices are fabricated on a 2cm x 2cm large-area single crystal SiNM which is transferred defect-free onto a Kapton substrate with an SU-8 bottom cladding. Photonic crystal tapers are implemented at the strip-photonic crystal waveguide interfaces, which lowers the coupling loss and enables operation closer to the band edge. Subwavelength grating (SWG) couplers are employed at the input and output of the device in order to enable device characterization. Preliminary chemical sensing data suggests a sensitivity of ~80 nm/RIU from the flexible devices. Bending tests are performed in order to demonstrate sensitivity independent operation. Such a demonstration opens vast possibilities for a whole new range of high performance, light-weight and conformal sensor systems.

8990-29, Session 6

Integrated silicon microring resonator devices for point-of-care diagnostic applications *(Invited Paper)*

Mi Kyoung Park, Qing Liu, A*STAR Institute of Microelectronics (Singapore); Kyung Woo Kim, Institute of Microelectronics, Agency for Science, Technology and Research (Singapore); Yong Shin, Jack Sheng Kee, Junfeng Song, Guo-Qiang Lo, Dim-Lee Kwong, A*STAR Institute of Microelectronics (Singapore)

Miniaturized laboratory system, Lab-on-a-chip (LOC), is poise to revolutionize clinical testing in point-of-care setting. Label-free silicon microring resonators are one of the most promising sensor components in LOC system due to their high sensitivity, extremely small footprint, multiplexing capability and low fabrication costs. However, typical microring resonators require an expensive and bulky high-resolution wavelength-tunable laser in order to accurately measure the resonance wavelength shift caused by biomolecule bindings. Therefore, biosensors based on conventional microring resonators may not be suitable for cost-effective POC application. In this work, we present our recent progresses in the development of integrated LOC devices based on silicon microring sensors for POC applications. Our approach is based on an electrical tracing-assisted silicon dual-microring resonator sensor system, where one of rings is used as a sensing element and the other ring integrated with an electrical controller is used as a tracing element. The dual-microring sensor system requires a low-cost broadband light source instead of a tunable laser, which allows the development of cost-

effective POC diagnostic device by significantly reducing the device cost and increasing its portability. On the other hand, we have developed an isothermal solid-phase amplification/detection (ISAD) technique for the detection of nucleic acids in body fluids that can be performed without labelling in real-time by utilizing both silicon microring-based solid-phase amplification and isothermal recombinase polymerase amplification. The integrated LOC system consists of dual-microring sensors and microfluidic device together with ISAD technique offers true realization of “sample-to-answer” POC device for human disease diagnosis.

8990-30, Session 6

Sensing platform based on micro-ring resonator and on-chip reference sensors in SOI

Shahina M. Chakkalakkal Abdulla, Peter J. Harmsma, Bart M. de Boer, Jose M. Pozo, Johannes H. van den Berg, Alfred Abutan, Ronald A. J. Hagen, Dario M. R. LoCascio, TNO (Netherlands)

We report on the development of a Silicon-On-Insulator (SOI) compact photonic sensing platform. The sensor elements are Micro Ring Resonators (MRRs), integrated with reference MRRs on a single chip. We have developed a dedicated easy-to-use free-space optical coupling setup to enable testing without the need for tedious fiber-chip attachment.

In order to enable correction for variations in environmental conditions such as temperature and mechanical stress, we have studied the performance of uncoated sensing MRRs, and of SU8- and SiO2-covered reference MRRs. The sensitivity to ambient refractive index was determined by measuring the response to varying salt concentrations in de-ionized water, and ranges from 50 to 130 nm/RIU depending on the MRR configuration. The reference MRRs showed negligible sensitivity to ambient index..

We also analyzed the stability over time of the SU8 and SiO2 cover layers in water, and found that the SU8 causes a slow drift in MMR response over tens of pm due to water permeation, until stabilization occurs after approximately 40 minutes. Even though the use of SU8 is beneficial for ease of processing and costs, we believe that SiO2 is the material of choice for typical applications.

In addition, we present our free-space optical coupling set-up, which enables us to quickly align and perform tests on MRR sensors, typically in combination with microfluidic flow cells. The platform allows non-photonic experts to characterize surface activation processes using MRRs. We believe that such a concept is essential for the use of MRRs in biosensing research.

8990-31, Session 6

Integrated stripe and slot waveguides in silicon-on-sapphire for mid-infrared VOC detection in water

Yi Zou, The Univ. of Texas at Austin (United States); Swapnajit Chakravarty, Omega Optics, Inc. (United States); Xiaochuan xu, Wei-Cheng Lai, Parker Wray, The Univ. of Texas at Austin (United States); Dakota Crisp, Southeast Missouri State Univ. (United States); Ray T. Chen, The Univ. of Texas at Austin (United States)

A chip-integrated infrared spectrometer for remote, in situ sensing and spectroscopic identification of volatile organic compounds (VOCs) in water taking advantage of large absorption cross-sections in the midinfrared (mid-IR) is highly desired. Interband cascade lasers(ICL) in mid-IR wavelengths and quantum cascade lasers (QCLs) at longer wavelengths can probe the fundamental molecular vibrations of most molecules. We previously demonstrated on chip sensing by near infrared absorption signatures in a 300 micron long photonic crystal slot waveguide that enabled detection of 100ppbxylene in water.Based on Beer-Lambert absorption law, theslot waveguide device provides large optical field intensity in a low index slot at the center of the waveguide to enhance interaction between the optical field and the analyte which when combined withthe large absorption cross-sections in the mid-IR increases the sensitivity to analyte detection. Preliminary strip and slot waveguide devices have been fabricated in silicon-on-sapphirefor operation at 3.4micron wavelength. Light from an ICL guided by optical fibers is coupled into and out of the devices using integrated sub-wavelength grating couplers. Propagation loss of 2.1dB/cm has been experimentally observed for strip waveguides. Devices are covered with nearly transparent poly dimethyl siloxane (PDMS). PDMS serves as the solid phase micro-extraction layer which extracts the VOC from water and enables absorbance measurements independent from the strong absorbance of water. Transmitted intensity is measured in presence and absence of xylene as a representative VOC and its absorbance determined on chip from the difference in transmitted intensity.

8990-32, Session 6

Silicon molecular sensor chip array with microfluidic and optomechanical interface *(Invited Paper)*

Pavel Cheben, Siegfried Janz, Dan-Xia Xu, Martin Vachon, Nicaulas Sabourin, H. McIntosh, H. Ding, Shurui Wang, Jens Schmid, André Delâge, Jean Lapointe, Adam Densmore, Rubin Ma, William Sinclair, S. M. Logan, Roger MacKenzie, Q. Y. Liu, D. Zhang, Greg Lopinski, O. Mozenson, National Research Council Canada (Canada); M. Gilmour, H. Tabor, Public Health Agency of Canada (Canada) and National Microbiology Lab. (Canada)

A silicon wire molecular biosensor microarray chip and supporting instrumentation is presented. Chips with 128 independent sensors have been fabricated and tested. The sensor element is a millimeter long silicon photonic wire waveguide folded into a spiral ring resonator with a diameter of 50 microns. An array o 128 sensors occupies a 2 mm x 2 mm area on a 6 mm x 9 mm chip. The size and layout of the sensor array is compatible with commercial spotting tools. Fluid samples are delivered to the chip by a microfluidic channel fabricated monolithically on the chip. Light is coupled from the sensor chip using 2D arrays of sub-wavelength surface grating couplers and the signals are collected by a two-dimensional photodetector array. 128 optical sensor outputs are interrogated using an optical interface instrument for real-time simultaneous multi-channel readout. Temperature induced drifts are effectively cancelled by using ring resonators as a temperature reference, with sensing response stabilized to an equivalent of 0.01 degree C without any active environment temperature control. Connection of the fluid delivery system and optical alignment are performed using a robust automatic system with no active user input or any alignment steps. Several application examples will be presented, including a multiplexed assay for serotyping E. coli bacteria using serospecific polyclonal antibody probe molecules.

8990-33, Session 6

Comparative sensitivity analysis of integrated optical waveguides for near-infrared volatile organic compounds with sub-ppb detection in water

Wei-Cheng Lai, The Univ. of Texas at Austin (United States); Swapnajit Chakravarty, Omega Optics, Inc. (United States); Yi Zou, Liang Zhu, Ray T. Chen, The Univ. of Texas at Austin (United States)

We compare experimentally the detection sensitivity of volatile organic compounds (VOCs) in water by near-infrared absorption spectroscopy by four different integrated optical waveguide devices, namely stripe waveguide, slot waveguide, photonic crystal waveguide (PCW) and photonic crystal slot waveguide (PCSW). The principle of chip-integrated absorption spectroscopy is based on Beer-Lambert absorption. In strip waveguides, the analyte overlaps with the evanescent mode only. The effective absorbance can be enhanced in integrated waveguides on chip by increasing the analyte overlap with the propagating optical mode in the low-index slot in a slot waveguide or by slowing down the propagating optical mode in a PCW thereby increasing the interaction time with the analyte. Both effects are combined in a PCSW. Devices are coated with SU8 polymer for solid phase micro-extraction that effectively extracts the VOC from water and allows measurement of VOC absorbance independent from the strong absorption signatures of water. SU8 is transparent in the near-IR and therefore enhances signal-to-noise ratio compared to poly dimethyl siloxane (PDMS). Xylene in water is used for the demonstration of the four waveguides absorbance comparisons. Stripe waveguide show the least absorbance among the four integrated optical devices. We successfully detected 1 ppb xylene in water by using a SU8 coated 300 µm long PCW device. The choice of SU8 vastly improves the detection sensitivity compared to 100ppb demonstrated previously with PDMS coated PCSW of the same geometric length. Results will be presented to demonstrate another anticipated order of magnitude improvement in sensitivity with SU8 coated PCSW.

8990-34, Session 7

High-speed silicon-based integrated optical modulators for optical fiber telecommunications *(Invited Paper)*

Kensuke Ogawa, Fujikura Ltd. (Japan)

There have been growing demands for small-footprint high-speed optical modulators in dense wavelength-division multiplexing (DWDM) optical-fiber telecommunication networks at data transmission rates of 100 Gbit/s or higher per wavelength channel. Silicon-based photonic integrated circuits allow small-footprint high-speed optical modulator with low fabrication cost for high-speed data transmission in the DWDM networks. In this paper, design and characterisation of silicon-based photonic integrated circuits are reviewed in the light of 100-Gbit/s monolithically integrated silicon-based optical modulator. The monolithic optical modulator consists of key elements such as nested Mach-Zehnder (MZ) modulator for in-phase (I) and quadrature (Q) modulation in quadrature phase-shift keying (QPSK) format, and polarization rotator (PR) and polarization beam combiner (PBC) to launch optical signals in dual-polarization (DP) QPSK format using orthogonal linear polarization states.

The IQ MZ modulator includes lateral PN junction rib-waveguide phase shifters, and is suitable for zero-chirp IQ modulation with passive optical insertion loss as low as 9 dB. The modulator has a footprint as small as 3x5 mm^2. Clear QPSK constellation diagrams are obtained at symbol rates up to 32 Gbaud with bit error rate lower than 10^-5, free from noise floor.

A new partial rib waveguide is proposed for PR and incorporated with directional-coupler PBC for DP-QPSK transmission. The partial rib waveguide consists only of a silicon core and silica clads, thus can be accommodated monolithically with the IQ MZ modulator in simultaneous fabrication process. Low-loss polarization rotation with excess optical loss of 0.5-1.0 dB is demonstrated in a broad wavelength range of 1500-1600 nm.

8990-35, Session 7

High contrast and accurate high-speed simulation of silicon-based modulators

Ching Eng Png, A*STAR Institute of High Performance Computing (Singapore); Minjie Sun, A*STAR Institute of High Performance Computing (Singapore) and National Univ. of Singapore (Singapore); Soon Thor Lim, A*STAR Institute of High Performance Computing (Singapore); David J. Thomson, Univ. of Southampton (United Kingdom)

High-speed optical modulators are the workhorse of an optical network. Silicon-based ones received intense research interest globally recently and as a result experienced rapid performance improvements. It is now common for such devices to operate in multiple gigabit regime, typically in excess of 10Gb/s. These devices are largely based on the depletion of carriers arranged around a rib topology and embedded into Mach-Zehnder Interferometers (MZI). High-speed eye diagrams have become the de-facto standard to gauge the performance of modulators by considering key information such as rise/fall times, extinction ratios, and jitter characteristics. To achieve meaningful and representative eye diagram simulation results, the critical physical operating effects must be included in modeling and simulations.

Here, we accurately evaluate the performance of a silicon-based MZI device by simulating the eye diagram based on its inherent electrical and subsequent optical modeling of individual silicon depletion modulators. Furthermore, we include real-time pseudo-random-binary-sequence data and investigate its effects on the entire modulator device including the physical co-planar waveguides, reflections, capacitance, conductance, and transitioning times to model time response, to obtain effective complex refractive index from optical simulations of the phase shifter arms of the MZI. In turn this simulates phase change and resultant loss induced by each arm. This methodology is suitable for interferometer-based devices and has been applied to silicon-based depletion modulators at 40-Gb/s and demonstrated good agreement with experimental data. The attraction of our accurate and efficient methodology will come to the fore when considering a system of multiple high-speed modulators chained together.

8990-36, Session 7

Comparison of performances of 40 Gbit/s silicon modulators fabricated on 200-mm and 300-mm SOI wafers

Delphine Marris-Morini, Institut d'Électronique Fondamentale (France); Charles Baudot, STMicroelectronics (France); Jean-Marc Fédéli, CEA-LETI (France); Gilles Rasigade, Institut d'Électronique Fondamentale (France); Nathalie Vuillet, STMicroelectronics (France); Aurélie Souhaité, CEA-LETI (France) and STMicroelectronics (France); Melissa Ziebell, Institut d'Électronique Fondamentale (France); Pierrette Rivalin, CEA-LETI (France); Segolene Olivier, CEA-LETI-Minatec (France); Paul Crozat, David Bouville, Institut d'Électronique Fondamentale (France); Sylvie Menezo, CEA-LETI (France); Frédéric Boeuf, STMicroelectronics (France); Laurent Vivien, Institut d'Électronique Fondamentale (France)

We present 40 Gbit/s optical modulators based on pipin and interleaved pn junctions phase shifters. Those structures were processed both on 200 and 300mm SOI wafers, available in large-scale microelectronic foundries. Both Ring Resonators (RR) and Mach Zehnder (MZ) modulators were fabricated. As an example, MZ modulator based on 0.95 mm long interleaved pn junction phase shifter delivered a high ER of 7.8 dB at 40 Gbit/s with low optical loss of only 4 dB. Ring modulator

was also fabricated and characterized at high-speed, exhibiting 40 Gbit/s. Further optimization to still increase device performances will be discussed.

8990-37, Session 7

Silicon high-speed modulator for advance modulation: device structures and exemplary modulator performance *(Invited Paper)*

Biljana Milivojevic, Stefan Wiese, James Whiteaway, Christian Raabe, Cisco Optical GmbH (Germany); Anujit Shastri, Cisco Systems Inc. (United States); Mark Webster, Peter Metz, Sanjay Sunder, Bill Chattin, Sean P. Anderson, Bipin Dama, Kal Shastri, Cisco Systems, Inc. (United States)

Fiber optics is well established today due to the high capacity, speed, unrivaled flexibility and quality of service. However, state of the art optical elements and components are hardly scalable in terms of cost and size required to achieve competitive port density and cost per bit.

Next-generation high-speed coherent optical communication systems targeting data rate of 100-Gb/s and beyond goes along with innovations in component and subsystem areas. Consequently, by leveraging the advanced silicon micro and nano-fabrication technologies, significant progress in developing CMOS platform-based silicon photonic devices has been made all over the world. These achievements include the demonstration of high-speed IQ modulators, which are important building blocks in coherent optical communication systems.

In this paper, we demonstrate a silicon photonic QPSK modulator based on a metal-oxide-semiconductor (MOS) capacitor structure, address different modulator configuration structures and report our progress and research associated with high-speed advance optical modulation in silicon photonics.

8990-38, Session 8

Rapid-melt-growth-based GeSi waveguide photodetectors and avalanche photodetectors *(Invited Paper)*

Neil Na, Chih-Kuo Tseng, National Tsing Hua Univ. (Taiwan); Yimin Kang, Intel Corp. (United States); Ming-Chang M. Lee, National Tsing Hua Univ. (Taiwan)

GeSi based photodetectors and avalanche photodetectors on silicon photonics platform have been widely studied in the past decade due to its low cost nature and compatibility with CMOS fabrication process. Conventionally, high-quality Ge on Si is obtained by a direct epitaxy growth or by a wafer/die bonding technique, which complicates the possible on-chip integration with CMOS electronics such as transimpedance amplifier, equalizer and limiting amplifier etc. Recently, rapid-melt growth of Ge on insulator emerged as a new method to produce high-quality Ge strips. In this talk, we present our effort in making waveguide based photodetectors and avalanche photodetectors using Ge rapid-melt growth. First, we demonstrate a high-performance, high-speed GeSi heterojunction photodiode by a self-aligned microbonding technique utilizing surface tension. Such a method is subsequently extended to fabricate a novel butt-coupled metal-semiconductor-metal as well as p-i-n high-speed Ge photodetector. At the same time, we study the possibility of operating Ge avalanche photodetectors at a low bias voltage to be compatible with standard CMOS IC power supply. Based on the theoretical and numerical results, a new type of GeSi avalanche photodetector in three-terminal configuration is proposed and demonstrated, reaching the lowest possible operation bias voltage constrained by Zener tunneling breakdown.

8990-39, Session 8

Low-cost radioactivity monitoring with scintillating fibers and silicon photomultipliers

Paolo Finocchiaro, Luigi Cosentino, Alfio Pappalardo, Carlotta Scirè, Sergio Scirè, Gianfranco Vecchio, Istituto Nazionale di Fisica Nucleare (Italy)

A new detector technology was developed, particularly suitable for low-cost radioactivity monitoring in radwaste storage sites. It consists of a scintillating optical fiber coupled at each end to a silicon photomultiplier (SiPM). The single photon sensitivity of the SiPM, along with the left-right coincidence constraint, allows to achieve a good sensitivity to gamma radiation even though using a thin 1mm diameter plastic scintillating fiber. Simulation results are in perfect agreement with the measured behavior, and several implementations are under way.

These detectors, also sensitive to charged particles, have also been tested at CERN with a high intensity electron beam, proving that they can effectively be used as beam monitors and beam loss monitors. The possibility to freely choose the fiber length and shape makes them very flexible both conceptually and physically.

Any improvement in the SiPM development technology reflects immediately into an improvement in our detector performance, as will be shown at the conference.

8990-40, Session 8

Design and development of a fNIRS system prototype based on SiPM detectors

Delfo N. Sanfilippo, Giuseppina Valvo, Massimo C. Mazzillo, Angelo Piana, Beatrice Carbone, Lucio Renna, Giorgio P. Fallica, STMicroelectronics (Italy); Diego Agrò, Giuseppe Morsellino, Maurizio Pinto, Riccardo Canicattì, Natale Galioto, A. Tomasino, Gabriele Adamo, Salvatore Stivala, Antonino Parisi, Luciano Curcio, Costantino Giaconia, Alessandro C. Busacca, Univ. degli Studi di Palermo (Italy); Roberto Pagano, Sebania Libertino, Salvatore A. Lombardo, Istituto per la Microelettronica e Microsistemi (Italy)

Functional Near Infrared Spectroscopy (fNIRS) uses near infrared sources and detectors to measure changes in absorption due to neurovascular dynamics in response to brain activation.

The use of Silicon Photomultipliers (SiPMs) in a fNIRS system has been estimated potentially able to increase the spatial resolution.

Dedicated SiPM sensors have been designed and fabricated by using an optimized process.

We performed responsivity measurements increasing the optical incident power; the temperature of the SiPM was monitored. We also carried out responsivity measurements on a broad spectrum, from ultraviolet to near infrared.

The design and implementation of a portable fNIRS embedded system, hosting up to 64 IR-LED sources and 128 SiPM sensors, has been carried out. The system has been based on a scalable architecture whose elementary leaf is a flexible board with 16 SiPMs and 4 couples of LEDs each operating at two wavelengths.

An ARM based microcontroller has been joined with a multiplexing interface, able to control power supply for the LEDs and collect data from the SiPMs in a time-sharing fashion and with configurable temporal slots.

The system will be validated by using a phantom made by materials of different scattering and absorption indices layered to mimic a human head. Its optical properties will be determined using the diffuse radial reflectance measurement technique.

A graphical user interface will be developed to display the changes in concentration and oxygenation of hemoglobin induced by brain activity.

The fNIRS system prototype using SiPMs has been developed in the framework of the ARTEMIS "High Profile" European Funded Project (grant agreement 269356).

8990-41, Session 8

Responsivity measurements of 4H-SiC Schottky photodiodes for UV light monitoring

Gabriele Adamo, Diego Agrò, Salvatore Stivala, Antonino Parisi, Luciano Curcio, Andrea Ando', Alessandro Tomasino, Costantino Giaconia, Alessandro C. Busacca, Univ. degli Studi di Palermo (Italy); Massimo C. Mazzillo, Delfo N. Sanfilippo, Giorgio P. Fallica, STMicroelectronics (Italy)

We report on the design and electro-optical comparison of three novel classes of 4H-SiC vertical Schottky UV detectors (hereafter named SiC8, SiC10, SiC20) based on the pinch-off surface effect and obtained employing Ni_2Si interdigitated strips whose pitch is, 8, 10 and 20µm, respectively. We have measured, in dark conditions, forward and reverse I–V characteristics as a function of the temperature and C–V characteristics.

The leakage current was a few picoamperes at -10V and 25°C and was slightly increasing at higher temperatures, because of the very low thermal generation (via the recombination centers) in the material bandgap. As expected, any temperature increase was producing a decrease of the bias threshold because of thermal generation.

C–V characteristics show that the capacitance did not significantly decrease when the reverse biases were increasing. This is ascribed to the surface pinch-off condition between contiguous depleted regions, occurring even at low reverse voltages. We have also observed a slight temperature dependence of the capacitance, especially at low reverse biases.

Responsivity measurements of the three classes of devices as a function of the wavelength (230–400nm) and of the applied reverse bias are reported. We have found a peak at 290nm. The SiC10 class exhibits the best results, being the area among adjacent strips almost fully depleted (i.e., active) at -9.4V and having an increased space/strip width ratio, in the interdigit geometry, with respect to the SiC8. The SiC20, instead, does not reach full depletion and this explains its lower performances.

8990-42, Session 8

Potentialities of silicon photomultiplier

Roberto Pagano, Sebania Libertino, Domenico Corso, Consiglio Nazionale delle Ricerche (Italy); Giuseppina Valvo, Delfo N. Sanfilippo, Giorgio P. Fallica, STMicroelectronics (Italy); Salvatore A. Lombardo, Consiglio Nazionale delle Ricerche (Italy)

Silicon Photomultiplier (SiPM) is the youngest detector in the family of solid state photon-detectors and, at the tim,e the only one able to compete with traditional Photomultiplier Tubes (PMT), thanks to its capability to resolve single photon arrival with good timing resolution and high gain. In the last 10 years many researchers and companies hard worked in the development and improvement of large area detectors. However, the SiPM dimension is limited due to its intrinsic dark counts. In this work, we present our main results on the study of the electrical and optical performances of different area SiPMs produced by STMicroelectronics. Their potentialities and limits are identified using both experimental measurements and electrical simulations (using ATHENA by Silvaco®) performed both on single pixel and full arrays having up to 4000 pixels. Moreover, the SiPM was tested in different experiments showing its aptitude to replace PMT in many applications.

In particular, we used SiPM at room temperature (RT) as photodetector in a classical spectrophotometric system to study: fluorescence decay of chemical compounds; photoluminescence (PL) spectra of semiconductors and organic materials; PL lifetime. First attempts to use SiPM to study the photon diffusion in highly scattering material in the near infrared spectrum will be also discussed. They will show the good device sensitivity even at large distance from the light source. Main results of all this experiments will be also compared with those obtained with a traditional PMT, showing the high potentiality of SiPM.

8990-43, Session 8

SNR measurements of silicon photomultipliers in the continuous wave regime

Gabriele Adamo, Diego Agrò, Univ. degli Studi di Palermo (Italy); Salvatore Stivala, Univ degli Studi di Palermo (Italy); Antonino Parisi, Costantino Giaconia, Alessandro C. Busacca, Univ. degli Studi di Palermo (Italy); Giorgio P. Fallica, STMicroelectronics (Italy)

We report on our SNR measurements carried out, in the continuous wave regime and at room temperature, on a novel class of silicon photomultipliers (SiPMs) fabricated in planar technology on silicon P-type substrate. Measurements have been performed employing a lock-in amplifier and a He-Ne laser as light source.

SiPM SNR is given by the ratio of the SiPM current, filtered and averaged by a lock-in amplifier, and the rms deviation of the same current. The latter is obtained with the lock-in amplifier set in the "noise" mode. In our measurements we employed a 10Hz equivalent noise bandwidth, around the lock-in amplifier reference frequency. The measured noise takes into account the shot noise, resulting from the photocurrent and the dark current, while background light is not present in our setup. We have found the SNR dependence with respect to the frequency and we report our measurements at three different reference frequencies (1, 10, 100kHz).

Our measurements highlight the SNR ascending trend as a function of the incident optical power, keeping the applied bias constant (28.7V, while the breakdown voltage was at 28.0V). We have also performed SNR measurements by varying the applied bias, keeping the incident optical power constant (7pW) within the linear range of the SiPM.

The device exhibits the best performances at a bias value of 30V. The SNR is almost independent from frequency in the evaluated range. Our results show the outstanding features in terms of SNR of these SiPMs without the need of any cooling system.

8990-44, Session 8

Tuneable high-responsivity lateral silicon p-i-n photodiodes with single, dual MOS gate and grating structures

Kamran Abid, Muhammad A. Naeem, Univ. of the Punjab (Pakistan); Jahan Akbar, Hazara Univ. (Pakistan); Faiz Rahman, Electrospell Ltd. (United Kingdom)

The device described here is a novel hybrid silicon photonics structure. This device acts as a hybrid transistor-diode where the lateral diode part of the device detect incident light and the vertical transistor like structure can be used to adjust the current flow through the device. The device has a cathode, an anode and a channel region with SiO_2 shielding as gate dielectric. These p and n regions are referred to as source and drain while considering the device as a MOSFET. Different structures can be usefully integrated over the gate dielectric i.e. SiO_2 shielded region. It has three variations i.e. with single and dual MOS gates and a grating

structure. The single gate structure is with “I” shaped gate whereas the dual gate is with “ horizontal U-shaped” dual gates. The single gate structure is further varied with offset single gate and Centre single gate structure, whereas the dual gate structure is with normal dual gates and overlapping dual gates structure. The devices showed hybrid nature and thus were characterized for diodes and MOSFETs simultaneously. The characterization results exhibited interesting behavior in short wavelength region, where normally silicon is not sensitive to.

These variations became basis for a nice shift of device sensitivity to selective short wavelength region, i.e. the device with higher gate bias (more negative w.r.t source) became more sensitive to blue wavelengths (480 nm) as against red wavelengths (630 nm). Furthermore, the device sensitivity was controlled by gate bias in all devices. However, the swapping sensitivity response was clearly evident in overlapping dual gates device structure.

The device variation with grating pattern over the gate dielectric showed the device polarization response which is wavelength neutral in the visible part of the EM radiations.

The device unlike to traditional MOSFETs has a partial gate structure. The partial clear region is a source of incident radiations to get into the device. These devices have two driving parameters to control the lateral conduction. These two includes the gate-bias control and the intensity of the incident radiation. The fab process is CMOS compatible, thus making the devices possible to monolithically integrate with CMOS circuitry.

The device characteristics are comparable to that of conventional MOSFETs. Electrical and optical characterizations are presented that emphasize the hybrid character of the device.

8990-45, Session 9

Wavelength division multiplexing using 10- and 12-channel silicon photonic transmitters

Edgar Huante-Ceron, Jason J. Ackert, Andrew P. Knights, McMaster Univ. (Canada)

Wavelength Division Multiplexing provides a means via which optical links may operate at data-transfer rates of N x D_r, where N is the number of available channels and D_r is the individual data-rate of a single modulation component. Whereas a great deal of effort has been used to increase the speed of operation of both Mach Zehnder and micro-ring silicon photonic modulators, there has been less work on expanding the number of modulated channels for short-reach applications. In this work we will discuss our recent design and fabrication of both 12 and 10 channels micro-ring based transmitters. We will describe a method through which greater control over the characteristic performance of 12 passive microrings can be achieved by adjusting the dimension of the waveguide in the bus/ring coupling region. We will then proceed to describe an active silicon photonic ten-channel micro-ring based transmitter designed and fabricated in a CMOS compatible process by connecting in series ten silicon waveguide micro-ring resonators of different radii to a common waveguide bus. The ten silicon micro-rings have varying radii of 12.0 to 12.045um (allowing a pre-tuning displacement of resonant wavelength), with centre wavelength around 1550nm and a gradual increment in radius of 4.5pm leading to a channel spacing of 0.4nm. Each micro-ring is selectively doped via ion implantation to form a pn-junction inside the rib-waveguide. Losses in the micro-ring associated with the doping can be tailored by carefully choosing the position of the pn-junction relative to the waveguide centre, allowing an augmentation in doping concentration without significantly increasing optical absorption. This approach is particularly attractive for MPW fabrication in which doping concentration may be fixed but design may require a variation in loss across the chip. The optical signal in each micro-ring can be independently monitored through a drop-port detector and resonance can be finely tuned thermally by a resistor located on top of each micro-ring. The quality factor of the resonator is 11000, with a frequency modulation of 10GHz for each micro-ring. The foot print of the device is 2800um long and 255um wide.

8990-46, Session 9

Strain engineering in germanium microdisks

Abdelhamid Ghrib, Moustafa El Kurdi, Institut d’Électronique Fondamentale (France); Mathias Prost, Institut d’Électronique Fondamentale (France) and STMicroelectronics (France); Malo de Kersauson, Institut d’Électronique Fondamentale (France); Ludovic Largeau, Lab. de Photonique et de Nanostructures (France); Olivia Mauguin, Laboratoire de Photonique et de Nanostructures, CNRS - UPR 20 (France); Grégoire Beaudoin, Lab. de Photonique et de Nanostructures (France); Sébastien Sauvage, Xavier Checoury, Institut d’Électronique Fondamentale (France); Gérald Ndong, Marc Chaigneau, Razvigor Ossikovski, Ecole Polytechnique (France); Sylvain David, Laboratoire des Technologies de la Microélectronique, CNRS-UJF (France); Isabelle Sagnes, Lab. de Photonique et de Nanostructures (France); Philippe Boucaud, Institut d’Électronique Fondamentale (France)

A germanium laser has been recently demonstrated. This achievement opens the route to realize a monolithic integrated source on silicon. The keystone of a germanium laser device is optimizing tensile strain and n-doping. In order to realize an integrated compact source, we demonstrate highly strained n-doped germanium microdisks by a process relying on initially compressed silicon nitride (SiN) deposition. Two approaches have been developed. In the first one, the germanium layers (300-500 nm) are grown on a GaAs substrate by metal-organic chemical vapor deposition. The germanium disks are fabricated using electronic lithography and ICP dry-etching from the blanket wafer. The GaAs pedestal is then under-etched by an acid solution and an initially compressed SiN layer is lastly deposited. It leads to a high strain transfer but with a significant inhomogeneity along the growth direction. In the second approach, germanium is grown on a lattice-mismatched InGaAs buffer layer which is pre-patterned into micro-pillar on GaAs substrate. The growth on InGaAs induces a biaxial tensile strain in the Ge films and leads to tensile-strained Ge micro-pillars. Depositing SiN provides an additional strain-transfer to the top of germanium. This two-strain transfer method leads to an enhanced overlap between the confined optical mode and the strained film.

Micro-disks resonators are optically studied under cw and pulsed pumping. We evidenced gallery modes exhibiting Q-factors up to 1350. A photoluminescence red-shift up to 445 nm is observed, corresponding to more than 1% biaxial strain. Strain has been also analyzed by µ-Raman spectroscopy and finite element modeling.

8990-47, Session 9

Low-loss and flatband silicon-nanowire-based 5th-order coupled resonator optical waveguides (CROW) fabricated by ArF-immersion lithography process on a 300-mm SOI wafer

Seok-Hwan Jeong, Daisuke Shimura, Takasi Simoyama, Photonics Electronics Technology Research Association (Japan); Miyoshi Seki, Nobuyuki Yokoyama, Minoru Ohtsuka, Keiji Koshino, National Institute of Advanced Industrial Science and Technology (Japan); Tsuyoshi Horikawa, National Institute of Advanced Industrial Science and Technology (Japan) and PETRA (Japan); Yu Tanaka, Ken Morito, Photonics Electronics Technology Research Association (Japan)

We present flatband, low-loss and low-crosstalk characteristics of Si-nanowire-based 5th-order coupled resonator optical waveguides (CROW) fabricated by ArF-immersion lithography process on a 300-mm silicon-on-insulator (SOI) wafer. We theoretically specified why phase controllability over Si-nanowire waveguides is prerequisite to attain desired spectral response, discussing spectral degradation by random phase errors during fabrication process. It was experimentally demonstrated that advanced patterning technology based on ArF-immersion lithography process showed extremely low phase errors even for Si-nanowire channel waveguides. As a result, the device exhibited extremely low loss of <0.2dB and low crosstalk of <–40dB without any external phase compensation. Furthermore, fairly good spectral uniformity for all fabricated devices was found both in intra-dies and inter-dies. The center wavelengths for box-like drop channel responses were distributed within 0.4 nm in the same die. This tendency was kept nearly constant for other dies on the 300-mm SOI wafer. In the case of the inter-die distribution where each die is spaced by ~3cm, the deviation of the center wavelengths was as low as ±1.8 nm between the dies separated by up to ~15 cm. The spectral superiority was reconfirmed by measuring 25 Gbps modulation signals launched into the device. Clear eye openings were observed as long as the optical signal wavelengths are stayed within the flat-topped passband of the 5th-order CROW. We believe these high-precision fabrication technologies based on 300-mm SOI wafer scale ArF-immersion lithography would be promising for several kinds of WDM multiplexers/demultiplexers having much complicated configurations and requiring much finer phase controllability.

8990-48, Session 9

Chirped photonic crystal mode converters for broad-band coupling with highly-dispersive photonic crystal microring resonators

Stanley M. Lo, Vanderbilt Univ. (United States); Jonathan Y. Lee, Univ. of Rochester (United States); Sharon M. Weiss, Philippe M. Fauchet, Vanderbilt Univ. (United States)

We demonstrate evanescent coupling between a photonic crystal (PhC) waveguide and a PhC embedded microring resonator on the silicon-on-insulator platform.

PhC embedded microring resonators have potential new applications for on-chip optical interconnects and sensing, by taking the advantage of the slow-light effect.

As the device is operated in the slow-light regime, in-/out-coupling from/to the outside network could be challenging due to the phase mismatch. In our previous work, we achieved the phase matching by reducing the width of the silicon waveguide[1]. However, this approach has the disadvantage of narrow bandwidth due to different dispersion characteristics between the silicon waveguide and the PhC.

In order to enhance the coupling bandwidth and provide better control on the coupling between the waveguide and the resonator, we design and fabricate a photonic crystal coupling waveguide with chirped photonic crystal mode converters attached at both ends. The mode converter comprises 6 linearly chirped air holes that adiabatically couple the light between the silicon waveguide mode and the PhC mode. 3D FDTD simulations reveal a coupling bandwidth of >100nm.

From our preliminary experiment, the optical spectra show a photonic bandgap located at ~1590nm. At the resonances in the slow-light regime, a loaded quality factor as high as ~2000 was measured and a group index of ~13 in the PhC embedded microring resonator was estimated from the non-uniform free spectral range. The images of out-of-plane near-field scattering patterns confirm the existence of the bandgap and the successful coupling into the micro-resonator.

[1] Optics Letters, Vol.37, 58(2012).

8990-49, Session 9

Self-coupled optical waveguide (SCOW) resonators for optical signal processing *(Invited Paper)*

Linjie Zhou, Shulin Li, Jingya Xie, Qianqian Wu, Jianping Chen, Shanghai Jiao Tong Univ. (China)

We report our recent progress on a novel type of optical resonators based on self-coupled optical waveguides (SCOW). The SCOW resonators are standing-wave resonators with both the clockwise (CW) and the counterclockwise (CCW) modes being co-excited. This makes them distinct from regular microring resonators. Two types of SCOW resonators are investigated for optical signal processing. The first one is formed by a waveguide with two folding points. The CW and CCW modes are sequentially excited without direct coupling. Split and enhanced resonance dips are observed from the SCOW resonator, depending on the two coupling coefficients. When two SCOW resonators are connected in series, coupled-resonator-induced transparency (CRIT) effect is present. The transparency peak can be tuned by the phase between the two SCOW resonators. The other type of SCOW resonator is formed by a waveguide with three folding points. The CW and the CCW modes are mutually-coupled in this case. Second-order optical filtering spectrum is generated. With two phase tuning performed to separately control the external and the mutual-resonator coupling, the filtering band profile can be easily tailored. Since the CW and CCW modes are fully utilized in our SCOW resonator, it is more compact and fabrication-tolerant compared to coupled microring resonators to achieve a similar spectrum. The system performances of the SCOW resonators in optical signal filtering, delay, and differentiation are examined.

8990-50, Session PWed

Hybrid integrated InGaAsP-Si laser using selective area metal bonding method for optical interconnection

Hongyan Yu, Lijun Yuan, Institute of Semiconductors (China); Li Tao, Peking Univ. (China); Baojun Wang, Institute of Semiconductors (China); Weixi Chen, Peking Univ. (China); Song Liang, Institute of Semiconductors (China); Yanping Li, Guangzhao Ran, Peking Univ. (China); Jiaoqing Pan, Institute of Semiconductors (China); Wei Wang, Institute of Semiconductors, Chinese Academy of Sciences (China)

An evanescently-coupled, hybrid InGaAsP/Silicon laser operating at 1.55 µm is presented by selective area metal bonding (SAMB). The III-V laser, fabricated on a p-InP substrate with a semi-insulating InP:Fe buried heterostructure (BH), serves to provide optical gain. On the SOI wafer, a 3-µm wide and 500-nm high Si waveguide is formed and the bonding metal (AuSn alloy) is selectively deposited in the regions which are 6 µm away from the Si waveguide on each side. The InGaAsP gain structure is flip-chip bonded onto the patterned SOI wafer using SAMB method which separates laterally the optical coupling area and the metal bonding area to avoid strong light absorption by the bonding metal. The hybrid laser runs with a maximum single-sided output power of 9 mw at room temperature. The slope efficiency of the hybrid laser is about 0.04 W/A, 4 times that of the laser before bonding which indicates that the light confinement is improved after the bonding. The hybrid laser has achieved 10°C continuous wave lasing. A near-field image of the hybrid laser is studied. As the inject current increases, the light spot markedly shifts down to the Si waveguide and covers the Si waveguide region, which demonstrates that the light generated in the III-V active region is coupled into the Si waveguide. This method allows for different III-V devices to be bonded onto any desired places on a SOI substrate. The simplicity and flexibility of the fabrication process and high yield make the hybrid laser a promising light source.

8990-51, Session PWed

Silicon Mach-Zehnder interferometer racetrack microring for sensing

Yule Xiong, Winnie N. Ye, Carleton Univ. (Canada)

SOI-based microring resonators (MRRs) have attracted extensive attentions as ultra-compact sensors. Recently, a new structure design combining a ring and a Mach-Zehnder interferometer (MZI) was proposed as sensors for biomedical applications, and as modulators for communications applications. In this design, the MZI uses two identical couplers, where one arm is formed by connecting the access waveguide of the couplers, while the other arm is part of the microring. Such a device may have only one major resonance with a high extinction ratio in a very broad wavelength span (quasi-free spectral range, quasi-FSR), which offers a very large measurement range for sensing applications. 2?2 multimode interference (MMI) couplers were used to couple the microring and the bus waveguides as MMI couplers have broader wavelength responses.

In this work, we present the first experimental demonstration of the MZI racetrack microrings using MMI couplers for sensing applications. Using a ring with a radius of 6 µm we achieved a quasi-FSR of 19.7 nm. Near the 1510 nm wavelength, the major resonance of the MZI racetrack microring demonstrates a high extinction ratio of ~22.6 dB with a full-width-half-maximum (FWHM) of 0.61 nm, and a quality factor Q of ~2,500. To demonstrate the uses for sensing applications, we measured the resonance shifts corresponding to the concentration change of the ambient aqueous solutions of sucrose. DI water was used as the reference for calibration to avoid any other variations, such as temperature change.

8991-1, Session 1

Graded-index core polymer optical waveguide for high-bandwidth-density optical printed circuit boards: fabrication and characterization *(Invited Paper)*

Takaaki Ishigure, Keio Univ. (Japan)

We theoretically and experimentally demonstrate that graded-index (GI) core polymer optical waveguides are a promising component realizing high-bandwidth-density on-board interconnects. As a fabrication method of GI circular core polymer optical waveguides, we introduce the Mosquito method utilizing a micro-dispenser. By the Mosquito method, GI circular core polymer parallel optical waveguides with low-loss and low inter-channel crosstalk are fabricated successfully without using any types of photo mask. In the Mosquito method, a viscous silicone monomer (approximately 20,000 cPs) is dispensed from a thin needle into a cladding monomer film by horizontally scanning the needle. Although the commercially available needles have an inner diameter larger than 100 um, the core diameter dispensed from the needle with 150-um inner diameter is sufficiently controlled to be less than 50 um maintaining almost perfect circular core shape. In addition, using a needle with a 100-um inner diameter, we succeeded in fabricating 9-um diameter core polymer waveguides, which operate as a single-mode waveguide. Furthermore, the Mosquito method is capable of accurately controlling the core diameter and inter-core pitch: less than 5-um variations are observed in core size and pitch when fabricating waveguides with a 50-um core diameter and 250-um pitch.

We also demonstrate that the GI-core polymer waveguides enable remarkably low loss waveguide circuits involving waveguide crossings in a mono layer. Since the Mosquito method is not suitable for the crossed waveguide fabrication, we show an alternative technique to realize the low-loss GI-core crossed waveguide: the Photo-addressing method which is developed by Sumitomo Bakelite Co., Ltd.

8991-2, Session 1

Multilayer single-mode polymeric waveguides by imprint patterning for optical interconnects

Tia Korhonen, Noora Salminen, Annukka Kokkonen, Mikko Karppinen, VTT Technical Research Ctr. of Finland (Finland)

Low-loss single-mode waveguides are fabricated for optical interconnection applications. Such waveguides operating at telecom wavelength window are attractive for communicating between micro-photonic integrated circuit (PIC) chips, such as Silicon PICs, on the carrier and board level, as well as for enhanced coupling of photonic devices to fibers for longer reach interconnects.

Manufacturing of the waveguides is based on direct pattering of optical polymeric materials by UV nanoimprinting. The advantages of the technology include the applicability to stack multiple layers of waveguides, fabrication on various substrate materials, such as, silicon wafers and circuit boards, as well as simultaneous fabrication of refractive and diffractive coupling structures, such as, micro-mirrors and gratings.

Multilayer waveguides were implemented using the so-called inverted rib waveguide process, that is, the shape of the waveguide cores are imprinted on the under-cladding layer as grooves and then the core material is deposited on the cladding layer filling the grooves and forming a thin (<0.5 µm) slab layer. The subsequent deposition of the upper cladding layer finalises the first waveguide layer and also starts the manufacturing of the next waveguide layer by imprint patterning the core 'grooves' followed by the deposition of the core material, and so on. Losses measured from the 27-cm long waveguide spirals made of commercial ORMOCER materials were 0.35 dB/cm at 1305 nm and 0.86 dB/cm at 1530 nm, which are only circa 0.1 dB/cm higher than the material losses. The core dimensions were ca 5 µm in width and ca 4 µm in thicknesses, optimised for 1300...1600 nm wavelength operation.

8991-3, Session 1

Laser-written polymer waveguides for embedded printed circuit board computing applications

Kevin L. Kruse, Christopher T. Middlebrook, Michigan Technological Univ. (United States)

Integrating polymer optical waveguides for board-to-board high speed data communications require prototyping samples for proof-of-concept studies before moving to large scale production. A laser direct writing (LDW) method is shown as a cost savings alternative to photolithographic prototyping large substrate samples. The LDW setup consists of a 3-axis high-precision motion platform with a commercially available UV laser diode coupled to a lens-capped single mode fiber. The correlation between writing parameters and the resulting waveguide dimensions is discussed theoretically and confirmed experimentally with Dow Corning© UV-Cured Optical Elastomers for both multimode and single-mode feasibility. Laser written waveguide radial bends and crossings are also evaluated to show manufacturing capabilities for advanced prototyping designs. Polymer waveguides fabricated with the LDW method are experimentally validated with losses comparable to polymer waveguides manufactured with the photolithographic process (< 0.05 dB/cm).

8991-4, Session 1

Performance of step index multimode waveguides with tuned numerical aperture for on-board optical links

Krzysztof Nieweglowski, Ronny Henker, Klaus-Jürgen Wolter, Frank Ellinger, Technische Univ. Dresden (Germany)

This paper discusses experimental results of optical characterization of low-loss, robust, high-speed optical link basing on step index (SI) polymeric multimode waveguides. Planar polymer multimode waveguides are the most promising approach to realize optically functionalized hybrid printed circuit boards which combine fabrication compatibility and high cost-efficiency. Single-mode waveguides feature high bandwidth, but especially for the mature laser sources (VCSEL) with 850nm wavelength the assembly tolerances for efficient passive waveguide-chip coupling become critical. Alternatively, graded index polymer waveguides combine the enhancement of performance and relaxation of assembly tolerances, but feature complicated fabrication. The fabrication of investigated SI waveguides use mature technology (UV photolithography). In order to enhance the bandwidth of optical waveguides tuning of numerical aperture (NA) by material adoption has been implemented. However, changing the NA of waveguides influences the geometrical design rules (e.g. minimum bending radius) and tolerance requirements for optical coupling interfaces. Therefore a trade-off between tolerance requirements, bandwidth and design rules have to be found. In this paper experimental performance of SI polymeric waveguides will be investigated. Using insertion loss measurement waveguide's attenuation coefficient (< 0.05 dB/cm) and influence of design parameters on optical loss will be examined. Near- and far-field analyses show respectively mode filling and conversion and determine the beam divergence (NA) along the waveguide. The performance at high data rates of SI planar optical waveguides will be also characterized with optical transmission

measurements up to 25 Gbit/s. The measurement results will be finally analyzed in order to derive design rules for on-board optical interconnects with multi Gbit/s x m performance.

8991-5, Session 1

Photonic wire bonding as an enabling technology for multi-chip photonic systems

Nicole Lindenmann, Tobias Hoose, Karlsruher Institut für Technologie (Germany); Sönke Steenhusen, Fraunhofer-Institut für Silicatforschung (Germany); Muhammad Billah, Sabastian Koeber, Karlsruher Institut für Technologie (Germany); Ruth Houbertz-Krauss, Fraunhofer-Institut für Silicatforschung (Germany); Christian Koos, Karlsruher Institut für Technologie (Germany)

Over the last years, tremendous progress has been made in the field of monolithic photonic integration, leading to a large device portfolio on the Silicon-On-Insulator (SOI), Indium-Phosphide (InP) as well as the Gallium-Arsenide (GaAs) platform. Despite the progress in photonic integration, there is currently no respective technology that could serve the needs of a flexible chip-to-chip connectivity scheme.

Photonic wire bonding was recently introduced to cope with these demands. The fabrication of photonic wire bonds (PWB) exploits the capabilities of 3D direct write laser lithography based on multi-photon polymerization (MPP) in photopolymers. Through the 3D structuring capability of the method, photonic wire bonding allows for flexible adaption of interconnect waveguides to the given module geometries.

An overview over our research in photonic wire bonding is given which focuses on different material concepts that are suitable for 3D structuring by MPP. Novel material approaches could help to further affect and thus to simplify the fabrication process as well as to improve the properties of the PWB, such as optical quality and temperature stability. PWB can be structured in solid resists such as SU8, as well as liquid systems such as purely organic acrylates and inorganic-organic hybrid polymers (ORMOCER®s). Particularly the latter enable custom-designed optical properties such as low absorption losses in the data and telecom wavelength regime or refractive indices, dependent on their chemical composition. Additionally, ORMOCER®s feature an excellent patternability for PWB applications whose performance will be discussed with respect to other materials' performance.

8991-6, Session 2

Efficient waveguide coupling interfaces for subwavelength-scale metal-optic cavities

(Invited Paper)

Kyoungsik Yu, Youngho Jung, KAIST (Korea, Republic of)

Many studies have been reported in design, fabrication, and characterization of subwavelength-scale nanocavities and nanolasers, which are attractive for dense photonic integrated circuit applications due to their small sizes and low energy/power consumption. However, broad radiation patterns emanating from such small resonator structures pose great challenges to efficient coupling from/to the optical waveguides.

In this presentation, we review various approaches to solve this practical and fundamental issue. For example, a recent paper have proposed dielectric shield nanoscale patch lasers that can be coupled to dielectric waveguides with the coupling efficiency of 22% by placing the gain medium at the off-axis position [1]. We also discuss the use of metal slot waveguides with low propagation losses and wavelength dependency. In order to increase the coupling efficiency, we emphasize the importance of the radiation pattern engineering from the subwavelength-scale resonators and the effective index matching with the waveguides.

[Reference]

[1] Q. Ding, A. Mizrahi, Y. Fainman, and V. Lomakin, "Dielectric shielded nanoscale patch laser resonators," Opt. Lett. 36(10), 1812–1814 (2011)

8991-7, Session 2

10-40 GHz on-chip micro-optical links with all-integrated Si Av LED optical sources, waveguides, and SiGe detectors

Kingsley A. Ogudo, Lukas W. Snyman, Tshwane Univ. of Technology (South Africa) and Micro Systems Technology Development SA (South Africa); Jean-Luc Polleux, Carlos Viana, Zerihun Tegegne, Univ. Paris-Est Marne-la-Vallée (France)

Si Avalanche based LEDs have been developed that effectively emit up to 100nW / µm 2 in the 650 -850nm regime (Snyman et al, Japanese Journal Applied Physics, 2007; Snyman et al , Proc SPIE, 2008, 2009, 2010 ; Snyman et al , IEEE Journal of Quantum Electronics, June 2010). Correspondingly, small micro-dimensioned detectors with pW/ µm 2 sensitivity (for the same wavelengths) can be realized also in CMOS integrated circuitry. Latest research results also show that specific Si CMOS Av LEDs can be developed that emit mainly in the 650 -850nm regime. Subsequent analyses showed that that both silicon nitride and Si oxi-nitide offer good possibilities for development of such waveguides, utilizing either 0.2 to 2 micron trench-, or CMOS over-layer based technology.

Advanced optical simulation software (RSOFT BeamPROP and RSOFT FULL WAVE) were used to design specific CMOS based waveguides operating at 650 - 750nm wavelength using CMOS materials and processing parameters. The results showed that effective single mode wave-guiding channel strips of 0.2 -1.5 micron wide, embedded in silicon oxide , can be realized with loss characteristics of below 0.5 dB.cm-1 and with dispersion characteristics (bandwidth-length product) of up to 100 Ghz-cm. Micro-bending, multi-plane coupling and chip edge coupling are possible (Snyman et al, SPIE JM3, 2013) .

The above design technologies were now effectively realized by combining front end expertise in Si Av LED technology (Snyman et al) and the integrated bipolar Si-Ge phototransistor technology (Polleux etal, ESIEE, Cedex, France) .

It is believed that the all silicon , on chip, micron dimensioning , achieved modulation bandwidths through parasitic eliminations, all compete most favorably with best achievements internationally (compare IBM technology, 2010).

The technology as developed have recently been extensively patented in the form of USA patent applications US 2012 017 0942, US 2012 012 015 3864, US 2012 015 4812: as well as in Provisional RSA Patent Applications 2009/04162, 2009/04163 , 2009/04509 , 2009/04508 , 2010/00200, 2010/02021 , 2013/5678 and three PCT patents filed by TUT, June 2010.

8991-8, Session 2

Fabrication and characteristics of the Si-photonics-integrated vertical resonant-cavity light-emitting diode

DuanHua Kong, Taek Kim, Sihan Kim, Hyun-Gi Hong, Igor Shcherbatko, Young-Soo Park, Samsung Advanced Institute of Technology (Korea, Republic of); Kyoung-Ho Ha, Gitae Jeong, SAMSUNG Electronics Co., Ltd. (Korea, Republic of)

We designed and fabricated a silicon-on-insulator (SOI) and III-V integrated 1.3um vertical Resonant-Cavity Light-Emitting Diodes for optical interconnecting by using the direct wafer bonding. The device including a InP based front bragg reflector(DBR), a InGaAlAs based active layer and a SOI high-contrast-grating(HCG) as the back reflector. Successfully got 1.3um optical spectrum from the fabricated device.

8991-9, Session 2

Fabrication and characterization of multilayer silicon photonic structures for optical interconnects

Amrita Banerjee, Jun Tan, Siamak Abaslou, Robert Gatdula, Wei Jiang, Rutgers, The State Univ. of New Jersey (United States)

Silicon photonics has become a preferred platform for optical interconnects. Multilayer silicon photonic structures have aroused interest as the complexity of optical interconnects evolves. Multilayer structures can increase the interconnect density and enable more complex interconnect architectures. We fabricate some essential multilayer optical interconnect structures on a silicon-on-insulator wafer and characterize their performance. Electron beam (e-beam) lithography is employed to pattern the silicon photonic structures in each layer. The patterns will be dry-etched and silicon oxide will be used as the inter-layer dielectric. Fundamental issues such as inter-layer alignment and planarization will be addressed. High-end e-beam lithography tool is capable of achieving high alignment accuracy. However, detailed examination and optimization of the fabrication processes are necessary to ensure the structure morphology is compatible with the requirements of silicon photonics. Processing considerations including the choice of resists and planarization mechanisms will be discussed. Various microscopy tools including SEM and AFM are used to characterize the structure morphology and alignment accuracy. Preliminary optical testing results will be presented.

8991-47, Session 2

Spoked-ring microcavities: enabling seamless integration of nanophotonics in unmodified advanced CMOS microelectronics chips

Mark T. Wade, Jeffrey M. Shainline, Univ. of Colorado Boulder (United States); Jason S. Orcutt, Rajeev J. Ram, Massachusetts Institute of Technology (United States); Vladimir Stojanovic, University of California Berkeley (United States); Milos A Popovic, Univ. of Colorado Boulder (United States)

We present the spoked-ring microcavity, a nanophotonic building block enabling energy-efficient, active photonics in unmodified, advanced CMOS microelectronics processes. The cavity is realized in the IBM 45nm SOI CMOS process – the same process used to make many commercially available microprocessors including the IBM Power7 and Sony Playstation 3 processors. In advanced SOI CMOS processes, no partial etch steps and no vertical junctions are available, which limits the types of optical cavities that can be used for active nanophotonics. To enable efficient active devices with no process modifications, we designed a novel spoked-ring microcavity which is fully compatible with the constraints of the process. As a modulator, the device leverages the sub-100nm lithography resolution of the process to create radially extending p-n junctions, providing high optical fill factor depletion-mode modulation and thereby eliminating the need for a vertical junction. The device is made entirely in the transistor active layer, low-loss crystalline silicon, which eliminates the need for a partial etch commonly used to create ridge cavities. In this work, we present the full optical and electrical design of the cavity including rigorous mode solver and FDTD simulations to design the Q-limiting electrical contacts and the coupling/excitation. We address the layout of active photonics within the mask set of a standard advanced CMOS process and show that high-performance photonic devices can be seamlessly monolithically integrated alongside electronics on the same chip. The present designs enable monolithically integrated optoelectronic transceivers on a single advanced CMOS chip, without requiring any process changes, enabling the penetration of photonics into the microprocessor.

8991-10, Session 3

A 1.3 tb/s parallel optics VCSEL link *(Invited Paper)*

Kobi Hasharoni, Shuki Benjamin, Amir Geron, Stanislav Stepanov, Niv Margalit, Gideon Katz, Michael Mesh, Compass-EOS (Israel)

A high bandwidth optical interconnect is designed based on a parallel optics VCSEL link. The transceiver is based on direct assembly of large 12x14 element VCSEL and PD matrices on top of a CMOS chip using Gold pillars to compensate for the thermal expansion coefficient differences. A 2-lens relay was used to couple light from each of the 168 elements into a 12x14 fiber bundle array using multimode fibers; one microlens array is flip chip assembled on the optoelectronic devices while the second array is assembled on the fiber bundle matrix. The CMOS chip designed is a mixed signal device with both digital and analog circuits including laser driver and Serializer (Tx); trans-impedance and limiting amplifiers, equalizer, clock data recovery and Deserializer (Rx). The data rate is 8Gb/s resulting in a full duplex bandwidth of 1.34Tb/s. Tight packaging of the interconnect leads to a data density of 64Gb/s/mm^2; these are the highest values reported for an optical interconnect. Optical links of 300m are made possible with BER<10^-12 while the power efficiency is 10.2 pJ/bit including the optical SerDes arrays.

This optical interconnect enables a passive, full mesh backplane for telecom and datacom applications requiring very large BW connectivity (e.g. > 10Tb/s) which is otherwise impossible to achieve. Thus, chip-to-chip, board-to-board and rack-to-rack optical connectivity can be realized using the technology via the passive backplane. This has already been implemented in high-end core and edge telecom routers in which h the digital part of the CMOS chip acts a traffic manager and a switch fabric resulting in a switchless multi-chassis router design.

8991-11, Session 3

Photonic integration enabling new multiplexing concepts in optical board-to-board and rack-to-rack interconnects *(Invited Paper)*

Dimitrios Apostolopoulos, Paraskevas Bakopoulos, Dimitrios Kalavrouziotis, Giannis Giannoulis, Giannis Kanakis, Nikos Iliadis, Christos Spatharakis, National Technical Univ. of Athens (Greece); Johan Bauwelinck, Univ. Gent (Belgium); Hercules Avramopoulos, National Technical Univ. of Athens (Greece)

New broadband applications are causing the datacenters to proliferate, raising the bar for higher interconnection speeds. So far, optical board-to-board and rack-to-rack interconnects relied primarily on low-cost commodity optical components assembled in a single package. Although this concept proved successful in the first generations of optical-interconnect modules, scalability is a daunting issue as signaling rates extend beyond 25Gb/s. In this paper we demonstrate our work towards the development of two technology platforms for migration beyond Infiniband enhanced data rate (EDR), introducing new concepts in board-to-board and rack-to-rack interconnects.

The first platform is developed in the framework of MIRAGE European project and relies on proven VCSEL technology, exploiting the inherent cost, yield, reliability and power consumption advantages of VCSELs. Wavelength multiplexing, PAM-4 modulation and multi-core fiber (MCF)

multiplexing are introduced by combining VCSELs with integrated Si and glass photonics as well as BiCMOS electronics. An in-plane MCF-to-SOI interface is demonstrated, allowing coupling from the MCF cores to 340x400 nm Si waveguides. Development of a low-power VCSEL driver with integrated feed-forward equalizer is reported, allowing PAM-4 modulation of a bandwidth-limited VCSEL up to 40 Gbaud.

The second platform, developed within the frames of the European project PHOXTROT, considers the use of modulation formats of increased complexity in the context of optical interconnects. Powered by the evolution of DSP technology and towards an integration path between inter and intra datacenter traffic, this platform investigates optical interconnection system concepts capable to support 16QAM 40GBd data traffic, exploiting the advancements of silicon and polymer technologies.

8991-12, Session 3

100 Gigabit ethernet using a single wavelength source transmitting a CAP signal with a QAM receiver

Jinlong Wei, Univ. of Cambridge (United Kingdom); Qixiang Cheng, Univ of Cambridge (United Kingdom); David G. Cunningham, Avago Technologies Ltd. (United Kingdom); Richard V. Penty, Ian H. White, Univ. of Cambridge (United Kingdom)

Recently, carrierless amplitude and phase (CAP) modulation has been investigated for high speed optical data links. The main advantages of CAP are its high spectral efficiency and easy implementation by using analogue transversal filters for signal generation and recovery, and thus its great potential for low cost and low power dissipation. The major disadvantage of high speed optical CAP data links are their high sensitivity to timing jitter at the receiver because the recovered CAP signal has a narrow horizontal eye opening as a result of the interference between the two orthogonal channels. However, this obstacle can be overcome using a modified quadrature amplitude modulation (QAM) receiver instead of a conventional CAP receiver. In this work therefore, detailed simulations have been undertaken to investigate the feasibility of 100 Gigabit Ethernet links employing a single laser source and hybrid CAP-16/QAM-16, CAP-32/QAM-32, CAP-64/QAM-64 transmitter/receiver schemes. Results have shown that, in comparison with the case of using a standard CAP-16/32/64 receiver, the use of a modified QAM-16/32/64 receiver not only lowers system timing jitter sensitivity by 8 times but also improves the optical link power margin. For example, CAP-16/QAM-16 has about 3 dBo better power margin than standard CAP-16 when operating over a SMF length of 2 km with a jitter of ±1 ps. For practical jitter conditions of ±3 ps, the aforementioned three hybrid CAP/QAM systems can support single laser 100 Gb/s transmission over 10 km of SMF. Whilst equalized standard CAP supports transmission over only 5 km SMF with reduced jitter tolerance of ±1ps.

8991-13, Session 3

Array fiber welding on micro-optical glass substrates for chip-to-fiber coupling

Henning Schröder, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); Marco Queiser, Technische Univ. Berlin (Germany); Lars Brusberg, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); Norbert Arndt-Staufenbiel, Klaus-Dieter Lang, Technische Univ. Berlin (Germany)

High bandwidth parallel optical transceivers are highly demanded for optical interconnects in data centres and in high performance computing. Such transceivers are composed of VCSEL- and photodiode components, and the appropriate driving and amplifying circuitry. For high density fiber optical connectors lens arrays have to be used. We propose an advantageous adhesive free method to interconnect optical fibers with such kind of lens arrays. Common approaches using adhesive bonding have high challenges in terms of yield, reliability and optical performance.

We introduce our novel fiber welding approach for joining directly fused silica fibers on borosilicate glass substrates with integrated micro optics, e.g. lenses. It is a thermal process with a precise heat input by a CO2-laser, which is combinable with passive or active alignment of every single fiber to the substrate. Since the fiber is accessed only from one side, a two dimensional high-density fiber array can be realized. The manufacturing time of such an interconnection is very short. By the glass-to-glass interface high power transmission is enabled and the occurrence of misalignment and degradation are prevented. The paper presents our laboratory setup for array fiber welding and experimental results of such connections, which are compared to UV-adhesive joinings. Also further investigation, for example optical characterization and reliability tests are included. Finally a machine concept, which is under development, will be discussed.

8991-14, Session 4

Efficient and scalable single-mode waveguide coupling on silicon-based substrates *(Invited Paper)*

Edris M. Mohammed, Ricky J. Tseng, Brandon Rawlings, Shawna M. Liff, Ibrahim Ban, William Mcfarlane, Miriam R. Reshotko, Peter Chang, Intel Corp. (United States)

One of the key challenges in a Single mode (SM) optical interconnect system is the efficient coupling of optical signals from on-chip waveguides to single mode fibers with low insertion loss (IL) and relaxed alignment tolerance. On Silicon (Si) substrate horizontal and vertical coupling are possible using different optical structures but vertical coupling allows the use of two-dimensional arrays and scales the aggregate bandwidth while the former is limited to one dimension and consumes more chip space to scale bandwidth. In this paper we discuss a SM optical interconnect system that consists of Si based substrate and a micro-lensed fiber optic connector. The Si substrate integrates arrays of 700nm x 350nm SiN single mode waveguides, 4um x 4um polymer spot size converters, 45 degree metallized polymer waveguide mirrors and microlens arrays. The connector also has similar microlens arrays and 90 degree bent fibers. In this architecture optical signals from SiN waveguide are evanescently coupled to polymer spot size converter, reflected vertically off the 45 degree mirror and coupled to microlens arrays on the substrate for collimation. The collimated beam is received by the connector and focused on to the fiber using the microlenses integrated on the connector. Integration of microlenses on the Si Substrate and the fiber optic connector relaxes optical alignment tolerance. We measured total IL of less than 10 dB for the combined unit and measured lateral (x-y) misalignment tolerance of 20um for 0.5dB loss. Due to the relaxed tolerance between these units standard semiconductor bonding tools could be used to assemble them.

8991-15, Session 4

Fabrication of Fresnel micro lens array in borosilicate glass by F2-laser ablation for glass interposer application

Lars Brusberg, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); Marcel Neitz, Technische Univ. Berlin (Germany); Henning Schröder, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); Thomas

Fricke-Begemann, Jürgen Ihlemann, Laser-Lab. Göttingen e.V. (Germany)

The future need for more bandwidth forces the development of optical transmission solutions for rack-to-rack, board-to-board and chip-to-chip interconnects. The goals are significant reduction of power consumption, highest density and potential for bandwidth scalability to overcome the limitations of the systems today with mostly copper based interconnects. For system integration the enabling of thin glass as a substrate material for electro-optical components with integrated micro-optics for efficient light coupling to integrated optical waveguides or fibers is becoming important. Our glass based packaging approach merges micro-system packaging and glass integrated optics. This kind of packaging consists of a thin glass substrate with integrated micro lenses providing a platform for photonic component assembly and optical fiber or waveguide interconnection. Thin glass is commercially available in panel and wafer size and characterizes excellent optical and high frequency properties. That makes it perfect for microsystem packaging. A suitable micro lens approach has to be comparable with different commercial glasses and withstand post-processing like soldering. A benefit of using laser ablated Fresnel lenses is the planar integration capability in the substrate for highest integration density. In the paper we introduce our glass based packaging concept and the Fresnel lens design for different scenarios like chip-to-fiber, chip-to-optical-printed-circuit-board coupling. Based on the design the Fresnel lenses were fabricated by using a 157nm fluorine laser ablation system. The paper presents all characterization results (microscope, surface quality, lens profile, optical characteristics) and discusses the novel lens approach for photonics packaging.

8991-16, Session 4

Low-loss connections between no-polish optical fibers In elastically deformable connectors

Tsuyoshi Aoki, Hidenobu Muranaka, Shigenori Aoki, Fujitsu Labs., Ltd. (Japan); Katsuki Suematsu, Mitsuhiro Iwaya, Masato Shiino, Takeshi Yagi, Furukawa Electric Co., Ltd. (Japan)

For widely disseminating optical interconnection, cost-effective multifiber optical connectors are required. We have proposed a novel elastic optical connector to avoid high-cost end-face polishing processes. The connector has elastically deformable structure which enables the accommodated no-polish fibers to be protruded and buckled at mating. Therefore, the variations in both fiber lengths and mounted positions of no-polish fiber ribbons are cancelled. We have demonstrated the low-loss connection between no-polish multimode fibers and film waveguides by using prototype connectors. However, the size of previously reported elastic connectors was relatively large and low-loss connections between no-polish fibers have not been verified.

In this paper, we report down-sized elastic connectors, which are compatible with standard Mechanically Transferrable (MT) connectors, by reshaping the deform mechanism as well as low-loss connecting between laser-cleaved no-polish fibers. To realize MT compatible elastic connector, we developed an N-shaped folded deformable part which is precast in the frame. The part functions as a spring along mating direction in narrow space. We confirmed that the fabricated connector shows elastic deform behavior. To realize low-loss connections between fibers without reflection, smooth end-faces of the fibers to realize physical contact of the fiber cores is indispensable. By adopting a laser cleaving technique, we found that the end-faces of fibers have not only smooth surface but also slightly protruding dome-shape like end-faces of fibers in a polished connector. We verified that the connections between the laser-cleaved multimode fibers show low-loss connecting about 0.2 dB. The detail will be reported at the presentation.

8991-17, Session 4

New single-mode multi-fiber expanded-beam passive optical interconnect

Mike Hughes, Toshiaki Satake, Darrell Childers, US Conec Ltd. (United States)

This paper describes the design and performance of next generation, single-mode, multi-fiber, debris insensitive, expanded beam, interconnect components. This low cost, dense optical interconnect technology combined with recent advances next generation, high bandwidth, SM, silicon photonic based Tx/Rx devices is enabling unprecedented bandwidth densities for extended distances at reduced costs.

A monolithic, multi-fiber ferule with integrated collimating lenses was designed with the same overall footprint as a traditional MT-type, multi-fiber rectangular ferrule. The new optical ferrule was designed with precision micro holes for alignment to the lens array allowing for future incorporation of multiple rows of fibers into a single ferrule unit. The monolithic, lensed based ferule design enables a low-cost, no-polish fiber termination methodology.

The ferrule tested was manufactured with an array of 16 fibers in the footprint associated with traditional, 12 fiber, physical contact MT ferules via use of novel, molded in, end-face alignment features. Multiple optical models were built with ray tracing methodology to predict the insertion loss and return loss with varying refraction index, transmissivity and surface reflection properties of the ferrule.

Empirical optical performance results closely match the optical modeling predictions. Insertion losses of <1.5dB were measured along with return loss values <=-30dB. Further analysis was done to characterize the robustness of the new interconnect with regard to debris insensitivity. Do to the nature of the expanded beam, free-space optical design, the impact of debris on the optical mating surface of the interconnect was significantly reduced when compared to traditional, physical contact single mode interconnects.

8991-18, Session 5

Silicon-on-insulator optical modulators for integration in photonic optical circuits *(Invited Paper)*

Graham T. Reed, David J. Thomson, Frederic Y. Gardes, Goran Z. Mashanovich, Youfang Hu, K. Li, P. W. Wilson, Univ. of Southampton (United Kingdom); Lars Zimmermann, IHP GmbH (Germany); Henri Porte, Photline Technologies (France); Bernhard Goll, Horst Zimmermann, Technische Univ. Wien (Austria); Dieter Knoll, S. Lischke, IHP GmbH (Germany); S. W. Chen, S. S. H. Hsu, National Tsing Hua Univ. (Taiwan); J. M. Fedeli, CEA-LETI-Minatec (France); Kapil Debnath, Univ. of St. Andrews (United Kingdom); Thomas F. Krauss, The Univ. of York (United Kingdom); Liam O'Faolain, Univ. of St. Andrews (United Kingdom)

This paper summarises our work on modulators for integration, either as a front end approach, or a co-location of custom electronic drivers, approaches that have yielded data rates up to 50Gb/s from a range of device variants. As well as more conventional depletion based devices, we also report photonic crystal cavity based modulators for very low power consumption, as well as other device variants aimed at improving device performance metrics.

8991-19, Session 5

Integrated DWDM silicon photonic transceiver with self-adaptive CMOS circuits for chip-to-chip optical interconnects

Chin-Hui Chen, Hewlett-Packard Co. (United States); Cheng Li, Texas A&M Univ. (United States) and Hewlett-Packard Co. (United States); Rui Bai, Oregon State Univ. (United States); Ayman Shafik, Texas A&M Univ. (United States); Marco Fiorentino, Zhen Peng, Hewlett-Packard Co. (United States); Patrick Chiang, Oregon State Univ. (United States) and Fudan Univ. (China); Samuel Palermo, Texas A&M Univ. (United States); Raymond G. Beausoleil, Hewlett-Packard Co. (United States)

The rapid scaling of microprocessors has shifted the critical bottleneck of high-performance computing systems from the computational units to the communication infrastructure. By taking advantage of the parallelism and capacity of dense wavelength-division-multiplexed (DWDM) technology, optical interconnects using nanophotonics offer a high-bandwidth, low-latency, and energy-efficient solution within a small footprint, when compared with their electrical counterparts.

In this paper, we report our progress on developing a silicon photonic transceiver with hybrid photonic/electronics integration, incorporating CMOS circuits with a photonics substrate to form a DWDM optical link targeting high-performance computing applications. We have demonstrated a transmitter incorporating wire-bonded pre-emphasis drivers and carrier-injection-based microring modulators operating at 5 Gbps, for an energy-efficiency of 808 fJ/bit. Both thermal and bias-tuning schemes are utilized to lock the resonance of the microrings to the input channel wavelengths and compensate for environmental fluctuations. Integrated silicon resistive heaters show a tuning efficiency of 11 ?W/GHz for 5 um microrings, while bias-tuned feedback compensation demonstrates a maximum wavelength tuning of 0.22 nm at 425 ?W power consumption. We also demonstrated a self-adaptive receiver, with an energy efficiency of 275 fJ/bit at 8 Gbps, which reduces the transimpedance amplifier (TIA) power by 14% when the input sensitivity is relaxed by 2 dB.

These components will be brought together into a 16-channel DWDM system by flip-chip bonding a CMOS transceiver chip onto a photonic chip with microring modulators and waveguide germanium photodiodes. The channel grid will be provided by an external quantum-dot-based comb laser at wavelengths near 1.3um with 80 GHz channel spacing.

8991-20, Session 5

Two-dimensional beam steering on silicon nanomembranes

David N. Kwong, The Univ. of Texas at Austin (United States); Amir Hosseini, Omega Optics, Inc. (United States); Ray T. Chen, The Univ. of Texas at Austin (United States)

We demonstrate an integrated optical beam steering system using a 16 element optical phased array fabricated on SOI with a silicon device layer thickness of 250nm. 2D beam steering is achieved using a combination of wavelength tuning and TO phase shifting, with a switching power of P_π=20mW per channel. The output coupling to free space is achieved using a thin polysilicon overlay. Compared to conventional shallow etched gratings, this structure eliminates the need for precisely controlled etching due to the built-in oxide etch stop layer, thereby greatly simplifying the fabrication complexity.

8991-21, Session 5

Composite-CMOS integrated photonics for high-bandwidth WDM optical interconnects *(Invited Paper)*

Timothy Creazzo, Elton Marchena, Stephen B. Krasulick, Skorpios Technologies, Inc. (United States); Paul K. Yu, Skorpios Technologies, Inc. (United States) and Univ. of California, San Diego (United States); Derek A. Van Orden, John Y. Spann, Christopher C. Blivin, Hong Cai, Lina He, John M. Dallesasse, Robert J. Stone, Amit Mizrahi, Skorpios Technologies, Inc. (United States)

Bandwidth requirements continue to drive the need for low-power, high speed interconnects. Harnessing the mature CMOS technology for high volume manufacturing, Silicon Photonics has emerged as a top candidate for providing a viable solution for high bandwidth, low cost, low power, and high packing density, optical interconnects. The major drawback of silicon, however, is that it is an indirect bandgap material, and thus cannot produce coherent light. Consequently, different integration schemes of III/V materials on silicon have been explored. Here, the current state-of-the-art for optical interconnects in Silicon Photonics is reviewed. Particular emphasis is placed on a recently proposed Composite-CMOS integration platform that enables high bandwidth WDM optical interconnects.

8991-22, Session 5

Hybrid silicon-electro-optic polymer integrated high-performance optical modulators

Xingyu Zhang, The Univ. of Texas at Austin (United States); Amir Hosseini, Omega Optics, Inc. (United States); Ray T. Chen, The Univ. of Texas at Austin (United States)

We design and demonstrate a compact and low-power band-engineered electro-optic (EO) polymer refilled silicon slot photonic crystal waveguide (PCW) modulator. The EO polymer is engineered for large EO activity and near-infrared transparency. A PCW step coupler is used for optimum coupling to the slow-light mode of the band-engineered PCW. An effective in-device r33 over 1000pm/V is demonstrated for over a 8nm optical wavelength range.

8991-23, Session 6

A holistic way towards high-performance, low-energy and low-cost data centers and HPCs: PhoxTroT *(Invited Paper)*

Tolga Tekin, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany) and Technische Univ. Berlin (Germany); Nikos Pleros, Ctr. for Research and Technology Hellas (Greece); Dimitrios Apostolopoulos, National Technical Univ. of Athens (Greece)

PhoxTroT.eu is focusing on on-board, board-to-board and rack-to-rack optical interconnects. The goal of this large-scale EU research effort is the deployment of optimized technologies to tailor dedicated interconnect layers towards high-performance, low-energy and low-cost Data Center and High-Performance Computing Systems. A “mix&match” technology by synergizing the different fabrication platforms such as CMOS electronics, Si-photonics, polymers, glass, III-Vs,and plasmonics will enable generic building blocks (transmitters, modulators, receivers,

switches, optochips, multi- and single-mode optical PCBs, chip- and board-to-board connectors) to extend the performance beyond Tb/s and to reduce the energy by more than 50%.

8991-24, Session 6

Silicon/electro-optic polymer hybrid directional coupler switch

Oscar D. Herrera, Roland Himmelhuber, Kyung-Jo Kim, Robert A. Norwood, Nasser N. Peyghambarian, The Univ. of Arizona (United States)

A silicon waveguide in an electro-optic (EO) polymer cladding-base directional coupler (DC) switch is designed and fabricated. The design consists of a passive silicon directional coupler surrounded by an EO polymer cladding. EO polymer offers very high Pockels coefficient (up to 300 pm/V), fabrication flexibility, and negligible phase-velocity mismatch at high speeds, leading to commercially demonstrated bandwidths of 100GHz. Due to the tight confinement of silicon waveguide the constraints on the EO polymer film quality are low. This is of great benefit because the polymer film can be applied at the back-end of the fabrication process. Waveguide fabrication can be achieved by either optical or electron-beam lithography, which benefits from straightforward integration of microelectronic and photonic devices on a single silicon chip. For efficient coupling between the two waveguides low crosstalk must be achieved. The driving electrodes are placed on top of the buried oxide (BOX) layer to the left and right of the DC's coupling region. Because of the electrode geometry, both waveguides experience the same EO effect and therefore have the same propagation constant (β) to provide low crosstalk. Both by using coupled mode theory to solve for the coupling coefficient (κ) and using simulation software (FIMMWAVE) we optimized our design for efficient coupling and effective poling conditions. The benchmark design consists of two 255nm wide waveguides separated by 500nm optimized for TE propagation. With an electrode separation of 4μm and coupling length of 1cm, a switching voltage (Vs) of < 10V at an r33 of 250pm/V is expected.

8991-25, Session 6

Tunable optofluidic couplers for dynamic card-to-backplane optical interconnects

Guomin Jiang, Sarfaraz Baig, Michael R. Wang, Univ. of Miami (United States)

Optical interconnects have been extensively researched for high-speed computing systems because of the speed limitations and drawbacks of electrical data buses. Most of optical interconnect architectures are based on point-to-point link topologies, resulting in higher cost per link and lower energy efficiency. A shared bus topology can effectively multicast signals to all plug-in cards. But most of them set a fixed power distribution to each link after device fabrication. They are not energy efficient since they consume optical single power even when the cards are not plugged into the backplane. We reported earlier dynamic array waveguide evanescent couplers for multi-card backplane optical interconnect. One drawback of the approach is that the waveguide cores must be exposed in air for coupling purpose that may subject to dust and handling damage. In this paper, we present the fabrication of polymer waveguides with tunable optofluidic couplers by using a vacuum assisted microfluidic (VAM) soft lithographic technique for dynamic card-to-backplane optical interconnects. The tunable optofluidic coupler on the backplane consists of polymer waveguides with 45° integrated waveguide mirrors and a perpendicular microfluidic channel. The operation of the tunable optofluidic coupler is realized by controlling the position of air bubbles and index matching liquid in the perpendicular microfluidic channel for refractive index modulation. The dynamic activation and deactivation of the backplane optofluidic couplers can save the optical signal power for card-to-backplane optical interconnection. A 10 Gbps eye diagram of the card-to-backplane optical interconnect link has been demonstrated showing the high performance of the interconnect structures.

8991-26, Session 6

Microsecond regime free-space fiber optic switch: 32-port to 32-port scalable device

Brittany Lynn, Alexander A. Miles, Pierre-Alexandre J. Blanche, John Wissinger, The Univ. of Arizona (United States); Daniel N. Carothers, Texas Instruments Inc. (United States); Robert A. Norwood, Nasser N. Peyghambarian, The Univ. of Arizona (United States)

Presented here is a 32 x 32 optical switch for telecommunications applications capable of reconfiguring at speeds of up to 12 microseconds. The free space switching mechanism in this interconnect is a digital micromirror device (DMD) consisting of a 2D array of 10.8 μm mirrors optimized for implementation at 1.55μm. Hinged along one axis, each micromirror is capable of accessing one of two positions in binary fashion. In general reflection based applications this corresponds to the ability to manifest only two display states with each mirror, but by employing this binary state system to display a set of binary amplitude holograms, we are able to access hundreds of distinct locations in space.

We previously demonstrated a 7 x 7 switch employing this technology, providing a proof of concept device validating our initial design principles but exhibiting high insertion and wavelength dependent losses. The current system employs 1920 x 1080 DMD, allowing us to increase the number of accessible ports to 32 x 32. Adjustments in imaging, coupling component design and wavelength control were also made in order to improve the overall loss of the switch. This optical switch performs in a bit-rate and protocol independent manner, enabling its use across various network fabrics and data rates. Additionally, by employing a diffractive switching mechanism, we are able to implement a variety of ancillary features such as dynamic beam pick-off for monitoring purposes, beam division for multicasting applications and in situ attenuation control.

8991-27, Session 6

Chip-to-chip optical interconnects based on flexible integrated photonics

Lan Li, Yi Zou, Hongtao Lin, Juejun Hu, Univ. of Delaware (United States); Xiaochen Sun, Ning-Ning Feng, LaXense, Inc. (United States); Sylvain Danto, Kathleen A. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Tian Gu, Michael W. Haney, Univ. of Delaware (United States)

We analyze a chip-to-chip optical interconnect platform based on our recently developed flexible substrate integration technology. We show that the architecture achieves high bandwidth density (100 Tbs/cm2), and does not require optical alignment during packaging. These advantages make the flexible photonics platform a promising solution for chip-to-chip optical interconnects. We also report initial experimental results on the fabrication and characterization of the flexible photonics platform. Low loss (0.8 dB/cm), high-index-contrast chalcogenide glass waveguides were fabricated using a single-step, resistless thermal nanoimprint patterning process. Superior mechanical flexibility of the waveguide devices (sub-mm bending radius) was attained using nano-mechanical designs to minimize strain exerted on the photonic device layer during mechanical deformation. We further validated a SU-8 planarization and adhesive bonding process for III-V active photonic integration on the flexible substrates. These results pave the path towards the demonstration of a novel planar, flexible optical interconnect platform with fully-integrated optoelectronic functionalities.

8991-28, Session 7

Silicon microphotonics for ultra-low-power interconnects *(Invited Paper)*

Michael Watts, Massachusetts Institute of Technology (United States)

We present on recent results of ultralow power modulators, filters, detectors, and even on-chip erbium doped lasers with the ultimate goal of achieving femtojoule-per-bit-class communication links for on-chip communications. Having achieved record low power modulators consuming just 1fJ/bit at data rates as high as 25Gb/s, our emphasis has shifted toward addressing the power consumption of other components in the communication link including on-chip lasers. By incorporating erbium gain materials on chip, we are addressing one of the long-standing silicon photonic integration challenges with low power and uncooled lasers implemented in a CMOS-compatible manner.

8991-29, Session 7

Plasmonic modulator for three-dimensional chip-to-chip optical interconnects

Fanghui Ren, Xiangyu Wang, Alan X. Wang, Oregon State Univ. (United States)

Today's research in optical interconnects focuses on the integration of PLC components with VLSI chips. However, as 3-D integrated circuits are emerging as rising stars for next-generation technology, existing PLC-based optical interconnects are facing great challenges. First, PLC photonic devices can only provide intra-plane photon manipulation. It requires surface-normal micro-mirrors to act as vias for layer-to-layer connection. Second, existing silicon photonic modulators have relatively low bandwidth due to limited carrier mobility. While plasmonic photonic devices are expected to be extremely compact and high bandwidth, the high optical absorption of metals prevents them from being used in optical interconnects. Surface-normal plasmonic modulators based on metallic photonic crystal slab provides high coupling efficiency with laser diodes, less complexity in fabrication, lower optical loss and expandability with surface-emitting laser arrays for large-scale parallel optical interconnects. In this structure, the discrete guided-modes induced by Bragg-grating-modulated SPPs couple to the broadband Fabry-Perot resonance in the narrow slits, resulting in strong asymmetric Fano resonances with sharp plasmonic bandgaps. In this paper, we successfully demonstrate that we can use surface-normal plasmonic modulator to control the optical transmission by modulating the plasmonic bandgap of the metallic photonic crystal slab with a moderate index perturbation. More than 60% modulation depth is achieved with only an index modulation of 0.0043. Further work is suggested to obtain an even sharper transitional edge for high-speed modulation by using $LiNbO_3$ or nonlinear polymers as the dielectric substrate with even smaller index perturbation ($\Delta n \sim 0.001$) and ultra-high speed.

8991-30, Session 7

Tunable nanoscale-effecient plasmonic demultiplexer

Mohamed A. Swillam, Abdulilah Azzazi, The American Univ. in Cairo (Egypt)

The importance of wavelength division demultiplexers (WDM) reside in its aggressive use in many areas of industry which are based on signal processing, especially in the fields of telecommunications, optical computing, integrated photonics circuits and sensing applications. Plasmonic wavelength division demultiplexers are essential component for on chip nanoscale plasmonic systems .

In this work we present nanoscale plasmonic wavelength-selective demultiplexer based on feedback resonator. The device is optimized using FDTD technique to achieve a demultiplexed full width at half max of 12 nm with minimal insertion. The device is based on a thin layer of silver with waveguides etched onto it having total area of less that 0.3 um2. The device can be easily tuned to any specific wavelength in the IR range.

8991-31, Session 7

Ultra-low and compact loss coplanar waveguide crossing *(Invited Paper)*

Amir Hosseini, Omega Optics, Inc. (United States)

Broadband silicon waveguide crossing arrays with <0.01dB-per-crossing loss are proposed using cascaded multimode self-focusing sections with subwavelength grating to reduce the modal phase errors. Record 0.02dB loss per crossing and <-40dB cross-talk are experimentally demonstrated.

8991-32, Session 8

Transforming computing architectures with a fast and scalable photonic switch fabric *(Invited Paper)*

Clint L. Schow, IBM Thomas J. Watson Research Ctr. (United States)

The trend for optics displacing electronics at ever-shorter distances as communication speeds increase continues, but as long as optics only offers a better "wire," the choice between optical and electrical interconnects largely hinges on challenging cost and power consumption comparisons. Exploiting the unique features of low-latency switched photonic networks to yield system-level performance advantages can potentially open new opportunities for the deployment of optics beyond the traditional and continuing replacement of copper.

8991-33, Session 8

Optical RAM-enabled cache memory and optical routing for chip multiprocessors: technologies and architectures *(Invited Paper)*

Nikos Pleros, Ctr. for Research and Technology Hellas (Greece); Pavlos Maniotis, Theonitsa Alexoudi, Dimitris Fitsios, Christos Vagionas, Sotirios Papaioannou, Aristotle Univ. of Thessaloniki (Greece) and Ctr. for Research and Technology Hellas (Greece); Konstantinos Vyrsokinos, George T. Kanellos, Ctr. for Research and Technology Hellas (Greece)

The processor-memory performance gap, commonly referred to as "Memory Wall" problem, owes to the speed mismatch between processor and electronic RAM clock frequencies, forcing current Chip Multiprocessor (CMP) configurations to consume more than 50% of the chip real-estate for caching purposes. In that perspective, optical RAMs storing and retrieving information in the form of light with psec-scale memory access times seem to hold the potential for replacing small-size caches, offering at the same time a cache memory system being fully-compatible with optically interconnected CPU-memory architectures. In this article, we present our recent work spanning from integrated optical RAM cell architectures relying on the Silicon-on-Insulator technology platform up to complete optical cache memory architectures and optical router systems for Chip Multiprocessor configurations. We review both

the experimental and the respective underlying theoretical framework for optical RAM cells when using SOAs as the active switching elements and proceed with the demonstration of new optical cache architectural paradigms introducing WDM principles in the storage area, showing that CMP performance speed-up up to 40% can be obtained requiring lower than 20% of cache capacity compared to state-of-the-art electronic cache memories. Given that optical caches facilitate the exchange of optical traffic between different processor clusters in a CMP configuration, we go a step further and present e/o router subsystems with up to Tb/s routing capacity and up to 48 i/o ports for CMP interconnection purposes currently pursued within the FP7 PhoxTrot project, shaping a roadmap for future optically-enabled ultra-fast and low-power CMP architectures.

8991-34, Session 8

Demonstration of fully-enabled data centre subsystem with embedded optical interconnect

Richard C. Pitwon, Alex Worrall, Kai Wang, Paul Stevens, Alistair A. Miller, Xyratex Technology Ltd. (United Kingdom); Katharine Schmidtke, Finisar Corp. (United States)

The evolution of data storage communication protocols and corresponding in-system bandwidth densities is set to impose prohibitive cost and performance constraints on future data storage system designs, fuelling proposals for hybrid electronic and optical architectures in data centres. The migration of optical interconnect into the system enclosure itself can substantially mitigate the communications bottlenecks resulting from both the increase in data rate and internal interconnect link lengths.

In order to assess the viability of embedding optical links within prevailing data storage architectures, we present the design and assembly of a fully enabled data storage array platform, in which all internal high speed links have been implemented optically requiring the deployment of midboard optical transceivers, an electro-optical midplane and proprietary pluggable optical connectors for hard disk drives. We present the design of a high density optical layout to accommodate the midplane interconnect requirements of a low profile data storage enclosure with 24 hard disk drives and the design of a proprietary optical connector and interface cards, enabling standard hard disk drives to be plugged into an electro-optical midplane.

Crucially we have also modified the platform to accommodate far longer optical interconnect lengths up to 50 meters in order to investigate and validate alternative future data center architectures based on disaggregation of modular subsystems.

The optically enabled data storage system has been fully validated, with both 6 Gb/s and 12 Gb/s SAS data traffic successfully conveyed along internal optical links with bit error rates (BER) of less than 10^-15.

8991-35, Session 8

Mixed-level optical-system simulation incorporating component-level modeling of interface elements

Pablo V. Mena, Bryan D. Stone, Evan K. Heller, Dan Herrmann, Enrico Ghillino, Rob Scarmozzino, Synopsys, Inc. (United States)

While system-level simulation can allow designers to assess optical system performance via measures such as signal waveforms, spectra, eye diagrams, and BER calculations, component-level modeling can provide a more accurate description of coupling into and out of individual devices, as well as their detailed signal propagation characteristics. In particular, the system-level simulation of interface components used in optical systems, including splitters, combiners, grating couplers, waveguides, spot-size converters, and lens assemblies, can benefit from more detailed component-level modeling. Depending upon the nature of the device and the scale of the problem, simulation of optical transmission through these components can be carried out using either electromagnetic device-level simulation, such as the beam-propagation method, or ray-based approaches. In either case, system-level simulation can interface to such component-level modeling via a suitable exchange of optical signal data. This paper presents the use of a mixed-level simulation flow in which both electromagnetic device-level and ray-based tools are integrated with a system-level simulation environment in order to model the use of various interface components in optical systems for a range of purposes, including, for example, coupling to and from optical transmission media such as single- and multimode optical fiber. This approach enables case studies on the impact of physical and geometric component variations on system performance, and the sensitivity of system behavior to misalignment between components.

8991-36, Session 8

Fabrication of modulators and 2x2 switches in SOI based on the carrier depletion mechanism for optical interconnects *(Invited Paper)*

Francisco Lopez Royo, Antoine Brimont, Univ. Politècnica de València (Spain); Christos Vagionas, George Dabos, Nikos Pleros, Ctr. for Research and Technology Hellas (Greece) and Aristotle Univ. of Thessaloniki (Greece); Costas Vyrsokinos, Ctr. for Research and Technology Hellas (Greece); Amadeu Griol, Juan Hurtado, Laurent Bellieres, Nuria S. Losilla, Pablo Sanchis, Luis Sanchez, Javier Marti-Sendra, Univ. Politècnica de València (Spain)

Silicon-photonic 2x2 electro-optical switching elements and modulators based on the carrier depletion mechanism using both dual-resonator and MZI layout configurations have been developed. The passive photonic structures were developed and optimized using a fast design-fabrication-characterisation cycle. The main objective is to deliver small-footprint, low-loss and low-energy silicon photonic electro-optical switching elements and modulators equipped with standard input-output grating couplers and radio-frequency electrical contact tips to allow their characterization in high-speed probe-station setups. The insertion losses, crosstalk, power consumption and BER performance will be addressed for each electro-optical structure. The fabrication steps, including low loss waveguide patterning, pn junction and low resistive ohmic contact formation have been optimized to produce high performance devices with relaxed fabrication tolerances, employing both optical and electron-beam lithography.

8991-37, Session 9

Development of electro-optical PCBs with embedded waveguides for data center and high-performance computing applications *(Invited Paper)*

Marika P. Immonen, TTM Technologies, Inc. (Finland); Jinhua Wu, Hui Juan Yan, Long Xiu Zhu, Peifeng Chen, Tarja Rapala-Virtanen, TTM Technologies, Inc. (China)

Power consumption and scaling the performance and quantity of electrical interconnects for data traffic inside boards and backplanes are one of the critical barriers envisaged in next?generation Data Center (DC) and High?Performance Computing (HPC) applications. In this paper, we report developments of electro-optical PCBs (EO-PCB) with embedded polymer waveguide layers. We show results for fabricating realistic

product emulator test vehicles that comprise of reasonable form factor PCBs with optical and electrical layers. The optical layer comprise of multiple waveguides exhibiting a full range of geometric configurations required to meet practical optical routing functions. Test patterns include varied cross-sectional sizes, 90° bends of varying radii (20mm – 2mm), cascaded bends with varying radii, waveguide crossings with varied crossing angles (90° - 20°), splitters, tapered waveguides and waveguide interconnect to midboard interface slots. Moreover, results for fabricating electrical interconnect structures (e.g. tracing layers, vias, plated vias) top/bottom and through optical layers in OE-PCB stack are shown. The purpose of the complex routed copper layers is to enable the crucial demonstration of the fabrication and thermal robustness challenges inherent to electro-optical PCBs with optical layers. Process compatibility with accepted practices and challenges in production scale up for high volumes are key concerns to meet the yield target and cost efficiency. Results include material attenuation, waveguide transmission loss, misalignment tolerance, and effect of lamination and reflow soldering on the waveguides.

The reported work is part of PhoxTrot, a European Union funded collaborative project carried under 7th Framework programme. The developed electro/optical PCB technology will be applied in the multimodal project demonstrator deployments for intra-card communications.

8991-38, Session 9

Polymer integration of optoelectronic devices in on-board and board-to-board optical communication systems

Erwin Bosman, Bram Van Hoe, Jeroen Missinne, Geert Van Steenberge, Univ. Gent (Belgium) and IMEC (Belgium)

The rising potential of optical communication over short distances has given rise to increased development in the fields of optoelectronic devices, driving electronics, optical waveguiding materials and fabrication techniques. The optical coupling however between the waveguides and the optoelectronics is still a bottleneck, since it results in a higher cost compared to the electrical counterparts.

The problem of optical coupling often starts with the limited available packaging technologies for optoelectronic chips, necessary for the galvanic interconnection and fan-out of the chips. The standard packages do not allow a short optical path between e.g. the lasercomponent and the optical waveguide entry, introducing the need for lenses etc. We demonstrate a coupling approach by embedding the bare die optoelectronics in the substrate of the optical system, enabling a comparable performance to butt-coupling.

The embedding technology is developed and demonstrated for two very different optical systems. One system is an integrated optical singlemode circuit @ 1550nm based on nano-imprinted waveguides on top of a silicon chip. The opto-electronic devices are mounted into etched cavities inside the silicon chip, in very close contact with the imprinted waveguides on top (free optical path length lower than 30?m). The second system is a multimode optical backplane @ 850 nm. The embedding approach for the optoelectronics allows the coupling of 2-dimensional VCSEL and photodiode arrays to a stack of waveguide arrays, propagating over the backplane. This increases the data rate density on the backplane beyond the state-of-the-art, since this approach can be scaled in two dimensions.

8991-39, Session 9

Optical connecting devices fabricated by self-written waveguide technology for smart optical interconnect

Tadayuki Enomoto, Yukinobu Soeda, Osamu Mikami, Tokai Univ. (Japan)

The success of smart optical interconnects for practical use, such as high-capacity data transfer systems, strongly depends on the development of sophisticated coupling technologies achieving both high coupling efficiency and easy alignment.

One promising technology for solving these problems is self-written waveguide (SWW) technology which uses light-curable resin. We fabricated a micro light-path converter on the top of MT connector. Four channel SWWs are fabricated by irradiating a blue laser beam (406nm wavelength) from a multi-mode fiber on a reflecting mirror in light-curable resin. The SWWs are covered by cladding resin. This converter is useful for connecting between fibers and an optical wiring board.

We have further developed this fiber-SWW technology into a new technology we call the “Mask-Transfer SWW method”. The Mask-transfer SWW technology involves contact exposure of UV-curable resin through a photomask. Alignment of the photomask pattern with the target can be precisely accomplished by employing a conventional mask-aligner. We proposed a new V-grooving method by applying the Mask-Transfer SWW method. V-grooves are a well-known technique for aligning optical fibers for coupling. Unlike the conventional methods and material, this new method has an advantage that V-grooves can be easily fabricated precisely on any kinds of substrates as designed. Therefore, optical coupling between fibers and devices is achieved simply and efficiently.

Other unique connecting devices fabricated using both the fiber-SWW and Mask-Transfer SWW methods are presented. We believe that these devices will be a key for smart optical interconnects in near future.

8991-40, Session 9

Towards roll-to-roll manufacturing of polymer photonic devices

Harish Subbaraman, Omega Optics, Inc. (United States); Xiaohui Lin, Zeyu Pan, Ray T. Chen, The Univ. of Texas at Austin (United States)

In this research work, the roll-to-roll printability of polymer photonic devices is investigated by choosing a suitable material system, and by optimizing the system design. The metal and polymer inks are optimized to be compatible with high-rate printer. Hardware and software tools are developed for aligned printing between successive layers. Alignment accuracy <70 microns at 5m/min is demonstrated using a customized R2R system. The minimum accuracy is limited by the printhead nozzle pitch, which can be improved with further advancement in the printing technology. Our technique will enable high-rate and low-cost development of polymer photonic devices.

8991-41, Session 10

Advances in integrated photonic circuits for packet-switched interconnection *(Invited Paper)*

Kevin Williams, Ripalta Stabile, Technische Univ. Eindhoven (Netherlands)

Sustained increases in capacity and connectivity are needed to release congestion in a range of broadband communication network nodes.

Packet routing and switching in the electronic domain are leading to unsustainable energy- and bandwidth-densities, motivating research into hybrid solutions: photonic hardware is introduced for massive-bandwidth data transport and switching while the electronic domain is clocked at more modest GHz rates to manage routing. Commercially-deployed optical switching engines using MEMS technologies are unwieldy and too slow to reconfigure for future packet-based networking. Optoelectronic packet-compliant switch technologies have been demonstrated as laboratory prototypes, but they have so far used discretely pigtailed components, which are impractical for control plane development and product assembly.

Integrated photonics has long held the promise of reduced hardware complexity and may be the critical step towards packet-compliant optical switching engines. Recently a number of labs world-wide have prototyped optical switching circuits using monolithic integration technology with up to several hundreds of integrated optical components per chip. Our own work has focused on multi-input to multi-output switching matrices. Recently we have demonstrated 8x8 space and wavelength selective switches using gated cyclic router arrays and 16x16 broadband switching chips using monolithic multi-stage networks. We now operate these advanced circuits with custom control planes implemented with FPGAs to explore real time packet routing in multi-wavelength, multi-port test-beds. We review our contributions in the context of state of the art photonic integrated circuit technology and packet optical switching hardware demonstrations.

8991-42, Session 10

Silicon photonic integrated devices for datacenter optical networks *(Invited Paper)*

Marco Fiorentino, Chin-Hui Chen, Géza Kurczveil, Di Liang, Zhen Peng, Raymond G. Beausoleil, Hewlett-Packard Labs. (United States)

The evolution of computing infrastructure and workloads has put an enormous pressure on datacenter networks. It is expected that bandwidth will scale without increases in the network power envelope and total cost of ownership. Networks based on silicon photonic devices promise to help alleviate these problems, but a viable development path for these technologies is not yet fully outlined.

In this paper, we report our progress on developing components and strategies for datacenter silicon photonics networks. We will focus on recent progress on compact, low-threshold hybrid Si lasers and the CWDM transceivers based on these lasers as well as DWDM microring resonator-based transceivers.

8991-43, Session PWed

Pitch control of multi-channel graded-index core polymer waveguide for optical PCB using the Mosquito method

Ryota Kinoshita, Keio Univ. (Japan); Daisuke Suganuma, Keio University (Japan); Takaaki Ishigure, Keio Univ. (Japan)

For further advancement of high-performance computers, optical interconnects are highly anticipated because of the capability of high-bandwidth-density wirings with low power consumption. Optical printed circuit boards (O-PCBs) incorporated with multimode polymer optical waveguides are currently drawing much attention, because their easy processability and capability of high-density wirings. We have proposed to introduce graded-index (GI)-cores into the polymer optical waveguides, and have experimentally and theoretically demonstrated excellent optical characteristics of the GI-core waveguides, compared to the conventional step-index (SI)-core counterparts. In this paper, we focus on a fabrication method of GI-core waveguides utilizing a micro-dispenser (the Mosquito method). In the Mosquito method, a viscous core monomer is dispensed from a thin needle directly into a cladding monomer, which enables to fabricate circular-shaped GI-cores on board. On the other hand, since the multiple cores are written by repetitive needle scans, the core-position (inter-core pitch) accuracy would be of concern, compared to conventional photolithography methods.

In this paper, we succeeded in fabricating multi-channel GI circular-core polymer waveguides whose pitch is accurately controlled to 249 ± 4.1 µm using the Mosquito method by paying attention to the needle scanning procedure. Then, we demonstrate a 4 x 10 Gbps transmission over the fabricated GI-core waveguide by connecting the waveguide to a MMF ribbon with a 250-µm pitch, which is realized because the pitch of the fabricated waveguide is accurately controlled to 250 µm. This is the first demonstration of high-speed parallel transmission over multiple GI-cores in a polymer waveguide to the best of our knowledge.

8991-44, Session PWed

Surface normal coupling to multiple-slot and cover-slotted silicon nanocrystalline waveguides and ring resonators

John Covey, Ray T. Chen, The Univ. of Texas at Austin (United States)

No Abstract Available

8991-45, Session PWed

Dual-focus microlens array and Fresnel lens array fabricated by dry etching

Jong-Moo Lee, Electronics and Telecommunications Research Institute (Korea, Republic of)

There are various application fields of the microlens including homogenous illumination, interconnection of optical communication devices, image sensors, and optical data storage. We design and fabricate a dual-focus microlens array formed by combination of dual layers of spherical lenses. It is fabricated by dual photo lithography and dry etching processes based on accurate alignments of the layers or on self-alignments. The dual layers of microlens array are formed on a fused silica substrate which is transparent to wide range of wavelength from UV to IR.

We also design and fabricate Fresnel lens array on a fused silica substrate, by photo lithography and etching processes, for the purpose of beam shaping of laser beam. The simulated results and measured results of beam shaping with the Fresnel lens array are shown and to be discussed for its future applications.

8991-46, Session PWed

Quantify the significance of the thermo-optic effect in silicon photonic crystal waveguide electro-optic devices under forward bias

Jun Tan, Siamak Abaslou, Wei Jiang, Rutgers, The State Univ. of New Jersey (United States)

A silicon electro-optic device will generate heat during its operation. Whereas carrier injection tends to reduce the refractive index of silicon, heat generated from ohmic dissipation tends to increase the refractive index of silicon. Thus the thermo-optic effect will counter-act the electro-optic effect. Understanding the relative magnitude of the electro-optic effect versus thermo-optic effect is important to ensure reliable operation

of many silicon electro-optic devices, particularly those devices based on photonic crystal waveguides (PCWs). The electro-optic effect can be relatively easily modeled by modern semiconductor device simulators along with the silicon electro-optic coefficients, the thermo-optic effect in a silicon-on-insulator photonic device cannot be modeled precisely in most semiconductor device simulators. This is because that the heat conduction occurs in a spatial scale much larger than the electronic transport, which is the focus of most electronic device simulators. We will present a semi-analytic theory for modeling heat conduction and thermo-optic effect in a silicon PCW electro-optic device. The results show that for a silicon electro-optic device comprising a p-i-n diode under forward bias, the thermo-optic is usually relatively weak under small bias voltage and grows stronger as driving voltage increases. Eventually, the thermo-optic effect can grow to a magnitude that is comparable to the electro-optic effect at a sufficient bias. This is used to explain the spectral shift of the intermodal scattering signature observed in silicon PCW electro-optic device.

8992-1, Session 1

Automated design tools for biophotonic systems *(Invited Paper)*

Giacomo Vacca, Kinetic River Corp. (United States); Hannu Lehtimäki, Plan Energy Ltd. (Finland); Tapio Karras, Design Parametrics, Inc. (United States); Sean Murphy, SKMurphy, Inc. (United States)

Traditional design methods for flow cytometers and other complex biophotonic systems are increasingly recognized as a major bottleneck in instrumentation development. The many manual steps involved in the analysis and translation of the design, from optical layout to a detailed mechanical model and ultimately to a fully functional instrument, are labor-intensive and prone to wasteful trial-and-error iterations. We have developed two complementary, linked technologies that address this problem: one design tool (LiveIdeas (TM)) provides an intuitive environment for interactive, real-time simulations of system-level performance; the other tool (BeamWise (TM)) automates the generation of 3D CAD mechanical models based on those simulations. The strength of our approach lies in a parametric modeling strategy that breaks boundaries between engineering subsystems (e.g., optics and fluidics) to predict critical behavior of the instrument as a whole. The results: 70 percent reduction in early-stage project effort, significantly enhancing the probability of success by virtue of a more efficient exploration of the design space.

8992-2, Session 1

Miniature near-infrared spectrometer for point-of-use chemical analysis

Donald M Friedrich, JDS Uniphase (United States); Charles A Hulse, Photop Advanced Coating Center (United States); Marc von Gunten, JDSU (United States); Eric P Williamson, JDS Uniphase (United States); Christopher G. Pederson, Nada A. O'Brien, JDSU (United States)

Point-of-use chemical analysis holds tremendous promise for a number of industries, including agriculture, recycling, pharmaceuticals and homeland security. Near infrared (NIR) spectroscopy is an excellent candidate for these applications, with minimal sample preparation and the possibility for real-time decision-making. We will detail the development of a golf ball-sized NIR spectrometer developed specifically for this purpose. The instrument is based upon a thin-film dispersive element that is very stable over time and temperature, with less than 2 nm change expected over the operating temperature range and lifetime of the instrument. This filter is coupled with an uncooled InGaAs detector array in a small, rugged, environmentally stable optical bench ideally suited to unpredictable environments. The resulting instrument weighs less than 60 grams, includes onboard illumination and collection optics for diffuse reflectance applications in the 900-1700nm wavelength range, and is USB-powered. It can be driven in the field by a laptop, tablet or even a smartphone. The software design includes the potential for both on-board and cloud-based storage, analysis and decision-making. We will discuss the key attributes of the instrument, highlighting the fit-for-purpose optical performance achieved while simultaneously achieving miniaturization, ruggedization, and power consumption targets. Finally, we will show that our manufacturing process has enabled us to build instruments with excellent unit-to-unit reproducibility. We will show that this is a key enabler for instrument-independent chemical analysis models, a requirement for mass point-of-use deployment.

8992-3, Session 1

Multiplex grating Fabry-Perot cavity Bragg sensor based on SWIFTS (stationary-wave integrated Fourier transform spectrometer) technology

Mikhael de Mengin Poirier, Institut de Planétologie et d'Astrophysique de Grenoble (France)

SWIFTS, or Stationary-Wave Integrated Fourier Transform Spectrometer, is a highly integrated very high resolution spectrometer. This spectroscopy technology represents a major advance in the field and can be used as a Bragg interrogator. Combining this technology with fiber Bragg grating can result into a high precision Bragg sensor in strain and temperature.

SWIFTS combines groundbreaking nanotechnology research, integrated optics, microelectronics and embedded software, resulting in a single device that is more powerful in terms of spectral resolution than existing mini-spectrometers and a lot smaller than high-end spectrometers offering a similar level of resolution.

The ability to multiplex many Bragg gratings on the same fiber will depend on the bandwidth of the spectrometer as well as the spectrometer's resolution. High resolution will be very useful to improve absolute temperature or strain accuracy. In parallel, a Bragg grating fabry-perot cavity (GFPC) will replace the simple FBG. This new spectrometer has a sufficient resolution to resolve the modulation of the fabry-perot cavity formed by two FBG at the same wavelength in a single fiber. The FWHM of these modulating peaks is 12 pm and SWIFTS technology is the only one on the market able to perfectly resolve this kind of peaks.

A setup with four GFPC of 15 mm, 18 mm, 21 mm and 24 mm cavities on the same fiber has been tested.

In order to cater for this application, the SWIFTS principle can be implemented in a new configuration such as multi-channel spectrometer for high parallel multiplexing.

8992-4, Session 1

High-sensitivity higher-order Stokes stimulated Brillouin scattering for temperature and strain sensing

Victor L. Lambin Iezzi, Sébastien Loranger, Raman Kashyap, Ecole Polytechnique de Montréal (Canada)

Brillouin scattering has been previously used in distributed temperature and strain sensing (DTS) for long reach and in restricted areas with good accuracy and sensitivity. Several 10's of km can be sensed in real-time, and data acquisition with a spatial resolution of a few cm's is possible in DTS configuration. Such sensors are capable of sensing 0.1°C temperature changes or micro-strains over long distances or large areas. Sensing resolution is limited by the Brillouin frequency shift's sensitivity to temperature and strain, which are, respectively, ~1.3 MHz/°C and ~0.046MHz/$\mu\varepsilon$ for standard fiber. We propose here a new technique using higher order Stokes shifts of stimulated Brillouin scattering [1], to dramatically increase the sensitivity by the order of the Stokes shift, without affecting the resolution of the sensor. In this paper, an order of magnitude improvement is demonstrated attaining a sensitivity of ~13 MHz/°C, and ~0.46MHz/ $\mu\varepsilon$. Using a ring cavity configuration, a frequency comb is generated with a frequency spacing of twice the natural SBS frequency shift. Preliminary measurements show an increase in the Brillouin frequency shift's temperature sensitivity for each higher

order Stokes being used. We propose a way to incorporate this device in a BOTDR system, giving the ability to detect temperature or strain change with a higher sensitivity and with an equivalent spatial resolution of what is currently available commercially. Incorporating a novel reference multi-order SBS source into the system is shown to provide a new distributed sensing technology with higher sensitivity than currently available DTS systems.

References:

[1] S. Loranger, V. L. Iezzi, and R. Kashyap, “Demonstration of an ultra-high frequency picosecond pulse generator using an SBS frequency comb and self phase-locking,” Opt. Express, vol. 20, pp. 19455-19462, 2012.

8992-5, Session 2

Double-clad fiber couplers for efficient multi-modal sensing

Wendy-Julie Madore, Etienne De Montigny, Olivier Ouellette, Gabriel Bernard, Mikael Leduc, Caroline Boudoux, Nicolas Godbout, Ecole Polytechnique de Montréal (Canada)

Double-clad fibers are increasingly used in biomedical imaging and multimodal sensing as they combine the benefits of single-mode (coherent illumination and detection) and multimode (massive incoherent detection) fibers. To improve mechanical stability and decrease the coupling losses of the current free-space beam-splitter approach, all-fiber DCF couplers (DCFCs) were developed. Previously reported DCFCs allow for quasi-lossless transmission of coherent single-mode signal (illumination and collection) and >40% transmission of multimodal signal (collection). Previously demonstrated DCFCs have a theoretical multimodal collection efficiency limited to 50%. We herein present double-clad fiber couplers capable of transmitting >90% of single mode core signal, while extracting >80% of the multimode signal from the inner cladding. These all-fiber couplers are robust, achromatic, quasi-lossless and insensitive to environmental conditions.

Several fiber combinations and fabrication approaches were explored to address needs in several wavelength regions: the 1550nm band - used in telecommunications and sensing – as well as the 1300nm, 800nm and 600nm for biomedical applications. We detail our fabrication process and characterization technique for these different configurations. We demonstrate the potential of these devices in refractive index sensing at 1550nm. We also present a coupler for multimodal biomedical imaging at 1300nm, combining optical coherence tomography (OCT) with fluorescence imaging in the visible spectrum.

8992-6, Session 2

Influence of laser frequency noise on scanning Fabry-Perot interferometer based laser Doppler velocimetry

Peter John L. Rodrigo, Christian Pedersen, Technical Univ. of Denmark (Denmark)

Recently, we demonstrated experimentally a novel type of direct detection laser Doppler velocimeter (LDV) that uses an eye-safe laser source (l = 1.5 um), an optical circulator, a scanning Fabry-Perot interferometer (sFPI), and a monostatic coaxial optical transceiver. In the proof-of-principle demonstration of our sFPI-LDV system, a distributed-feedback fiber laser (FL) was used as a stable single-frequency source. In this work, we evaluate the performance of the sFPI-LDV employing an inexpensive alternative light source – a single-frequency semiconductor laser (SL) – and compare it with that using the FL. We focus on the influence of laser frequency noise on the measurement principle employed in the sFPI-LDV. We show that for practical sFPI scan rates (i.e. LDV update rates) of 10 Hz, the effective Doppler shift (or speed) resolution is worse for the SL case than for the FL case due to larger laser frequency noise of the former. For the sFPI-LDV using the SL, we show that the effective resolution improves and approaches the interferometer resonance bandwidth, given by the ratio of its free spectral range and its finesse, as the sFPI scan rate is increased. Understanding the impact of laser frequency noise on the sFPI-LDV speed resolution and the determination of a suitable sFPI scan rate are important for the optimal design of more industrial versions of our system in which compact and cheaper SL sources may be employed.

8992-7, Session 2

SPR based three channel fiber optic sensor for aqueous environment

Roli Verma, Banshi D. Gupta, Indian Institute of Technology Delhi (India)

We design surface plasmon resonance (SPR) based three channel sensor which can be utilized for the multiple parameter sensing. The sensing of various parameters simultaneously has been a matter of curiosity for researchers due to miniaturization, low cost and other issues. The motivation behind this study is to design a sensor which can detect three different parameters at a single platform. SPR is fascinating tool for the sensing of various chemical, biological, gas and environmental pollutants. We report here an experimental study on three channel fiber optic SPR sensor for multiple parameter sensing. We have fabricated sensor by coating of three different metals Silver (Ag) (30 nm), Gold (Au) (50 nm) and Copper (Cu) (40 nm) with one high index crystal TiO_2 (10 nm) over-layer on Cu, in three different unclad portions of 1 cm each and also separated by 1 cm. SPR spectra were recorded for aqueous sucrose solutions of varying refractive indices (RI) from 1.333 to 1.350. We have recorded SPR spectra for varying RI (1.333 to 1.350) when same sample is kept around all the three channels, the case of multi-channel sensing and also for different samples kept around all the channels, the case of multi-analyte sensing. It is found that there are three different and well separated resonance minima/dips corresponding to three sensing regions at different wavelengths in visible region. Resonance minima are shifted towards higher wavelength with increasing RI of the samples. All the channels operate at different wavelength range with different sensitivities as well.

8992-8, Session 2

Fiber optic surface plasmon resonance based ethanol sensor

Roli Verma, Banshi D. Gupta, Indian Institute of Technology Delhi (India)

In the present paper we have carried out experimental study of the surface plasmon resonance (SPR) based fiber optic ethanol biosensor using gel entrapment technique. In this study, using alcohol dehydrogenase (ADH) as a model enzyme, a simple and sensing platform has been developed for ethanol biosensor. The biosensor is fast and holds great promise for practical applications. The gel entrapment is easy, simple and gives homogeneous sensing surface. The sensor works on wavelength interrogation technique in which a dip in SPR curve at minimum transmitted power is obtained at particular wavelength called resonance wavelength for specific sensing medium. To fabricate the probe 1 cm length of total 15 cm length of the fiber is uncladed from the middle and coated with a plasmonic metal. Further, a suitable amount of enzyme (ADH) is immobilized over metal coated sensing region of optical fiber core. The ethanol samples of different concentrations are prepared in phosphate buffer solution. The experimental set up has been stabilized for the characterization of sensor and SPR spectra have been recorded for different concentrations of ethanol. It is found that the SPR dip shifts with the change in the concentration of ethanol samples in the vicinity of sensing region. The enzyme reacts with the ethanol and forms some

products which results in the change in position of dip in SPR curves. Hence this sensor can be utilized for the detection of ethanol content in food and beverages. The sensor is very sensitive, fast, and low cost.

8992-9, Session 2

Graphene-based all-fiber-optic temperature sensor

Huihui Lu, Jinan Univ. (China); Zhengwen Tian, Shaoshen Jin, Jinan Univ (China); Jianhui Yu, Guozhen Liao, Jun Zhang, Jieyuan Tang, Yunhan Luo, Zhe Chen, Jinan Univ. (China)

We demonstrate a novel all fiber-optic temperature sensor based on graphene film coated on a side polished fiber (SPF). Significantly enhanced interaction between the propagating light and the graphene film can be obtained via strong evanescent field of the SPF. Graphene can be obtained by a low cost, efficient, mass production way via an improved oxidation-reduction method which can make reduced graphene oxide (rGO) –a kind of graphene. The used side-polished fiber was fabricated by wheel side-polishing technique whose advantage is can make long polished surface to parallel the fiber core other than to have a tilt angle with the fiber core. The strong light–graphene interaction results in temperature sensing with a maximum optical power variation of 11.3dB in SPF experimentally. The novel temperature fiber sensor has a linear correlation coefficient of 99.4%, a sensitivity of 0.134dB/°C, a precision of better than 0.03°C, and a response speed of better than 0.0228°C/s. Such an graphene -based all fiber-optic temperature sensor is easy to fabricate, compatible with fiber-optic systems and possesses high potentiality in photonics applications such as all-optical fiber temperature sensing network.

8992-10, Session 3

Compact large-aperture Fabry-Perot interferometer modules for gas spectroscopy at mid-IR

Uula Kantojärvi, Aapo Varpula, Tapani Antila, Christer Holmlund, Jussi H. Mäkynen, Antti Näsilä, Rami Mannila, Anna Rissanen, Jarkko E. Antila, VTT Technical Research Ctr. of Finland (Finland); Rolf J Disch, Torsten A Waldmann, SICK AG (Germany)

VTT has developed Fabry-Perot Interferometers (FPI) for visible and infrared wavelengths since 90's. Here we present two new platforms for mid-infrared gas spectroscopy having a large aperture to provide high optical throughput but still enabling miniaturized instrument size. The systems comprise hermetically packed FPIs with thermistors, and customised electronics. Alignment and characterisation methods have been developed utilizing a FTIR device.

First platform is a tunable filter that replaces a traditional filter wheel, which operates between wavelengths of 4-5 um. The air gap is 2-5 um and the system is optimized to have a transmission peak width of 50-70 nm (FWHM). The modules have also been characterised at near-infrared because the higher interference orders enable the use of cheaper optical laboratory equipments for commercialisation.

Second platform is for correlation spectroscopy where the interferometer provides a comb-like transmission pattern mimicking an absorption of diatomic molecules at the wavelength range of 4.7-4.8 um. The air gap is ca. 1.2 millimeters, thus the order of interference is ca. 500. The FWHM of the transmission peak is ca. 1 nm.

The mirrors are Bragg reflectors having 2-4 thin layers of alternating polysilicon and silicon oxide. Sputtered metal electrodes are used for a capacitive air gap measurement and off-the-shelf piezo stacks for the actuation. Additional ground electrode is fabricated to increase a sensitivity of the capacitive measurement. The layers are fabricated using LPCVD and PECVD on a 3 mm-thick silicon wafer. Thick substrate makes possible spectral resolution over the whole optical aperture.

8992-11, Session 3

Measuring the refractive index with precision goniometers: a comparative study

Stefan Krey, Dennis Off, Aiko K. Ruprecht, TRIOPTICS GmbH (Germany)

Knowledge about the refractive index of optical materials is crucial for the production of good quality optical components. The highest accuracy of refractive index measurements can be achieved with goniometric measurements of prisms prepared from the optical material. The most common approach is the method of minimum deviation of Newton-Fraunhofer. The apex angle is measured in reflection with high precision with an autocollimator and the refraction angle is measured in transmission with an additional collimator. Measurement accuracies for the refractive index of 10-6 and repeatabilities of in the order of 10-7 can be achieved with this method. Several parameters like temperature and air pressure need to be taken carefully into account to reach this level of precision. Some setups require additional optical components like windows of a vacuum chamber or limit the positioning of the prism. These influences can be taken into account e.g. with a ray tracing approach. Another goniometric approach is the Abbe method. All measurements are done with an autocollimator without the need for an additional collimator. The refraction is measured in reflection using the backside of the prism as reflector. A further simplification of the measurement setup can be reached with a comparative measurement. The sample prism is placed into a v-block of two prisms of known refractive index and the refraction is measured in transmission. This enables to do very fast measurements of the refractive index.

In this paper we give an overview about current goniometric approaches to measure the refractive index, discuss the approaches regarding their error sources and accuracies and show measurement results.

8992-12, Session 3

Point-spread function-based characterization of optical systems

Yakov G. Soskind, Ronn P. Walvick, Christopher D. Giranda, David N Laslo, Richard Gifford, DHPC Technologies (United States)

The response of optical systems to a point source, known as the point-spread function (PSF), represents one of the most fundamental characteristics of an optical system. The PSF varies as a function of source spectral composition as well as position with respect to the optical axis. PSF characterization of optical systems can be used to predict their performance in imaging and non-imaging applications.

In this work we describe an electro-optical setup for automated characterization of the PSF of optical systems over a broad range of operating conditions and radiance levels, with spectral compositions ranging from ultraviolet (UV) to long-wave infrared (LWIR). Our test setup includes interchangeable radiance sources and computer controlled motion stages which allows for automated characterization of the optical system under test. The software-controlled characterization process provides quantitative analysis of the system's chromatic and monochromatic aberrations, including axial chromatism, field curvature, and field distortion. The developed process also defines system level characteristics, such as relative illumination, field of regard and magnification. Finally, we demonstrate characterization of the operational dynamic range of imaging and non-imaging sensors employing the described setup, including their threshold responsivity, as well as their saturation performance under intense illumination conditions.

8992-13, Session 3

Automated assembly of camera modules using active alignment with up to six degrees of freedom

Kim S. Bräuniger, Daniel Stickler, Daniel Winters, TRIOPTICS GmbH (Germany)

With the upcoming Ultra High Definition (UHD) cameras, the accurate alignment of optical systems with respect to the UHD image sensor becomes increasingly important. Even with a perfect objective lens, the image quality will deteriorate when it is poorly aligned to the sensor. For evaluating the imaging quality the Modulation Transfer Function (MTF) is used as the most accepted test. In the first part it is described how the alignment errors that lead to a low imaging quality can be measured. Collimators with crosshair at defined field positions or a target panel are used as object generators for infinite-finite or respectively finite-finite conjugation. The process how to align the image sensor accurately to the optical system will be described. The focus position, shift, tilt and rotation of the image sensor are automatically corrected to obtain an optimized MTF for all field positions including the center. The software algorithm to grab images, calculate the MTF and adjust the image sensor in six degrees of freedom within less than 30 seconds per UHD camera module is described. The resulting accuracy of the image sensor rotation is better than 2 arcmin and the accuracy position alignment in x,y,z is better 2 µm. Finally, the process of gluing and UV-curing is described and how it is managed in the integrated process.

8992-14, Session 3

Prototype development of the fast steering mirror for Giant Magellan Telescope

Young-Soo Kim, Ju Heon Koh, Hwa Kyoung Jung, Ho June Jung, Korea Astronomy and Space Science Institute (Korea, Republic of); Myung K. Cho, National Optical Astronomy Observatory (United States); Ho-Soon Yang, Korea Research Institute of Standards and Science (Korea, Republic of); Ho-Sang Kim, Kyoung-Don Lee, Institute for Advanced Engineering (Korea, Republic of); Hyo-Sung Ahn, Gwangju Institute of Science and Technology (Korea, Republic of); Won Hyun Park, College of Optical Sciences, The Univ. of Arizona (United States); Sug-Whan Kim, Yonsei Univ. (Korea, Republic of); Byeong-Gon Park, Korea Astronomy and Space Science Institute (Korea, Republic of)

GMT is going to develop two secondary mirror systems i.e. Fast Steering Mirror (FSM) and Adaptive Secondary Mirror. FSM is a conventional secondary mirror system with an added functionality of tip-tilt control in order to compensate wind effects and the telescope structure jitter. KASI is currently leading a consortium of R&D institutions in Korea and in USA for development of the FSM prototype. It is to acquire the key technologies, fabrication of highly aspheric off-axis mirror and tip-tilt control. A full-size off-axis aspheric mirror segment of 1 m in diameter has been fabricated and its testing methods have been developed. The surface figure error was achieved up to 12 nm rms on the aspheric off-axis mirror. Tip-tilt test-beds have been assembled to verify the performances of the tip-tilt mechanism. We present the results of the successful developments.

8992-15, Session 3

Automated multi-point analysis with multi-angle photometric spectroscopy

Travis Burt, Jeff Comerford, Cameron Bricker, Andrew R. Hind, David L. Death, Agilent Technologies Australia (Australia)

Reflection (R) and transmission (T) are fundamental measurements available for characterizing bulk optics and optical coatings. Historically the complete characterization of optical materials and coatings for precision optics has been largely accomplished on the basis of normal and near normal incidence measurements due to the experimental simplicity of such an approach. This simplicity, however, is not without compromise. Normal incidence transmission measurements are typically conducted in the sample chamber of a spectrophotometer whilst near normal reflectance measurements require the use of a suitable reflectance accessory. A consequence of this approach is that there is never any guarantee that reflectance and transmission measurements are made from exactly the same patch on the sample due to sample repositioning during the significant changes in instrument configuration between R and T measurements.

Multi-angle Photometric Spectroscopy (MPS) measures the reflectance and/or transmittance of a sample across a range of angles ([theta]i) from near normal to oblique angles of incidence (AOI). A recent development by Agilent Technologies, the Universal Measurement Spectrophotometer (UMS) combines both reflection and transmission measurements from the same patch of a sample's surface in a single automated platform for angles of incidence in the range 5°≤|[theta]i|≤85° (i.e. angles on either side of beam normal noted as +/-).

We describe the use of MPS on the UMS with rotational ([theta]) and vertical (z) sample positioning control. MPS([theta]i, [phi], z) provides for automated unattended multi-angle R/T analysis of samples (up to 20 pieces, 1 inch round) or mapping of single samples (up to 8 inch round). Examples are provided which demonstrate reduced cost-per-analysis in high volume testing as well as spatial spectroscopic information obtained on large diameter samples.

8992-16, Session 4

High-performance high-speed spectrum analysis of laser sources with SWIFTS technology

Fabrice Thomas, Resolution Spectra Systems (France) and Institut de Planétologie et d'Astrophysique de Grenoble (France); Mikhaël De Mengin, IPAG (France); Céline Duchemin, Resolution Spectra Systems (France); Etienne P. Le Coarer, Institut de Planétologie et d'Astrophysique de Grenoble (France); Christophe Bonneville, Thierry Gonthiez, Resolution Spectra Systems (France); Alain Morand, Pierre Benech, IMEP-LAHC (France); Jean-Baptiste Dherbecourt, ONERA (France); Eléonore Hardy, Eric Morino, Renaud Puget, Bruno Martin, Resolution Spectra Systems (France)

The needs of industry and research in the characterization and the testing of micro-lasers, such as VCSELs, or custom lasers sources rapidly evolve and require high-performance, high-speed, robust and easy-to-integrate analysis devices.

Current spectrometers are usually a trade-off between miniaturization and performances. The ZOOM Spectra spectrometer, first full system to benefit from the disruptive SWIFTS technology, is both a high-resolution solution and a high-speed solution, not a compromise between the two, and also an integrated easy-to-use system. The instrument is an alliance of integrated guided optics, groundbreaking nanotechnologies, microelectronics and embedded software. Ultra-high spectral resolution

(0.1 cm-1 / 3 GHz / 0.005 nm at 800 nm) in the visible and near-infrared domains, high-rate measurement capability (up to 30,000 spectra per second), and high trigger capacities are combined in this compact fully-factory-calibrated system. This spectrometer revolutionizes the control of tunable, multi-mode, pulsed and high-stability lasers, providing for the first time a dynamic real-time view of their behavior, contrary to Optical Spectrum Analyzers.

Several examples of full reconstructions of tunable lasers will illustrate the performances of the ZOOM Spectra spectrometer, with measurements of spectral widths of peaks, mode hopping detection, spacing between modes, and relative spectral density of each mode at high-speed. With an absolute precision down to few picometers, this high-resolution multi-wavelength meter allows fast spectral mappings of DFB, DBR, ECDLs and VCSELs sources, obtained in few seconds during temperature or current scans.

8992-18, Session 4

Image transport using Anderson localized modes in disordered optical fibers

Salman Karbasi, Ryan J. Frazier, Univ. of Wisconsin-Milwaukee (United States); Karl W. Koch, Corning Incorporated (United States); Thomas Hawkins, Clemson Univ. Research Foundation (United States); John Ballato, Clemson Univ. (United States); Arash Mafi, Univ. of Wisconsin-Milwaukee (United States)

An optical fiber with a transversely disordered yet longitudinally invariant refractive index profile can propagate a beam of light using transverse Anderson localization. A launched beam of light in the disordered optical fiber expands till it reaches its localization radius beyond which it propagates without further expansion. In contrast to a conventional single-core optical fiber in which a propagating beam of light can only couple to and propagate in the core, the beam of light can be coupled to any point at the tip of the disordered fiber. This property roots in the localized highly-multimodal property of disordered optical fibers that can be used for high quality optical image transport. We experimentally investigate the image transport in the disordered optical fibers and compare the quality of the transported image with the ones transported through the conventional optical fibers, as well as imaging fibers. The quality of transported images is also numerically explored by calculating the full-vectorial transversely localized modes of the disordered optical fibers. We present the conditions for which the disordered optical fiber can be used for high-quality image transport.

8992-19, Session 4

Improved hyperspectral imaging with a Schmidt-Czerny-Turner spectrograph

Brian C. Smith, Jason McClure, Princeton Instruments (United States)

Hyperspectral imaging is a powerful technique utilized in microscopy, forensics, fundamental physical and material science research, agricultural studies, and gaining interest for military target tracking and detection systems. The Czerny-Turner (CT) type spectrograph is the most common instrument found in such hyperspectral imaging experiments where the panchromatic image of the scene is incident over the vertical extent of the CT spectrograph's entrance slits and the dispersed image focused on to a focal plane array (FPA) detector. In this modality, vertical spatial resolution along the slit axis is obtained as a function of spectral content in the dispersion direction of the CT spectrograph. However, astigmatism present in all mirror based plano grating CT spectrographs distorts the vertical spatial resolution which precludes recovery of the true hyperspectral image.

We have developed a novel variant of the traditional CT spectrograph, called the Schmidt-Czerny-Turner (SCT) spectrograph. The SCT is a plano grating mirror based imaging spectrograph completely astigmatism free at all wavelengths across the FPA detector allowing high fidelity hyperspectral image to be generated. We present the results of a comparative study between similar focal length SCT and CT-type imaging spectrographs with particular attention to the spatio-spectral resolution obtained.

8992-20, Session 4

Viewports for vacuum applications: correlation between viewport thickness and stress induced birefringence

André Becker, Julius Weber, Michael Flämmich, Ute Bergner, VACOM Vakuum Komponenten & Messtechnik GmbH (Germany)

New technologies and requirements in laser-physics and laser-engineering expect high quality materials and surfaces for optical elements. Additionally, a number of these techniques operate under high vacuum or ultra-high vacuum conditions. Hence, a vacuum viewport has to fulfil the different requirements regarding optical quality and vacuum quality.

Tackling this challenge requires identifying parameters of critical importance to the manufacturing process as well as choosing materials that are suitable for precision optics applications under ultra-high vacuum conditions. From the vacuum technology point of view, the jointing technology to join the viewport and the flange has to fulfil cleanliness, outgassing and bakeout specifications. Here, the favourite technique has to be seen in soldering. However, heat treatment of the flange-viewport-interface leads to thermal expansion. After cooling down the vacuum window to room temperature, stress induced birefringence, lowers the optical performance of the window.

In this contribution we present an analysis of the different jointing technologies with respect to their influence to the stress induced birefringence. The investigated jointing methods are elastomer fitting, bonding, brazing and thermal fusion. We present and discuss the results of stress birefringence measurements and identify high potential jointing methods for the two vacuum regimes high vacuum and ultra-high vacuum that achieve minimal stress induced birefringence and maintain a high quality of the optical beam.

8992-21, Session 5

Coherent frequency combs in mid-infrared produced by self frequency modulated quantum cascade lasers *(Invited Paper)*

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

Coherent Frequency Combs, produced by mode-locked lasers can be used for precise time and frequency measurement, sensing, and spectroscopy. Using combination of two frequency combs with slightly different frequency spacing allows one to quickly obtain spectrum over large span of wavelength without using a tunable laser – a significant simplification of measurements. While frequency combs in visible and near IR ranges are now widely available thanks to mode-locked Ti-sapphire or fiber lasers, there is no comparable source in the mid-infrared range of 3-10 mm where the most versatile source of coherent radiation – Quantum Cascade Laser (QCL) cannot be mode-locked, primarily due to its short (picosecond) relaxation time. Our research has shown that while mode-locking in the conventional sense (ultra-short pulse) is indeed impossible, it does not mean that coherent frequency combs cannot be produced by QCL as a result of strong nonlinear interactions in the gain region. The QCL is shown to operate in the regime of self-frequency modulation in which the output power is CW, but the frequency of radiation is periodically modulated, hence in spectral domain the coherent comb is produced. We shall discuss the experiments at ETH in Zurich that confirm our results and show the first experimental data in which trace gas spectra had been obtained with the QCL combs.

8992-22, Session 5

Widely-tunable mid-infrared laser source as key component for molecular spectroscopy systems

Mathieu Giguère, Rajeev Yadav, Alain Villeneuve, Youngjae Kim, Alexandre Dupuis, Bryan Burgoyne, Genia Photonics Inc. (Canada)

Genia Photonics recently developed a widely tunable mid-infrared laser source (WTIRS) based on Difference Frequency Generation (DFG) of its commercially available Synchronized Programmable Laser (SL) originally designed for CARS and SRS. Capable of generating MIR light in the fingerprint region (6.25-10µm, 1000-1600cm-1), this laser source is perfectly suited to perform molecular spectroscopy. Thus a spectroscopy system using advanced detection schemes allowing for high performance and high speed will be presented.

Since the lasers are made of optical fiber communication components, and do not include any moving parts (even for the tuning), they are highly reliable by design. To ease the implementation, a long fiber (m to 10s of m) cable can be provided between the synchronized laser source and the DFG crystal assembly producing the mid-IR. We have demonstrated tuning in less than 100 µsec between any wavelengths in the tuning range. Any wavelength can be achieved in any order allowing for field programmability for identification of new molecules or detection of new threats.

Experimental results of remote explosive trace detection and gas concentration analysis will be presented. Advanced detection scheme such as match filtering will be compared with standard synchronous detection with lock-in amplifier to demonstrate the high performance capabilities of our technology.

8992-23, Session 5

Absolutely-referenced distance measurement by combination of time-of-flight and digital holographic methods *(Invited Paper)*

Markus Fratz, Fraunhofer-Institut für Physikalische Messtechnik (Germany); Claudius Weimann, Karlsruher Institut für Technologie (Germany); Harald Wölfelschneider, Fraunhofer-Institut für Physikalische Messtechnik (Germany); Christian Koos, Karlsruher Institut für Technologie (Germany); Heinrich A. Höfler, Fraunhofer-Institut für Physikalische Messtechnik (Germany)

We present a novel optical system for distance measurement based on the combination of optical time-of-flight metrology and digital holography. In addition absolute calibration of the measurement results is performed by a side-band modulation technique.

For the time-of-flight technique a diode laser (1470 nm) is modulated sinusoidally (128 MHz). The light reflected and scattered by an object is detected by an avalanche-photo-diode. The phase difference between the sent and detected modulation is a measure for the distance between the sensor and the object. This allows for distance measurements up to 1.3 m with resolutions of ~5mm. The interferometric setup uses 4 whispering-gallery-mode lasers to perform multiwavelengths-holographic distance measurements. The four wavelengths span the range from 1547 nm to 1554 nm. The unambiguous measurement measurement-range of the interferometric setup is approx. 7 mm while resolutions of 0.6 µm are observed. Both setups are integrated into one setup and perform measurements synchronously. To effectively combine both methods exact knowledge of the wavelength difference between the four lasers is crucial. For this aim the light of the lasers is modulated with frequencies of 36 GHz and 40 GHz using electro optic phase modulators. This modulation produces sidebands in the optical spectrum 36 GHz, 72 GHz,… apart from the peak wavelengths of the respective lasers. So beat-signals between different lasers are produced and the beat-frequencies are measured electronically. They can be compared with a time normal for absolute calibration. The setup shows a way to measure distances in the meter range with sub-micron resolution.

8992-24, Session 5

Combined far-field and multiprobe near-field imaging of hybrid photonic devices

Aaron Lewis, The Hebrew Univ. of Jerusalem (Israel); Hesham Taha, Nanonics Imaging Ltd. (Israel)

The wide diversity of the photonic devices and applications today requires instrumental platforms suitable for measuring light distribution at the nanometric scale and suitable for integration with online analytical techniques for multi-disciplinary characterization. In this presentation, we will demonstrate our multiprobe scan probe microscope technology as a platform for near-field and far-field optical imaging and manipulation of variety of photonic, plasmonic, hybrid photonic-plasmonic and optoelectronic devices. Such integrated systems can incorporate lens fiber nanomanipulators with near-field scanning probe microscopes suitable for injecting and collecting light distribution correlated with topographic structure. In addition, the platform allows for flexible integration with variety of instrumentation such as optical microscopes, confocal and fluorescence microscopes and different spectroscopy techniques such as Raman microscopes. We will demonstrate different examples of devices for effective light illumination of plasmonic and photonic structures. Furthermore, beside standard illumination protocols in the far-field the platform with near-field probes allows for variety of k-vectors for the effective excitation of plasmonic components in hybrid devices. Added to these passive measurements it will be shown that the same platform can be employed to characterize electrical and thermal properties of both passive and optical devices.

8992-25, Session 6

Ultrawide wavelength range (300nm-2µm) polarization-independent 500gs/s single-shot pulse all-optical real time oscilloscope (ORTO)

Jean-François Gleyze, Commissariat à l'Énergie Atomique (France); Steve Hocquet, Greenfield Technology (France); Patrice Le Boudec, Romain Arnaud, IDIL Fibres Optiques (France); Denis Penninckx, Commissariat à l'Énergie Atomique (France); Alain Jolly, ALPhANOV (France); Dominique Monnier Bourdin, Greenfield Technology (France); Bruno Chassagne, ALPhANOV (France)

Current developments of ultra-broadband oscilloscopes are mainly governed by the needs of future telecom networks. But a number of additional applications also involve specific needs for true real-time measurements. For example single-shot systems are of prime interest for Inertial Confinement Fusion (ICF) and plasma physics.

We previously [1] demonstrated such a design with 100GHz measurement bandwidth, in the basic form of an all-optical sampling oscilloscope (MULO).

This laboratory system has been improved recently in terms of stability and compactness, as a new all-in-one box system. Thanks to the addition of an optical-electro-optical (OEO) sub-converter at the input, we enlarged the possible applications areas, including analyse of electrical pulses with up to 60GHz measurement bandwidth. The newly integrated subset also increases the range of acceptable wavelengths considering optical pulses, from about 300nm up to 2?m.

Thanks to the use of inexpensive opto-electronic components at telecom wavelengths and to the optimization of the optical heart of the system, we achieve to demonstrate a very high sampling rates, up to 500Gs/s; this expected to enable much wider bandwidths in the near future.

In this talk, we will present latest developments and focus on integration highlights of this system. Fully representative measurement capabilities will be discussed, in relationship with the qualification of laser pulses from the LMJ front-end. Specific attention will be paid on the innovative OEO subset-system.

[1] A. Jolly, JF Gleyze, et al, "[1] "Demonstration of a true single-shot 100 GHz-bandwidth optical oscilloscope at 1053-1064 nm" Optics Express 17-14-12109

8992-26, Session 6

Spectroscopy-based photonic instrumentation for the manufacturing industry: contactless measurements of distances, temperatures, and chemical compositions

Bertrand Noharet, Erik Zetterlund, Oleksandr Tarasenko, Magnus Lindblom, Acreo Swedish ICT AB (Sweden); Jonas Gurell, Swerea IVF (Sweden)

The steady progress in photonic components in terms of cost-to-performance ratio, maturity and robustness opens new avenues for the commercial deployment of photonic sensor systems in a wide range of industrial applications. Advanced sensing can be used to optimize processes and thereby enable significant savings in energy consumption. Three cases of robust photonic instrumentation for process optimization and quality control in manufacturing industries are presented: improved metal recycling with laser-induced breakdown spectroscopy, quality control in precision machining by white-light interferometry with optical fiber probes embedded in machining tools, and process optimization in steel foundries by stand-off temperature measurements in blast furnaces with fiber lances and spectral techniques.

These techniques utilize low-cost spectrometers, and require dedicated calibration and signal processing methods:

• LIBS: advanced spectral analysis for the on-line correct classification of metal scrap on a conveyor belt.

• Distance measurement: detailed analysis of the encoded white-light spectrum after propagation in a Fabry-Perot cavity.

• Temperature measurement: analysis of the full black-body radiation spectrum to enable customization of the method to various specific process and increase robustness to process variations.

Each of these methods has been developed to guarantee robust operation in industrial environments with varying conditions. Experimental results will be presented, including on-line steel alloy analysis with correct classification rates in excess of 95%, distance measurements with an axial resolution of +/- 2nm over a range of 75µm, and continuous temperature monitoring of molten steel in oxygen blast furnaces with better than 1% accuracy.

8992-27, Session 6

Developing dual-beam laser Doppler interferometry system for opto-piezoelectric materials based ultrasonic parking sensors and optofluidics sensors

Po-Cheng Lai, Chih-Kung Lee, National Taiwan Univ. (Taiwan)

Adopting opto-piezoelectric materials, which utilized optical illumination pattern to effect the spatial force distribution induced by piezoelectric materials, to ultrasonic parking sensors and optofluidic chips represent a new research direction in industrial sub-system development. To accommodate performance requirements include wide bandwidth, ultrahigh precision, linear and angular measurement, etc. associated with the evaluation of industrial application systems such as the ones mentioned above, a newly developed laser Doppler vibrometer/ interferometer (AVID) was presented. The design configuration, completely orthogonal alignment procedures and the corresponding opto-mechanical design implemented, system performance verified, signal processing algorithms developed as well as the experimental results obtained will all be discussed in this paper. Emphasis will be on the experimental data obtained from AVID and the design changes developed based on the metrology outcome. The system performance improvement induced by the experimental verification done by AVID will be discussed in detail.

8992-28, Session 6

Influence of primary aberrations on coherent lidar performance

Qi Hu, Peter John L. Rodrigo, Christian Pedersen, DTU Fotonik (Denmark); Theis F. Q. Iversen, Windar Photonics A/S (Denmark)

In this work we investigate the performance of a monostatic coherent lidar system in which the transmit beam is under the influence of primary phase aberrations: spherical aberration (SA), astigmatism and coma. The experimental investigation is realized by probing the spatial weighting function of the lidar system using different optical transceiver configurations. A rotating belt is used as a hard target. Our study shows that the lidar weighting function suffers from both spatial broadening and shift in peak position in the presence of aberration. It is to our knowledge the first experimental demonstration of these tendencies. Furthermore, our numerical and experimental results show good agreement.

We also demonstrate how the truncation of the transmit beam affects the system performance. It is both experimentally and numerically proven that aberration effects have profound impact on the antenna efficiency, the optimum truncation of the transmit beam and the spatial sensitivity of a CW coherent lidar system. Under strong degree of aberration, the spatial confinement is significantly degraded. However for SA, the degradation of the spatial confinement can be reduced by tuning the truncation of the transmit beam, which results from the novel finding in this work, namely, that the optimum truncation ratio depends on the degree of SA.

8992-29, Session PWed

Improvement of image quality by polarization mixing

Ryosuke Kasahara, Izumi Itoh, Hideaki Hirai, Ricoh Co., Ltd. (Japan)

Polarization information is not visible to human eyes and valuable because it contains information about light source, angle and material of an object. But polarization information strongly depends on the direction of the light source and it's difficult to apply outdoors polarization image to various recognition algorithms because the angle of the sun is not fixed. In this presentation, we propose an image enhancement method for utilizing polarization information in many situations which the light source is not fixed such as outdoors. We take two strategies to overcome the problem. Firstly, we computed a combination of polarization image and brightness image. Because of the angle of the light source, polarization has no information about some scenes. Therefore, it is very difficult to use only polarization information in any scene for applications such as object detection. But if we use a combination of polarization image and brightness image, the brightness image can complement the lack of scene information. The second strategy is finding features which less depend on the direction of light source. We propose a method of extracting scene features based on analysis of the reflection model with polarization. As a result, our method delivers higher contrast image than the normal brightness image in many scenes. A polarization camera which has polarizers on each pixel of the image sensor was built and used for capturing images. We discuss several examples that demonstrate the improved visibility of objects by applying our proposed method, e.g. visibility of lane markers on wet roads.

8992-30, Session PWed

Single-snapshot 2D color measurement by plenoptic imaging system

Kensuke Masuda, Yuuji Yamanaka, Go Maruyama, Shoh Nagai, Hideaki Hirai, Ricoh Co., Ltd. (Japan); Lingfei Meng, Ivana Tosic, Ricoh Innovations, Inc. (United States)

Plenoptic cameras enable capture of directional ray information allowing digital refocusing, depth estimation, or multi-spectral imaging. The camera contains a lenslet array at the conventional image plane and a sensor at the back focal plane of the lenslet array. We have focused on multi-spectral imaging function of this camera and developed a plenoptic colorimetric camera using XYZ filters inserted in the pupil plane of the main lens. To achieve high measurement precision with this system, we need to consider end-to-end plenoptic system performance, which includes light source information, object information, optical system information, plenoptic image processing, and color estimation processing. Since in the optical system the final output image includes the chroma aberration and shading of the main lens and lenslet array, it is difficult to handle direct output value to estimate color with existing lens design and camera evaluation tools. Therefore, we have built an end-to-end imaging system simulation for a multi-spectral plenoptic camera and optimized the filter array layout to maximize the measured color accuracy. Our simulations show that such optimized plenoptic colorimetric camera achieves high color measurement precision. Finally, we take the color shading evaluation of display as an example, and describe a series of optimizations processing in plenoptic colorimetric camera.

8992-31, Session PWed

Six-axis interferometric coordinates measurement system for nanometrology

Jan Hrabina, Josef Lazar, Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic); Petr Klapetek, Miroslav Valtr, Czech Metrology Institute (Czech Republic); Ondrej Cip, Martin Cizek, Miroslava Hola, Mojmir Sery, Jindrich Oulehla, Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic)

We present an overview of approaches to the design of nanometrology coordinates measuring setup with a focus on methodology of nanometrology interferometric techniques and associated problems. The design and development of a nanopositioning system with interferometric multiaxis monitoring and control involved for scanning probe microscopy techniques (primarily atomic force microscopy, AFM) for detection of the sample profile is presented. Coordinate position sensing allows upgrading the imaging microscope techniques up to quantified measuring. Especially imaging techniques in the micro- and nanoworld overcoming the barrier of resolution given by the wavelength of visible light are a suitable basis for design of measuring systems with the best resolution possible. The practical measurement results of active compensation system for positioning angle errors suppression are presented as well as the analysis of overall achievable parameters. The system is being developed in cooperation with the Czech metrology institute and it is intended to operate as a national nanometrology standard combining local probe microscopy techniques and sample position control with traceability to the primary standard of length.

8992-32, Session PWed

Interferometric measurement system for cost effective e-beam writer

Simon Rerucha, Martin Sarbort, Martin Cizek, Jan Hrabina, Josef Lazar, Ondrej Cip, Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic)

The reliability of nanometer track writing in the large scale chip manufacturing process depends mainly on a precise positioning of the e-beam writer moving stage. Usually the laser interferometers are employed to control this positioning. Their complicated optical scheme leads to an expensive instrument which increases the e-beam writer's manufacturing costs.

We present a new design of an interferometric system useful in a currently developed cost effective e-beam writers. Our approach simplifies the optical scheme of known industrial interferometers and shifts the interference phase detection complexity from optical domain to the digital signal processing part. Besides the effective cost, the low number of optical components minimizes the total uncertainty of this measuring instrument.

The scheme consists of a single wavelength DFB laser working at 1550 nm, one beam splitter, measuring and reference reflectors and one photo-detector at the interferometer output. The DFB laser is frequency modulated by slight changes of injection current while the interference intensity signal is processed synchronously. Our algorithm quantifies the phase as two sinusoidal waveforms with a phase offset equal to the quarter of the DFB laser wavelength. Besides the computation of these quadrature signals, the scale linearization techniques are used for an additional suppression of optical setup imperfections, noise and the residual amplitude modulation caused by the laser modulation. The stage position is calculated on basis of the DFB laser wavelength and the processed interference phase.

To validate the precision and accuracy we have carried out a pilot experimental comparison with a reference interferometer over the 100 mm measurement range. The first tests promise only 2 nm deviation between simplified and the reference interferometer. Both detection chains have shared the optical paths in order to cancel out the geometric errors, the effects of mechanical vibrations and the refractive index of air influence.

The design of the interferometer principle was funded by the GACR project GAP102/10/1813. The work was also funded by TACR project TA03010663, and EU projects no CZ.1.05/2.1.00/01, CZ.1.07/2.4.00/31.0016 and CZ.1.07/2.3.00/30.0054.

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8993-1,

Smart Sensors: Why and when the origin was and why and where the future will be *(Keynote Presentation)*

Carlo Corsi, Consorzio CREO (Italy)

Smart Sensors is a technique developed in the 70's when the processing capabilities, based on read-out integrated with signal processing, was still far from the complexity needed in advanced IR surveillance and warning systems, because of the enormous amount of noise/unwanted signals emitted by operating scenario especially in military applications. The Smart Sensors technology was kept restricted within a close military environment exploding in applications and performances in the 90's years thanks to the impressive improvements in the integrated signal read-out and processing achieved by CCD-CMOS technologies in FPA. In fact the rapid advances of "very large scale integration" (VLSI) processor technology and mosaic EO detector array technology allowed to develop new generations of Smart Sensors with much improved signal processing by integrating microcomputers and other VLSI signal processors. Inside the sensor structure achieving some basic functions of living eyes(dynamic stare, non-uniformity compensation, spatial and temporal filtering. New and future technologies (Nanotechnology, Bio-Organic Electronics, Bio-Computing) are lightning a new generation of Smart Sensors extending the Smartness from the Space-Time Domain to Spectroscopic Functional Multi-Domain Signal Processing. History and future forecasting of Smart Sensors will be reported.

8993-7, Session 1

Exciton-polariton lasers in Magnetic Fields *(Invited Paper)*

Christian Schneider, Julian Fischer, Matthias Amthor, Sebastian Brodbeck, Julius-Maximilians-Univ. Würzburg (Germany); Ivan G. Savenko, Ivan A. Shelykh, Univ. of Iceland (Iceland); Alexander Chernenko, Institute of Solid State Physics (Russian Federation); Arash Rahimi-Iman, Julius-Maximilians-Univ. Würzburg (Germany); Vladimir D. Kulakovskii, Institute of Solid State Physics (Russian Federation); Stephan Reitzenstein, Julius-Maximilians-Univ. Würzburg (Germany); Na Young Kim, Stanford Univ. (United States) and National Institute of Informatics (Japan); Mikhail Durnev, St. Petersburg State Univ. (Russian Federation); Alexey Kavokin, St. Petersburg State Univ. (Russian Federation) and Univ. of Southampton (United Kingdom); Yoshihisa Yamamoto, Stanford Univ. (United States) and National Institute of Informatics (Japan); Alfred Forchel, Martin Kamp, Sven Höfling, Julius-Maximilians-Univ. Würzburg (Germany)

Polariton-Lasers do not rely on stimulated emission of cavity photons, which sets stringent conditions on the threshold current in a conventional laser. Indeed, it has been demonstrated in optically pumped systems, that such bosonic Lasers can outperform standard lasers in the weak light-matter coupling regime in terms of their threshold power. The polaritons, which consist of part light and part matter, can undergo a condensation process into a common energy state. The radiated light from such a system shares many similarities with the light emitted from a conventional photon laser, even though the decay of the polaritons is a spontaneous process.

We discuss properties of polariton lasers and condensates in GaAs based microcavities. Special emphasis is given to the system's response to an applied magnetic field, which has a tremendous influence on the condensation effect. We introduce the magnetic field interactions as a reliable tool to distinguish a polariton laser from a conventional photon laser device. In particular, we will discuss the first successful realization of an electrically pumped polariton laser, which marks a promising step towards the exploitation of polaritonic devices in the real world. We believe that our work can be extended to devices operated at room temperature by transferring the technology to large bandgap semiconductors, or even in GaAs samples with a modified layer design.

8993-8, Session 1

Random laser on planar GaAs waveguides *(Invited Paper)*

Olivier Gauthier-Lafaye, Lab. d'Analyse et d'Architecture des Systèmes (France); J. Campos, LAAS (France); Antoine Monmayrant, Françoise Lozes-Dupuy, Lab. d'Analyse et d'Architecture des Systèmes (France); K. Bhaktha, Institut Langevin, ESPCI ParisTech, CNRS (France); Patrick Sebbah, Ecole Supérieure de Physique et de Chimie Industrielles (France); Christian Vanneste, Lab. de Physique de la Matière Condensée (France)

We report random laser action in an active 2D GaAs waveguide.

Random photonic crystal consisting of randomly-placed air holes etched through a GaAs waveguide with InGaAs quantum wells were fabricated and tested under optical pumping.

The accuracy and reproducibility of the fabrication process based on ebeam lithography enabled parametric study of the structure to decorrelate the effect of the random distribution from that of other structural parameters (holes diameter, scaling factor, hole depth).

The planar geometry of this structure offers excellent optical access to the field through the surface.

Fabricated samples were optically pumped and the radiated field was recorded by an home-made hyperspectral imager as a function of pump power, wavelength and xy position.

This allowed to measure the scattering regime as a function of the geometrical properties of the structure using the so-called internal source technique.

It also permitted to observe laser action on delocalized modes with clear threshold and narrow spectral width.

Laser action was correlated to strong scattering regime, no laser action being observable in other scattering regimes.

In this contribution, the details of fabrication, the specific benefits and the open challenges of this planar geometry on GaAs/InGaAs will be detailed and discussed.

8993-9, Session 1

Quantum dot mode locked lasers for coherent frequency comb generation *(Invited Paper)*

Anthony Martinez, Cosimo Calo, Ricardo Rosales, Lab. de Photonique et de Nanostructures (France); Regan Watts, Dublin City Univ. (Ireland); Kamel Merghem, Lab. de Photonique et de

Nanostructures (France); Alain Accard, François Lelarge, III-V Lab. (France); Liam Barry, Dublin City Univ. (Ireland); Abderrahim Ramdane, Lab. de Photonique et de Nanostructures (France)

Monolithic semiconductor passively mode locked lasers (MLL) are very attractive components for many applications including high bit rate telecommunications, microwave photonics and instrumentation. Owing to the three dimensional confinement of the charge carriers, quantum dot based mode-locked lasers have been the subject of intense investigations because of their improved performance compared to conventional material systems. Indeed, the inhomogeneous gain broadening and the ultrafast absorption recovery dynamics are an asset for short pulse generation. Moreover, the weak coupling of amplified spontaneous emission with the guided modes plus low loss waveguide leads to low timing jitter.

Our work focuses on InAs quantum dash nanostructures grown on InP substrate intended for applications in the 1.55 µm telecom window. InAs/InP quantum dash based lasers, in particular, have demonstrated efficient mode locking in single section Fabry-Perot configurations. The flat optical spectrum of about 12 nm, combined with the narrow RF beat note linewidth of about 10 kHz make them a promising technology for optical frequency comb generation. Coherence between spectral modes was assessed by means of spectral phase measurements. The parabolic spectral phase profile indicates that short pulses can be obtained provided the intracavity dispersion can be compensated by inserting a single mode fiber.

8993-10, Session 1

Whispering gallery optical parametric oscillators

Ingo Breunig, Albert-Ludwigs-Univ. Freiburg (Germany); Karsten Buse, Fraunhofer-Institut für Physikalische Messtechnik (Germany)

Optical parametric oscillators (OPOs) almost arbitrarily convert the frequency of incident laser light. There is only one fundamental limitation: The incident light field has a shorter wavelength than the generated one. They are unique sources for widely tunable coherent and non-classical light. Nowadays, OPOs operate from the visible to the far infrared, and they are working horses for high-resolution spectroscopy. Furthermore, they play an important role in quantum-optical experiments.

A conventional OPO comprises a nonlinear-optical medium inside of a mirror resonator. The mirrors have to be high-reflection coated for the target wavelength- range of operation. Recently, a new class of OPOs has been developed: whispering gallery OPOs. These devices are based on total internal reflection. Thus, they do not require any coating. Since reflection losses are negligible, their oscillation threshold can be far below one milliwatt. Furthermore, with sub-millimeter diameters, they are the most compact OPOs demonstrated so far.

Our experimental results show that whispering gallery optical parametric oscillators are capable to emit coherent light tunable over hundreds of nanometers. They are operated in the visible as well as in the near-infrared. We have obtained up to 30 % conversion efficiency. These very promising results indicate a great potential for spectroscopic and sensing applications.

8993-11, Session 2

Terahertz quantum cascade lasers for time domain spectroscopy *(Invited Paper)*

Sukhdeep S. Dhillon, Joshua R. Freeman, Jean Maysonnave, Pierrick Cavalié, Kenneth Maussang, Jérôme Tignon, Ecole Normale Supérieure (France)

The use of THz radiation in both laboratories and industrial applications has greatly expanded over recent years. One of the most widely used system for the generation and detection of THz radiation is time domain spectroscopy (TDS). This system is based around a laser source producing infrared pulses of femtosecond (fs) duration. The envelope of the optical pulse is converted by a non-linear process into a transient electric field which, due to the short duration of the optical pulse, contains a broad range of frequencies in the THz region. Another very promising THz technology is the THz quantum cascade laser (QCL). This electrically driven semiconductor laser produces high power narrow band radiation in the THz region. In the past few years experiments have been conducted to bring these two important THz technologies together. This was first done to measure the gain the QCL with a THz TDS pulse and, more recently, this integration has been extended so that the QCL is seeded with the THz TDS pulse. This method ensures that the QCL field is phase-locked and synchronised with the TDS pulse. As a result time resolved coherent detection methods such as electro-optic sampling can be used for the detection of the QCL emission.

The synchronous and coherent detection of THz laser emission opens up new possibilities of the study of laser dynamics. These techniques will be discussed in detail as well as recent progress towards measurement of the QCL field in more exotic regimes such as modelocking.

8993-12, Session 2

Vertical-emitting terahertz quantum cascade lasers with a quasi-period Penrose patterning *(Invited Paper)*

Miriam S. Vitiello, Consiglio Nazionale delle Ricerche (Italy)

Distributed feedback (DFB) in semiconductor lasers is crucial for tailoring the shape, the symmetry and the frequency of the optical resonator eigenmodes while simultaneously allowing stable single mode operation.

In double-metal Terahertz quantum cascade lasers (QCLs), DFB action is commonly achieved by selectively patterning the waveguide top metallization to force the resonator to behave like a two-dimensional dielectric system for the TM photonic modes, with a spatial dependence of its dielectric contrast given by the pattern geometry. DFB patterns are normally periodic in order to match the shape of guided plane waves. However, a fine control over vertical emission is also possible either via second-order Bragg reflections, or by introducing optimally shaped defects in the periodic pattern. Quasi-periodic lattices show rich structures of Bragg peaks in their reciprocal space that are able to realize a distributed feedback effect.

We recently demonstrate vertical emission in the THz domain from QCLs based on a two-dimensional quasi-periodic Penrose photonic lattice. Laser action at 3.2 THz has been reached up to 120K with strong quantum efficiency dependence from the filling ratio of the quasi periodic pattern and an intense and highly collimated optical beam profile.

8993-13, Session 2

Microstrip-antenna-coupled distributed feedback terahertz quantum-cascade lasers

Tsung-Yu Kao, Xiaowei Cai, Qing Hu, Massachusetts Institute of Technology (United States); John L. Reno, Sandia National Labs. (United States)

The best terahertz quantum cascade lasers (QCL) have been demonstrated using the metal-metal waveguides. However, the subwavelength confinement in the waveguide results in divergent beam patterns and high facet reflectivity. The invention of third-order distributed feedback (DFB) structures utilizing end-fire antenna effect to reduce beam divergence and also enhance output power. Here we report a novel structure which enhances the power out-coupling efficiency even more while preserving all major advantages of previous approaches.

By introducing coupled microstrip antennas on THz DFB QC-Lasers , the radiation efficiency of each feedback aperture is greatly enhanced. Single mode emission ~3THz from a 31-period antenna-coupled third-order DFB laser yields ~4 times improvement in output power comparing with a corrugated third-order device fabricated on the same gain medium. This 31-period device has ~15x25 deg beam divergence and 4mW pulsed power (4%) at 10K with maximum lasing temperature (Tmax) at 134K (pulsed). When phase matching condition is met, emissions from 81 apertures (4-mm long) are coherently combined to form a narrow beam with 12.5 deg divergence. Further experiment demonstrated the new device at 4 THz (25-period, ~18um x 1-mm long. The 4THz device reaches >8 mW pulsed power (10%) at 12K with Tmax 109K (pulsed) and >77K (cw). The slope efficiency is 450 mW/A with 0.57% wall-plug efficiency -- the highest values reported for THz QC Lasers. It is worth pointing out although the antennas would be excited differently, similar enhancement in out-coupling efficiency can also be observed in second-order surface-emitting THz DFB lasers.

8993-14, Session 2

Tunable excitation of two-dimensional plasmon modes in InGaAs/InP HEMT devices for terahertz detection

Nima Nader Esfahani, Air Force Research Lab. (United States) and Solid State Scientific Corp. (United States) and Univ. of Central Florida (United States); Xin Qiao, Robert E. Peale, Univ. of Central Florida (United States); Walter R. Buchwald, Univ. of Massachusetts Boston (United States) and Solid State Scientific Corp. (United States); Joshua R. Hendrickson, Justin W. Cleary, Air Force Research Lab. (United States)

Plasmon excitation in the two dimensional electron gas (2DEG) of grating-gated high electron mobility transistors (HEMTs) gives rise to terahertz absorption lines, which may be observed via transmission spectroscopy and may result in a change in channel conductance. The plasmon dispersion relationship depends on sheet charge density which enables gate bias tunable plasmon excitation. Investigated here is a HEMT structure based on InGaAs/InP material systems with a grating-gate designed for THz frequencies. Optical and electrical measurements are completed using a FTIR spectrometer interfaced with a liquid-He cooled Si-bolometer for multiple gate biases. Empirical data is analyzed with and compared to finite element method (FEM) simulations and analytical theory. Field oscillations, characteristic of excited plasmons modes, are reflected in FEM simulations and agree with analytical transmission calculations showing corresponding resonant absorption features. Such absorption resonances, corresponding to altered channel conductance, give a means to use properly designed HEMTs as all electrical, voltage-tunable detectors or filters.

8993-15, Session 2

Recent progress toward realizing GaN-based THz quantum cascade laser *(Invited Paper)*

Hideki Hirayama, Wataru Terashima, RIKEN (Japan)

We are studying on terahertz-quantum cascade lasers (THz-QCLs) using III-Nitride semiconductor, which is a material having potentials for realizing wide frequency range of QCL, i.e., 1-15 THz and 1-10 μm range including the unexplored frequency range from 5 to 12 THz, as wall as realizing room temperature operation of THz-QCL. The merits of using an AlGaN-based semiconductor in comparison with GaAs or InP is that it has much higher longitudinal optical phonon energies (ELO) (> 90meV) than those of conventional GaAs-based materials (~ 36 meV). In our work, we firstly showed clearly that it is possible to design a GaN-based quantum cascade (QC) structure which operates in the THz range in which population inversion can be obtained, by performing numerical calculations based on a self-consistent rate equation model. Secondly, we succeeded in the molecular beam epitaxy (MBE) growth of QC stacking structure with a large number of periods and demonstrated the dramatic improvement of structural properties of QC structure, by introducing a new growth technique named "a droplet elimination by thermal annealing (DETA)". Finally, we for the first time successfully observed spontaneous electroluminescence due to intersubband transitions with peaks at frequencies from 1.4 to 2.8 THz from GaN/AlGaN QCL devices fabricated on high-quality AlN template prepared by metalorganic chemical-vapor epitaxy (MOCVD) on a sapphire substrate. In this paper, we demonstrate recent achievements on the quantum design, fabrication technique, and electroluminescence properties of GaN-based QCL structures.

8993-16, Session 3

Efficient coupling between a quantum dot and a gaussian beam via a broadband dielectric antenna: the photonic trumpet *(Invited Paper)*

Joël Bleuse, Julien Claudon, Commissariat à l'Énergie Atomique (France); Niels Gregersen, Technical Univ. of Denmark (Denmark); Mathieu Munsch, Commissariat à l'Énergie Atomique (France) and Univ. Basel (Switzerland); Adrien Delga, Commissariat à l'Énergie Atomique (France); Jesper Mørk, Technical Univ. of Denmark (Denmark); Jean-Michel Gérard, Commissariat à l'Énergie Atomique (France)

Photonic wire waveguides provide an efficient control over the spontaneous emission of quantum light sources [1], and constitute a broadband alternative to the traditional microcavity approach for the realization of bright sources of non-classical light, with applications to photonic quantum logic through strong non-linear interactions between single photons [2].

In a previous implementation of the concept, a sharp-end, tapered photonic wire embedding quantum dots exhibited a large photon extraction and a directional far-field emission [3]. However, this far-field matches poorly to a Gaussian beam — while the efficient feeding of light into a single-mode fiber is crucial for most applications. Moreover, the detailed geometry of these wires is critical, which compromises their reproducible fabrication.

We introduce a second implementation, where the taper is inverted, that overcomes the above-mentioned limitations [4]. Simulations show that this "photonic trumpet" simultaneously offers a great robustness against fabrication imperfections and a nearly perfect Gaussian-mode matching, while keeping the large extraction and good directivity. We also evidence the feasibility of these large aspect-ratio structures and demonstrate a 0.75-collection efficiency, single-photon source. Besides these assets, photonic trumpets are compatible with the making of electrical contacts for the realization of single-photon, light emitting diodes.

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8993-17, Session 3

On-chip single-photon sources for integrated quantum circuits

Martin Kamp, Sven Höfling, Johannes Beetz, Julius-Maximilians-Univ. Würzburg (Germany); Döndü Sahin, Leonardo Midolo, Sartoon Fattahpoor, COBRA Research School (Netherlands);

Thang B. Hoang, Andrea Fiore, COBRA Research School (Netherlands); Matthias Lermer, Julius-Maximilians-Univ. Würzburg (Germany)

Quantum information processing (QIP) has become a major field of research since switching from classical to quantum bits (Qbits) will open up completely new possibilities in communication and computing. Due to their long coherence and low transmission losses, single photons are promising candidates for flying Qbits. Up to now, most of the experiments that make use of single photons have been realized by bulky setups based on discrete components, which makes the realization of complex quantum circuits difficult. Therefore, the integration of basic building blocks for the generation, manipulation and detection of single photons on a chip is required in order to advance the state-of-the-art of photonic QIP in both science and applications. While passive quantum circuits based on integrated optics have already been demonstrated, the integration of sources and detectors is far more challenging due to the very different requirements concerning materials and fabrication technology. The talk will present recent results on the realization of on-chip single photon source for integrated quantum circuits. On-chip single photon sources were realized using self-assembled quantum dots (QDs) in photonic crystal waveguides. Due to the size variation of the QDs, a tuning mechanism is required to match the emission wavelength of the dots with resonances of the PhC or that of other quantum dots. One possibility is to use the quantum confined Stark effect, which has allowed us to demonstrate widely tuneable waveguide single-photon sources. We'll also present results on strain tuning of quantum dots inside photonic crystal cavities and discuss integration aspects of the sources.

8993-18, Session 3

Novel fiber-optic geometries for fast quantum communication

Jeffrey J. Perkins, Fiberguide Industries, Inc. (United States); Raymond T. Newell, Los Alamos National Lab. (United States); Charles R. Schabacker, Craig B. Richardson, Fiberguide Industries, Inc. (United States)

We propose a novel system for generation of defined orbital angular momentum states of the electromagnetic field via fiber optic geometry control, without the use of nonlinear effects. The output state has a defined orbital angular momentum. Additional implications of fiber tapers for hyper-entanglement are also discussed.

By utilizing the appropriate local-mode coupling equations, we project states of defined orbital angular momentum onto the mode structure of a few and multi-mode fiber optic, and determine the required taper geometry to generate hyper-entangled states of the electromagnetic field, as well as states with defined orbital angular momentum. The resulting system is entirely passive with low space and weight requirements.

Hamiltonians and scattering matrices to several orders of approximation are presented to describe the mode coupling in fiber optic tapers as necessary to determine the outputs of the system. The prospects for realization of a GHz bandwidth Quantum Communication system via passive optics are discussed. The anticipated hyper-entangled photon states are also determined. A comparison between square, round, and graded core fibers is presented in an effort to elucidate the effect of arbitrary geometry tapers on the output polarization and intensity distribution.

8993-19, Session 3

Waveguide single-photon and photon-number-resolving detectors for integrated quantum photonics *(Invited Paper)*

Andrea Fiore, Döndü Sahin, Technische Univ. Eindhoven (Netherlands); Alessandro Gaggero, Istituto di Fotonica e Nanotecnologie (Italy); Zili Zhou, Saedeeh Jahanmirinejad, Technische Univ. Eindhoven (Netherlands); Francesco Mattioli, Roberto Leoni, Istituto di Fotonica e Nanotecnologie (Italy); Johannes Beetz, Matthias Lermer, Sven Höfling, Martin Kamp, Julius-Maximilians-Univ. Würzburg (Germany)

Photons are one of the most promising implementation of quantum bits for quantum information processing and communications. Due to increasing complexity and loss, scaling quantum systems beyond few photons is only possible by integrating them into quantum photonic integrated circuits. Such circuits should comprise sources of single- and entangled-photons, linear optics components, and single-photon and photon-number-resolving detectors. Gallium arsenide represents a technology platform where all these functionalities can be integrated. We report the integration of detectors based on superconducting nanowires with GaAs-based waveguides. NbN nanowires deposited and patterned on top of ridge waveguides sense the evanescent field of guided photons. The absorption of a single photon can produce the transition from the superconducting to the resistive state, giving rise to a voltage pulse in the external circuit. Such waveguide single-photon detectors provide quantum efficiencies in the 20% range at 1300 nm, jitters of 60 ps and deadtimes of 10 ns. In order to increase the functionality, two electrically-separated wires have been patterned on top of a waveguide to sense the same guided mode, enabling the on-chip measurement of the second-order correlation function with an extremely compact, 50 micron-long device. Despite the close proximity of the two wires, no cross-talk was evidenced. Additionally, a waveguide photon-number-resolving (PNR) detector has been realised by patterning four wires on top of a waveguide, and connecting them in a series configuration. Clear PNR detection of up to four photons was demonstrated.

8993-20, Session 3

Series nanowire detector resolving up to twelve photons

Zili Zhou, Saeedeh Jahanmirinejad, Technische Univ. Eindhoven (Netherlands); Francesco Mattioli, Istituto di Fotonica e Nanotecnologie (Italy); Döndü Sahin, Giulia Frucci, Technische Univ. Eindhoven (Netherlands); Alessandro Gaggero, Roberto Leoni, Istituto di Fotonica e Nanotecnologie (Italy); Andrea Fiore, Technische Univ. Eindhoven (Netherlands)

We demonstrate a superconducting photon-number-resolving detector which is capable of resolving up to twelve photons at telecommunication wavelengths. It is based on a series array of twelve superconducting NbN nanowire elements. In each element the superconducting nanowire is connected in parallel with an integrated resistor (made of AuPd) and biased with an electric current slightly below its critical current. When one of the elements absorbs a photon, the superconducting nanowire becomes resistive and shunts the bias current to its corresponding parallel resistor, producing a voltage pulse in the readout. The photon-induced voltage pulses from the parallel resistors will be summed up into a single readout pulse with a height proportional to the number of firing elements and thus to the detected photon number. Each wire (100 nm wide) of the array is folded in a meander and the array covers an area of 12 ?m ? 12 ?m. In the experiment, the device was kept at a temperature of 1.2K and characterized using a 1310 nm pulsed laser. Twelve distinct output levels were observed, corresponding to the detection of n=1-12 photons. The maximum device quantum efficiency was ~0.18 % and the 1/e decay time was ~11.3 ns, which enabled a repetition rate of ~30 MHz. The jitter of the system was measured to be ~89 ps at the leading edge of the readout pulse. Photon statistics on the experimental data shows a good agreement with the theory.

8993-21, Session 3

Quantum frequency correlation engineering with a semiconductor microcavity at room temperature *(Invited Paper)*

Sara Ducci, Guillaume Boucher, Andreas Eckstein, Univ. Paris 7-Denis Diderot (France); Aristide Lemaître, Lab. de Photonique et de Nanostructures (France); Marco Liscidini, Univ. degli Studi di Pavia (Italy); John Sipe, Univ. of Toronto (Canada); Ivan Favero, Giuseppe Leo, Univ. Paris 7-Denis Diderot (France)

Photonics is playing a central role in the development of quantum information and communication technologies; in particular, the availability of sources able to generate versatile two-photon states according to the particular quantum information protocol requires a deep understanding of the generation of quantum correlations and the possibility to control it. In this work we present the frequency correlation engineering of the bi-photon state generated in a semiconductor microcavity working at room temperature; being based on a counterpropagating phase-matching scheme with a transverse pump, this device has already led to the generation of polarization entangled states violating Bell inequalities without post-manipulation of the generated photon. We demonstrate both theoretically and experimentally how the frequency correlation nature of the emitted photons can be tailored via the spatial properties of the transverse pump beam to produce correlated, anti-correlated and uncorrelated photon pairs. A novel technique, based on the stimulated version of SPDC, in which a seed signal pulse is injected together with a pump pulse, allows reconstructing the joint spectral intensity of the generated biphoton state with an unprecedented resolution. These results open the possibility to generate more exotic, spectral/polarization hyper-entangled photon pair states, with an quantum information density surpassing that of the purely polarization entangled state.

8993-22, Session 4

Confinement of photons and control of their emission using surface addressable photonic crystal membrane *(Invited Paper)*

Xavier Letartre, Cédric Blanchard, Romain Peretti, Corrado Sciancalepore, Ecole Centrale de Lyon (France)

High index contrast periodic structures can be exploited to perform an arbitrarily adjustable spatio-temporal molding of light at the wavelength scale. This tight control of photons is obtained through a shaping of resonant modes and a suitable adjustment of their coupling with propagative modes. In this talk, surface addressable (or above the light line) Bloch modes in photonic crystal membranes (PCMs) will be investigated. The concepts governing the properties of these modes will be first presented. It will be demonstrated that simple models can be considered to understand their behavior and, more specifically, their ability to capture photons during the desired lifetime. Bloch modes with a very large band witdth or a very high Q factor can be easily designed this way. The wide application range of these PCMs will be illustrated by different devices. Low Q Bloch modes will be first used as efficient and broadband reflectors and exploited to realize compact and efficient vertical cavity lasers with unprecedented functionalities. In addition, it will be shown that these kind of mirrors can be bent in order to confine photons in the 3 directions even in low index materials, opening the way to a new kind of emitters and sensors. Finally, the exploitation of high Q Bloch modes to design highly directional thermal emitters with wavelength selectivity will be presented.

8993-23, Session 4

Funneling of light in combinations of metal-insulator-metal resonators *(Invited Paper)*

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

Array of metal-insulator-metal (MIM) resonators are known to exhibit spectrally tunable, and angularly independent total absorption in strongly subwavelength volume [1,2]. Such nano-antennas are promising candidates in various applications like bio-chemical sensing, solar cells design, and photodetection.

Here, we experimentally demonstrate the total extinction of the reflectivity for a transverse magnetic polarized wave on a gold surface etched by both narrow 150 nm and deep 2 microns grooves. We also evidence the incidence-invariance of their spectral response, which undoubtedly shows the localized nature of the resonances [1]. We also unveil the funneling mechanism on these grooves which is namely responsible for the redirection and subsequent concentration of the incident energy flow from the surface toward the apertures of the MIM antenna. Then, we show both theoretically and experimentally that MIM resonators can be combined within the same subwavelength period and still behave independently. This permits to conceive surface with customizable absorption, which can for instance be used in dual band absorber or in omnidirectional wideband absorber [3]. An energetic analysis can also be applied on these more complex antennas geometries, which highlights a sorting effect: at each resonance wavelength, the photons are funneled towards the apertures of the corresponding MIM cavity. Eventually, we will address the issue of the number of antennas which can be combined into a subwavelength period.

[1] F. Pardo et al., Physical Review Letters, 2011

[2] P. Bouchon et al., Applied Physics Letters, 2011

[3] P. Bouchon et al., Optics Letters, 2012

8993-24, Session 4

Design and applications of flexible photonic membranes

Peter J. Reader-Harris, Blair C. Kirkpatrick, Andrea Di Falco, Univ. of St. Andrews (United Kingdom)

We present our recent results regarding the realization and characterization of photonic membranes on flexible substrates at visible wavelengths. The method consists of creating metamaterials and nanoplasmonic circuitry on flexible substrates, typically made of polymer. Here we explain the fabrication procedure and discuss the electromagnetic response for different plasmonic structures, including nano-antennas, fishnet geometries, and metasurfaces with response independent on polarization and angle of incidence. The advantage of this approach over rigid counterparts is twofold.

On one hand the photonic membranes can be transferred on different targets with irregular shapes. This allows decoupling the fabrication steps from the complexity of the topology of the target. Specific results are discussed in the framework of lab-on-fiber, where the photonic membranes are wrapped on the tip of a fiber. Potential applications include spectral filtering, field enhancement and imaging, depending on the chosen topology/pattern/meta-atom. A particularly interesting example on which we focus is a method to obtain sharp spectral features using a metallic nanowire array, which acts as a guided mode resonance filter with an additional Fano resonance. This circumvents the limitations of the spectral linewidth in metal filters due to losses setting an upper bound on the Q for metallic resonances.

The other advantage is that the photonic response can be tuned by changing the shape of the membranes after fabrication, e.g. via tailored

bending and stretching. Here we present the characterization of the opto-mechanical response of ultra-thin photonic membranes, discussing the physics involved, the details and the requirements of the optical setup.

8993-25, Session 4

Multilayer hole-mask colloidal nanolithography for large-area low-cost complex plasmonics

Jun Zhao, Univ. Stuttgart (Germany); Sarah Jaber, Paul Mulvaney, The Univ. of Melbourne (Australia); Harald W. Giessen, Univ. Stuttgart (Germany)

Plasmonic nanostructures are tremendously important for applications in the visible and near-IR range. The various applications include surface enhanced Raman spectroscopy (SERS), surface enhanced infrared absorption (SEIRA) spectroscopy, and plasmon sensors for liquids and gases. Recently, chiral plasmonic structures have become very attractive in analytical chemistry for enantionmer sensing. Chirality in stereochemistry means that a molecule has a left- and a right-handed version, which are called enantiomers. It is impossible to distinguish enantiomers by structural analysis, as they possess the same chemical and physical properties. The only one feature where they are different is their interaction with other chiral entities, in particular circularly polarized light. However, the chiral interaction of such molecules with electromagnetic radiation is extremely weak. One possible pathway is using plasmonic chiral structures to enhance the optical signal. It is highly desirable to fabricate large-area 3D chiral plasmonic structures in the nanometer size range, using a low-cost, fast, and easy technique.

Here we introduce such a method for different complex plasmonic nanostructures with different shapes over 1 cm2 of defect-free areas, namely multilayer hole-mask colloidal nanolithography followed by tilted angle metal evaporation. We utilize repetitive hole-mask colloidal lithography with sparsely distributed polystyrene beads. Multiple lithography leads to neat multishaped structures such as 3D chiral structures in C3 symmetry. Additionally, our manufacturing method is feasible to create polarization-independent split-ring metamaterials, broadband or multi-peak infrared antennas for SEIRA spectroscopy, as well as nanostructures with simultaneous SERS and SEIRA enhancement in the visible and near-IR range. Furthermore, large-area bi-metallic plasmonic structures show great potential for optical gas sensing as well as for hybrid chiral nonreciprocal devices.

8993-26, Session 4

Infrared near-field imaging and spectroscopy with broadband sources *(Invited Paper)*

Yannick De Wilde, Institut Langevin (France)

Scattering type near-field scanning optical microscopy (s-NSOM) can typically measure super-resolved images of the sample at a single wavelength. To generalize the concept, we have developed a versatile infrared s-NSOM which operates with broadband sources, allowing one to perform imaging and Fourier transform infrared (FTIR) spectroscopy in the near-field. Two configurations will be discussed in our presentation.

The first one, is based on the thermal emission produced by the sample itself, which is scattered in the near-field with a tip, in a configuration called thermal radiation scanning optical microscopy (TRSTM). We have recorded images and FTIR spectra of materials which support surface phonon polaritons. We show that the TRSTM probes both the spatial and frequency dependence of the electromagnetic local density of states (LDOS), and that the thermal emission is in this case quasi-monochromatic in the near-field, in striking contrast with blackbody-like far-field thermal emission spectra.

The second configuration utilizes the high brightness infrared source of the synchrotron SOLEIL, which is focused on the scattering tip while it scans the surface of the sample, or when a FTIR spectrum is recorded at a fixed position. As an external source is used here, the scattered signal probes the dielectric properties of the material trough the effective scattering cross section of the tip coupled with its image in the sample.

Work performed in collaboration F. Peragut (Institut Langevin), K. Joulain (Institut P'), J.-J. Greffet (Laboratoire Charles Fabry-IOGS), P.-O. Chapuis (Centre de thermique de Lyon), P. Roy (SOLEIL), J.-B. Brubach (SOLEIL).

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8993-2,

Massively-parallel intracavity trace molecular detection in the mid-infrared using broadband frequency combs *(Keynote Presentation)*

Konstantin L Vodopyanov, CREOL, College of Optics and Photonics, University of Central Florida (United States)

We generate ultra-broadband mid-IR frequency combs suitable for coherent Fourier transform spectroscopy using synchronously pumped optical parametric oscillators (OPOs) based on either periodically poled lithium niobate (PPLN) with a femtosecond Er-doped fiber laser as pump, or an orientation-patterned GaAs pumped by a Tm-doped fiber laser. Both OPOs operate near degeneracy to obtain the broadest bandwidth, which reached more than one octave (2.5-6.1 μm) in the case of Tm-fiber-pumped GaAs OPO. Intracavity spectroscopy of methane, isotopic carbon dioxide (13CO2), carbon monoxide, formaldehyde, ethylene and acetylene was performed by injecting trace amounts of gas directly into the OPO enclosure, or by using an intra-cavity gas cell with a volume ~30 cm3. Ro-vibrational absorption mid-IR spectra were measured in the Fourier domain with massive parallelism of data acquisition. We were able to detect several molecules simultaneously in a mixture and observed significant effective path length enhancement due to the intracavity effect. Detection limits in the ppb-range were demonstrated.

8993-27, Session 5

Room-temperature operation of far-infrared QCLs ([lambda] = 19-21 um) *(Invited Paper)*

Michael Bahriz, Guillaume Lollia, Alexei N. Baranov, Roland Teissier, Univ. Montpellier 2 (France)

InAs/AlSb quantum cascade lasers, which already proved their interest for short wavelength mid-IR lasers emitting around 3 μm, are also promising for the development of long wavelength lasers due to the small electron effective mass in InAs. InAs-based QCLs emitting up to 14 μm have been previously reported. Recently we demonstrated QCLs made of InAs operating near 21μm. Lower threshold current densities of these lasers, compared to GaAs and InGaAs lasers, confirmed the expected stronger optical gain of intersubband transitions in InAs-based QCLs. In this contribution, we present further studies of these devices with improved fabrication and quantum design.

We have studied different bonding techniques on a host InAs substrate and different metal layers for the metal-metal waveguide of these devices. Different design schemes based on vertical or slightly diagonal intersubband transitions have also been studied. Lasers emitting in the range of 19-21 μm have been characterized as a function of temperature and cavity length. An active region based on a four well vertical transition design demonstrated record threshold current densities, down to 0.65

kA/cm? at 80 K, and maximal operation temperatures of 291 K. The analysis of these results reveals the very large intersubband gain in the InAs-based QCLs and strong influence of the free carrier absorption on device performances.

The fabricated InAs/AlSb lasers outperform other QCLs operating in the wavelength range around 20 µm. These results confirm the great potential of this material system for QCLs operating in the far infrared.

8993-28, Session 5

Spectroscopy studies of strain-compensated mid-infrared QCL active regions on misoriented substrates

Justin S. Grayer, Charles R. Meyer II, Emily Cheng, Gregory E. Triplett, Denzil Roberts, Univ. of Missouri-Columbia (United States); Peter G. Schunemann, BAE Systems (United States)

In this work, we perform spectroscopic studies of AlGaAs/InGaAs quantum cascade laser structures that demonstrate frequency mixing using strain-compensated active regions. Using a three-quantum well design based on diagonal transitions, we incorporate strain in the active region using single and double well configurations on various surface planes (100) and (111). We observe the influence of piezoelectric properties in molecular beam epitaxy grown structures, where the addition of indium increases the band bending in between injector regions and demonstrates a strong dependence on process conditions that include sample preparation, deposition rates, mole fraction, and enhanced surface diffusion lengths. We produced mid-infrared structures under identical deposition conditions that differentiate the role of indium(strain) in intracavity frequency mixing and show evidence that this design can potentially be implemented using other material systems.

8993-29, Session 5

Polarization and isolation control for quantum cascade lasers in the mid-infrared

Sheng Wu, California Institute of Technology (United States) and Power Environmental Energy Research Institute (United States); Andrei Deev, California Institute of Technology (United States)

Control of polarization and isolation of the laser from feedback are of vital importance for many applications of lasers, especially in spectroscopy and communication. As a high gain laser source, Quantum Cascade lasers are especially susceptible to external feedback. However, currently there are very limited number of optical materials that are suitable for the control of polarization and consequently isolation in the mid-Infrared (MIR). Therefore, polarization control and isolation are quite challenging in the mid-Infrared.

We discuss the techniques we used in the MIR spectroscopy with quantum cascade lasers, and realize the control of polarization and isolation of the laser from feedback. Waveplates made of MgF_2 and Rutile will be discussed. We also compare the different degree of isolation achieved with different polarizors, i.e. Rutile, Holographic Wire Grid, and nanoparticle linear film polarizors.

We then show that we could use the isolation to improve the signal to noise ratios of our Hollow Waveguide (HWG) based spectroscopy platform. We also demonstrate saturated absorption spectroscopy inside HWG with the isolation realized by the waveplate and polarizors.

8993-30, Session 5

Spatial mode filtering of mid-infrared (mid-IR) laser beams with hollow core fiber optics

Jason M. Kriesel, Gina M. Hagglund, Nahum Gat, Opto Knowledge Systems, Inc. (United States); Vincenzo Spagnolo, Politecnico di Bari (Italy); Pietro Patimisco, Univ. degli Studi di Bari (Italy)

We describe measurements characterizing spatial mode filtering of Mid-Infrared (Mid-IR) laser beams using hollow core fiber optics. Mid-IR lasers operating in the wavelength range from λ = 3 µm to 14 µm, such as quantum cascade, interband cascade, and CO_2 lasers, are extremely useful for a range of molecular spectroscopy, remote sensing, and counter measure applications. For some applications it is highly desirable to have a single spatial mode (e.g., Gaussian beam profile), which can enable such benefits as higher signal-to-noise, lower beam divergence, and diffraction limited performance. However, beams exiting commercial Mid-IR lasers are often multi-mode; for example, QC lasers typically emit elliptical shaped beams rather than circularly symmetric beams. In several prior studies, hollow core fibers (i.e., hollow waveguides) with bore sizes as large as 30 times the wavelength have been shown to provide a convenient relatively low-loss means of delivering Mid-IR beams with a single spatial mode. This single mode behavior is essentially accomplished by the preferential damping of higher order modes. In this paper, we present a systematic study of the mode filtering capabilities of hollow fibers over a range of bore sizes, fiber lengths, fiber bend radii, laser mode quality, and laser wavelengths. These measurements are interpreted with calculations based on waveguide theory. The primary result is a determination of the needed parameters to effectively mode filter a given Mid-IR laser beam using a hollow core fiber optic cable. In addition, we also demonstrate the utility of mode-filtering with a specific example of reduced noise in high sensitivity trace gas analysis.

8993-31, Session 6

Infrared photodetector development at Fraunhofer IAF *(Invited Paper)*

Frank Rutz, Philipp Kleinow, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); Martin Walther, Fraunhofer-IAF (Germany); Rolf Aidam, Wolfgang Bronner, Lutz Kirste, Jasmin Niemasz, Robert Rehm, Johannes Schmitz, Tim Stadelmann, Matthias Wauro, Andreas Wörl, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); Alexander Sieck, Johann Ziegler, AIM INFRAROT-MODULE GmbH (Germany)

The Fraunhofer IAF can look back on many years of expertise in developing high-performance infrared photodetectors. Since pioneering the InAs/GaSb type-II superlattice detector development, extensive capabilities of epitaxy, process technology, and device characterization of single element detectors and camera arrays for the mid- and longwave infrared (MWIR & LWIR) have been established up to the level of small-scale production. Bispectral MWIR/MWIR and MWIR/LWIR cameras based on type-II superlattices or HgCdTe are specialities of the IAF. Moreover, the development of InGaAs-based short-wave infrared (SWIR) photodetectors for low-light-level applications has recently been initiated.

In this contribution, we report on the status of current photodetector development activities at IAF, covering detector design, epitaxial growth, process technology, and most recent electro-optical characterization results of focal plane arrays as well as single element detectors for the LWIR, MWIR, and SWIR.

8993-32, Session 6

Impact of Be-doping on InAs/InAsSb type-II superlattices for infrared detection

Elizabeth H. Steenbergen, Air Force Research Lab. (United States); Said Elhamri, T. J. Asel, Univ. of Dayton (United States); Gail J. Brown, Air Force Research Lab. (United States)

InAs/InAsSb superlattices (SLs) are promising materials for mid- and long-wavelength infrared (MWIR, LWIR) photodetectors due to the recently reported longer carrier lifetime than those of InAs/GaSb SLs at 77 K. However, the lifetime results are for unintentionally-doped n-type InAs/InAsSb SLs. Photodetectors with n-type absorbing regions rely on hole minority carrier transport to generate the current. This can be a disadvantage in SL photodiodes where the hole mobility in the vertical direction is extremely small at low temperatures, making collection of photo-generated minority carriers at varying depths difficult. Therefore, p-type SL absorber materials are preferred. However, if there is a high density of trap states or recombination sites due to the intentional dopants that limit the electron recombination lifetime, a longer hole lifetime that is traded for a higher electron mobility may result in a negative effect on the overall electrical properties, depending upon the magnitude of the lifetime and mobility changes. The carrier lifetimes and material properties of p-type InAs/InAsSb SLs have not been investigated yet and represent a crucial next step in developing the material for detectors. A systematic study of the impact of varying Be-dopant density levels on the InAs/InAsSb SL optical and electrical properties is performed using photoluminescence, photoconductive response, and Hall measurements.

8993-33, Session 6

Minority carrier lifetime studies of narrow bandgap antimonide superlattices

Linda Hoglund, David Z. Ting, Arezou Khoshakhlagh, Alexander Soibel, Cory J. Hill, Anita M. Fisher, Sam A. Keo, Sarath D. Gunapala, Jet Propulsion Lab. (United States)

The lifetime of minority carriers is a key parameter that defines both the dark current and quantum efficiency of photodetectors. Achievement of a long lifetime material is an important task for superlattice detector development that will advance the current state-of-the-art technology and will enable high performing detectors and FPAs. In this work, we have used the optical modulation response technique to investigate the minority carrier lifetimes in several narrow bandgap antimony based superlattices. The influence of different recombination processes, such as Shockley Read Hall, radiative and Auger recombination, respectively, was observed by studying the temperature dependence and the power dependence of the lifetime. Radiative and Shockley Read Hall recombination both influence the lifetimes of the studied superlattices, while the contribution from Auger recombination is negligible. These studies give an enhanced understanding in which parameters are currently limiting the detector performance of superlattice detectors and provide important information on how to improve future antimony based superlattice detectors.

8993-34, Session 6

Analysis of electrical and electro-optical characteristics of midwave infrared InAs/GaSb SL pin photodiodes

Marie Delmas, Rachid Taalat, Jean-Baptiste Rodriguez, Philippe Christol, Institut d'Electronique du Sud (France); Edouard Giard, Isabelle Ribet-Mohamed, ONERA (France); Julien Imbert, ONERA (France) and III-V Lab. (France); Sophie Derelle, ONERA (France); Virginie Trinite, III-V Lab. (France)

Important progresses have been obtained the last past years on the performances of mid-wavelength infrared (MWIR) InAs/GaSb superlattice (SL) photodiodes. These improvements were obtained by the use of particular device designs using barrier structures, neither by the choice of the SL period while the SL period composition governs the properties of the active zone material.

In this communication, we examine the influence of the SL period composition and thickness on the material and device properties of MWIR SL pin photodiodes. By using band gap flexibility of InAs/GaSb SL structure, several devices with different SL period thicknesses and compositions, but the same cut-off wavelength at 5 µm at 77K, were grown by molecular beam epitaxy on p-type GaSb substrates.

Optical and electrical characterizations (photoluminescence, absorption, current-voltage, capacitance-voltage, noise and photoresponse measurements) were performed and analyzed thanks band structure calculations and device modelling. The various results presented in this work demonstrate that the choice of the SL period composition and thickness has a very strong influence on the residual doping concentration, the dark current density, the shape of the spectral response, the quantum efficiency, and then on the performances of SL pin photodiode.

8993-36, Session 7

Quantum-engineered interband cascade photovoltaic devices *(Invited Paper)*

Rui Q. Yang, Hossein Lotfi, Lu Li, Robert T. Hinkey, Hao Ye, The Univ. of Oklahoma (United States); J. F. Klem, Sandia National Labs. (United States); L. Lei, T. D. Mishima, J. C. Keay, M. B. Santos, M. B. Johnson, The Univ. of Oklahoma (United States)

Quantum-engineered multiple stage photovoltaic (PV) devices are explored based on InAs/GaSb/AlSb interband cascade (IC) structures. These ICPV devices employ multiple discrete absorbers that are connected in series by wide-bandgap unipolar barriers using type-II heterostructure interfaces for facilitating carrier transport between cascade stages similar to IC lasers. The discrete architecture is beneficial for improving the collection efficiency and for spectral splitting by utilizing absorbers with different bandgaps. As such, the photo-voltages from each individual cascade stage in an ICPV device add together, creating a high overall open-circuit voltage, similar to multi-junction tandem solar cells. Furthermore, photo-generated carriers can be collected with nearly 100% efficiency in each stage. This is because the carriers travel over only a single cascade stage, designed to be shorter than a typical diffusion length. Here, we will present our recent progress in the study of ICPV devices, which includes the demonstration of ICPV devices at room temperature and above with narrow bandgaps (e.g. 0.23 eV) and high open-circuit voltages.

8993-37, Session 7

Recent development on the uncooled mid-infrared PbSe detectors with high detectivity *(Invited Paper)*

Binbin Weng, Jijun Qiu, Lihua Zhao, Zijian Yuan, Caleb Y. Chang, Zhisheng Shi, The Univ. of Oklahoma (United States)

To date, uncooled, low-cost Pb-salt (PbS and PbSe) photoconductive (PC) detectors remain the choice for many sensing applications in the 1-5 µm mid-IR spectral range. For nearly a century, oxygen has been widely accepted as the key element that triggers photo-response in polycrystalline PbSe photoconductive detectors. Our photoluminescence

(PL) and responsivity studies on PbSe samples, however, suggest that oxygen only serves as an effective sensitization improver and it is iodine rather than oxygen that plays the key role in triggering the photo-response. These studies shed light on the sensitization process for detector applications and ways to passivate defects in IV-VI semiconductors. As a result, a record high peak detectivity of 4.2?1010 cm•Hz1/2•W-1 was achieved at room temperature.

In this paper, we propose a charge-separation-junction (CSJ) model to explain the mechanism of PC Pb-salt detector. Such mechanism leads to carrier lifetime that is longer than theoretical value and thus high detectivity. Recent development on a low-cost fabrication of photovoltaic (PV) Pb-salt detector will also be discussed. Preliminary current-voltage curve is very encouraging. If successful, this could be a revolutionary development for mid-/far IR sensing and imaging applications. A low-cost, large-format detector focal plane array (FPA) with high detectivity that has been long desired but unattainable could become a reality.

8993-38, Session 7

Backside-configured surface plasmonic structure for infrared photodetector for enhancement

Guiru Gu, Xuejun Lu, Univ. of Massachusetts Lowell (United States)

A backside-configured surface plasmonic structure is reported for quantum dot (QD) infrared photodetector (QDIP) enhancement. The QDIP enhancement by the backside-configure plasmonic structure is compared with that by the top-configured plasmonic structure. The mechanism of the higher enhancement is analyzed by experimentally measuring the amplitude and phase of the front and backside plasmonic excitation. The experiment results agree well with the numerical simulation.

8993-39, Session 7

InSb photodetectors with PIN and nBn designs

Axel Evirgen, Johan Abautret, Institut d'Electronique du Sud (France) and SOFRADIR (France); Jean-Philippe Perez, Hocine Aït-Kaci, Philippe Christol, Institut d'Electronique du Sud (France); Joel Fleury, Sagem Défense Sécurité (France); Hervé Sik, Sagem SA (France); Alexandru Nedelcu, Romain Cluzel, Arnaud Cordat, SOFRADIR (France)

The InSb is the historical and always the emblematic material for high-speed photodetectors operating in the midwave infrared (MWIR) detection range (2-5µm). High performance InSb Focal Plane Arrays (FPAs) made of ion-implanted planar diodes are commercially available but their performances are strongly degraded for temperature operation over 80K.

To improve temperature operation of InSb MWIR photodetectors, two kinds of structures, with pin and nBn designs, were fabricated by MBE on n-type InSb substrate. Capacitance-voltage measurements performed on processed Epi-InSb pin mesa diodes revealed a background carrier concentration in the nid region ranging from 8E14 cm-3 to 1E15 cm-3 at 77K. Zero-bias resistance area product R0A, extracted from current-voltage measurements at 77K, as high as 106 ?.cm2 and dark current densities as low as 20 nA.cm-2 at -50 mV, two decades lower than standard ion-implanted planar diode, were measured. These values are among the best reported for photodiodes having cut-off wavelength around 5.5µm at 77K and highlight the potentiality of high quality MBE grown InSb structure as HOT detector.

Next, unipolar nBn InSb/InAlSb/InSb detectors were designed and fabricated. The first electrical characterizations have shown suppression of generation-recombination dark current mechanisms leading to significant performance improvement compared to usual pin photodiodes.

8993-40, Session 7

Design, fabrication, and characterization of InSb avalanche photodiode

Johan Abautret, Axel Evirgen, Institut d'Electronique du Sud (France) and SOFRADIR (France); Jean-Philippe Perez, Philippe Christol, Institut d'Electronique du Sud (France); Anne Rouvier, Romain Cluzel, Arnaud Cordat, SOFRADIR (France); Johan Rothman, CEA-LETI-Minatec (France)

Nowadays, an important effort concerns the improvement of midwave infrared (MWIR) photodetectors in order to satisfy the SWaP (Size, Weight and Power) criteria for passive or active infrared imaging applications. In particular, for scene with very low flux of infrared photons, high speed and sensitive infrared avalanche photodiodes (APDs) are required, motivating important research activities.

In the MWIR spectral range, best results were obtained by HgCdTe e-APDs with a gain record value higher than 5000 at V= -12.5V without additional noise. A promising alternative of HgCdTe MWIR APD could be the use of InSb material with a band structure that seems to be favorable for the fabrication of single-carrier multiplication APD initiated only by electrons (SCM e-APD).

With the assumption of multiplication only induced by electrons, an optimized separated absorption and multiplication (SAM) InSb avalanche photodiode (APD) structure was defined by theoretically studying both the absorber doping level and the multiplication layer thickness. Calculated gain value higher than 10 was achieved at V = -4.5V. Then, the SAM structure was fabricated by MBE on n-type InSb substrate. Electrical characterizations were made on mesa processed APD, in dark conditions and under illumination at 77K. The first results obtained show the potentiality of InSb material as APD device.

8993-41, Session 7

Antenna-coupled microcavity-enhanced quantum well infrared photodetector *(Invited Paper)*

Yanko Todorov, Yuk-Nga Chen, Benjamin Askenazi, Angela Vasanelli, Univ. Paris 7-Denis Diderot (France); Giorgio Biasiol, Lab. Nazionale TASC (Italy); Raffaele Colombelli, Institut d'Électronique Fondamentale (France); Carlo Sirtori, Univ. Paris 7-Denis Diderot (France)

I will report on our experimental investigations on antenna-coupled QWIP structures. The structures that we employ are inspired from our recent research on the ultra-strong light-matter coupling regime and consist of electrically connected double-metal patch antennas. These plasmonic antennas not only collect photons from the free space, but also act as microcavities where photodetection takes place. We have indeed observed that the photo-response of the device is strongly enhanced when the microcavity becomes resonant with the intersubband resonance.

However, our investigation shows that this design not only allows to increases the coupling of incident photons, but also brings an improvement on the intrinsic detector performances, such as the BLIP (Background-Limited Infrared Performance) temperature. Indeed, this design has the particularity that photons are absorbed in an effective area much smaller than the illuminated spot size. As the detector dark current is proportional to the device area, in our design the dark current

is reduced as comparison to the photo-generated current. This reduction has a direct impact on the BLIP temperature that rises from 72 K for conventional QWIP operating at 9 µm, to 86 K. These results therefore illustrate how the concept of antenna-coupled microcavity can be applied successfully to enhance the performances of infrared opto-electronic devices.

8993-42, Session 8

Mid-IR heterogeneous silicon photonics *(Invited Paper)*

Gunther Roelkens, Utsav Dave, Alban Gassenq, Nannicha Hattasan, Chen Hu, Bart Kuyken, Francois Leo, Aditya Malik, Muhammad Muneeb, Eva Ryckeboer, Sarah Uvin, Zeger Hens, Roel Baets, Univ. Gent (Belgium); Yosuke Shimura, Federica Gencarelli, Benjamin Vincent, Roger Loo, Joris Van Campenhout, IMEC (Belgium); Laurent Cerutti, Jean-Baptiste Rodriguez, Eric Tournie, Institut d'Electronique du Sud, CNRS, Univ. Montpellier 2 (France); Xia Chen, Milos Nedeljkovic, Goran Mashanovich, Li Shen, Noel Healy, Anna C. Peacock, Optoelectronics Research Ctr., Univ. of Southampton (United Kingdom); Xiaoping Liu, Richard Osgood, Columbia Univ. (United States); William M. J. Green, IBM Thomas J. Watson Research Ctr. (United States)

In this paper we present our recent work on mid-infrared photonic integrated circuits for spectroscopic sensing applications. We discuss the use of silicon-based photonic integrated circuits (either based on silicon-on-insulator or germanium-on-silicon waveguide circuits) for this purpose and detail how a variety of optical functions in the mid-infrared besides passive waveguiding and filtering can be realized, either relying on nonlinear optics or on the integration of other materials such as GaSb-based compound semiconductors, GeSn epitaxy and PbS colloidal nanoparticles. The integration of photodetectors resulting in fully integrated mid-IR spectrometers, semiconductor laser sources and nonlinear optics based spectral translators between the telecommunication wavelength range and the mid-infrared are discussed.

8993-43, Session 8

Advances toward monolithic broadly-tunable QCL sources *(Invited Paper)*

Mathieu Carras, Grégory Maisons, Bouzid Simozrag, Virginie Trinite, III-V Lab. (France); Mickael Brun, Pierre R. Labeye, Sergio Nicoletti, CEA-LETI-Minatec (France); Fahem Boulila, III-V Lab. (France); Luis Jorge Orbe Nava, Guillermo Carpintero del Barrio, Univ. Carlos III de Madrid (Spain)

The need for broadly tunable sources for Mid-Infrared spectroscopy has been identified for years. In order to detect complex molecules or a set of simple molecules, one needs a source with a small line width and tunable over a few tens of wave numbers. In order to achieve the realization of monolithic broadly tunable sources, III-V Lab together with LETI and UC3M has developed different approaches, all based on the use of multiplexed distributed feedback quantum cascade laser arrays on InP. We will focus on two different schemes: one using Silicon based 'arrayed waveguides' (AWG) and heterogeneous butt coupling for the combination of the QCL array, and the other one using evanescent coupling on InP/InGaAs passive waveguide and 'Echelle grating' for the combination.
In particular, we present the first realization of a hybrid tunable source around 4.5µm covering 2180 cm-1 to 2280cm-1. We will show realization of laser arrays at various wavelengths (from the 4.5µm region to the 9.5µm region) and compare the different technologies using, or not, iron doped InP for thermal management. We also show the realization of a coupled laser on InP to a passive InGaAs waveguide. We will compare the performances/characteristics of the' Echelle gratings' and AWG approaches in a product oriented way. We will show that all building blocks have been demonstrated towards the fabrication of the monolithic source.

8993-44, Session 8

DFB interband cascade lasers for tunable laser absorption spectroscopy from 3 to 6 µm *(Invited Paper)*

Michael von Edlinger, Julian Scheuermann, Lars Naehle, Christian Zimmermann, Lars Hildebrandt, Marc Fischer, Johannes Koeth, nanoplus GmbH (Germany); Robert Weih, Sven Höfling, Martin Kamp, Julius-Maximilians-Univ. Würzburg (Germany)

Tunable Laser Absorption Spectroscopy (TLAS) in the mid-infrared wavelength range, is of great interest for high accuracy gas sensing applications, since it bears significant advantages over other techniques, including high-speed measurement and ruggedness of the sensor. Many technologically and industrially relevant gas species have their strongest absorption features in this spectral region, especially between 3 and 6 µm. These include, e. g., important hydrocarbons like methane or propane, as well as nitric oxide and formaldehyde.

Interband Cascade Lasers (ICL) can provide monomode continuous wave (cw) emission above room temperature in this wavelength range. Being in some ways a hybrid technology between the interband-transition diode laser and the intersubband-transition quantum cascade laser, this approach combines high efficiency through cascading of optically active areas with uncomplicated adjustment of the emission wavelength while maintaining low operating voltages.

We present the simulation, design and manufacturing of application-grade distributed feedback (DFB) laser devices based on the ICL concept. Etched sidewall gratings defined by electron-beam lithography were chosen as wavelength selective elements in this work. Combined Si_3N_4 and SiO_2 passivation layers and thick gold electroplating provided efficient heat removal. The fabricated devices successfully target specific, technologically relevant, wavelengths in the spectral region from 3 to 6 µm. High Side Mode Suppression Ratios around 30 dB and tuning ranges up to 13 nm were achieved with output powers above 5 mW and low energy consumption in cw operation above room temperature. The presented results point out the high potential of DFB ICLs for the use in TLAS.

8993-45, Session 8

High-performance single-spatial mode GaSb type-I laser diodes around 2.1 µm

Augustinas Vizbaras, Edgaras Dvinelis, Mindaugas Greibus, Augustinas Trinkunas, Deividas Kovalenkovas, Ieva ?imonyte, Kristijonas Vizbaras, Brolis Semiconductors UAB (Lithuania)

Mid-infrared spectral region (2-4 µm) is gaining significant attention recently due to the presence of numerous enabling applications in the field of gas sensing, medical, environmental and defense applications. Major requirement for these applications is the availability of laser sources in this spectral window. Type-I GaSb-based laser diodes are ideal candidates for these applications being compact, electrically pumped, power efficient and able to operate at room temperature in continuous-wave. Moreover, due to the nature of type-I transition, these devices have a characteristic low operation voltage, typically below 1 V, resulting in low power consumption, and high-temperature of operation.

In this work, we present recent progress of 2.1 µm wavelength single-spatial mode GaSb type-I laser diode development at Brolis Semiconductors. Experimental device structures were grown by solid-source multi-wafer MBE, consisting of an active region with 2

compressively strained (~1.3 %) GaInAsSb quantum wells. Epi-wafers were processed into a narrow-ridge (2-4 μm) devices and mounted p-side up on CuW heatsink. Devices exhibited very low CW threshold powers of < 50 mW, and single spatial mode (TE00) operation with room-temperature output powers up to 200 mW in CW mode with a far-field fast axis divergence angle of ~ 57 degrees.

8993-46, Session 8

Highly-efficient single-mode broadband infrared light source based on PbS quantum dot composites

Kai Shen, Guomin Jiang, Younghun Paik, Sung Jin Kim, Michael R. Wang, Univ. of Miami (United States)

We present that highly efficient single-mode broadband infrared light source can be fabricated by PbS quantum dot composites with a vacuum assisted micro-fluidic fabrication technique. The infrared-emitting colloidal PbS quantum dots (QDs) have been successfully synthesized in Ar atmosphere by one-step reaction method. The sizes and optical properties can be tuned by adjusting the reaction time and temperature in order to satisfy different requirements. Quantum dot composites can be formed by incorporating high density PbS-SU-8 thinner solution in a host SU-8 photoresist which acts as protecting and maintaining QDs. By a novel vacuum assisted micro-fluidic fabrication technique, we flow this composites in a prepared Polydimethylsiloxane (PDMS) mold and cure them by UV light to fabricate the single-mold waveguide light source. Then we make a silver coating on the walls of the waveguide, which can enhance the light confinement in the waveguide. The highly efficient infrared waveguide output with broad spectral bandwidth and single-mode profile will be presented. As a competitive candidate of broadband light source, our method would provide wider bandwidth than superluminescence diodes (SLD) and much lower cost than supercontinuum (SC) sources as well as some tunability, benefitting telecommunications, biological imaging and many other fields.

8993-4,

Microwave stabilization and modulation of quantum cascade lasers *(Keynote Presentation)*

Carlo Sirtori, Lab. Matériaux et Phénomènes Quantiques, Univ. Paris 7-Denis Diderot and CNRS (France)

Microwave links with the optical domain have been widely exploited in recent years for the coherent control of laser emission. In this presentation we will show how similar ideas can be used to control phase and frequency of quantum cascade (QC) lasers operating in the mid- and far-infrared (THz region)1. Our purpose is to apply concepts and techniques, imported from microwave photonics, to speed up the exploitation of these devices which have the potential for extremely wide modulation band, of several tens of GHz2,3. The merging of QC and microwave technologies will spark new ideas for system applications and motivate physical investigations of carrier dynamics in QC lasers. We will illustrate techniques that allow phase-locking of QC lasers to a harmonic of the repetition rate of a fs-fiber laser. We will also show that the beat note, arising from the beating of the longitudinal modes, can be locked to an injected microwave with a modulation frequency sufficiently close to that of the laser roundtrip4. In this case the QC laser enters in a regime of active mode-locking4.

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8993-47, Session 9

Surface plasmon waves for broadband THz spectroscopy *(Invited Paper)*

Oleg Mitrofanov, Univ. College London (United Kingdom); Miguel Navarro-Cia, Univ. College London (United Kingdom) and Imperial College London (United Kingdom); Raimund Mueckstein, Michele Natrella, Chris Graham, Cyril C. Renaud, Alwyn J. Seeds, Univ. College London (United Kingdom); Filip Dominec, Petr Kuzel, Academy of Sciences of the Czech Republic (Czech Republic); Jean-Christophe Delagnes, Patrick Mounaix, Univ. Bordeaux 1 (France)

Applications of broadband THz spectroscopy on the micrometer length-scale are limited due to weak coupling of the THz waves to small objects. This problem can be mitigated by using surface plasmon waves, which can be confined to deep-sub-wavelength volumes within the broad band of frequencies. Although the surface waves are non-radiative in nature, they can be excited on metallic discontinuities without the use of narrow-band periodic structures. Detection of THz surface waves can be realised with the integrated sub-wavelength aperture THz near-field probe, which allows mapping their spatial and temporal distributions. Using the integrated THz near-field probe, we will demonstrate how the interaction between the sub-wavelength object and THz field can be enhanced by coupling THz pulses to THz surface waves.

8993-48, Session 9

Subwavelength metallic waveguides as a universal tool for extreme confinement of THz surface waves *(Invited Paper)*

Juliette Mangeney, D. Gacemi, Ecole Normale Supérieure (France); Raffaele Colombelli, Aloyse Degiron, Institut d'Électronique Fondamentale (France)

Research on surface waves supported by metals at THz frequencies is experiencing a tremendous growth due to their potential for imaging, biological sensing and high-speed electronic circuits. However, their manipulation is challenging because these waves are poorly confined and weakly bound to the metal surface. In recent years, many design strategies have been introduced to achieve increased modal confinement, including patterned surfaces, coated waveguides and a variety of sub-wavelength geometries. Our study shows the existence of sub-wavelength confinement of THz surface waves in all known types of approaches has in fact the same origin, independent from the physical mechanisms that bind the waves to the metal surface: the reduction of the transverse size of the waveguide [1]. Using a combination of numerical simulations and time-resolved experiments [2], we provide a unified framework to understand the field confinement and demonstrate that extreme confinement down to [lambda]/100 at a wavelength of 300 um can be achieved. The existence of such a universal behavior offers a new perspective on energy confinement and should benefit future developments in THz science and technology.

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8993-49, Session 9

Terahertz near-field probe incorporating a [lambda]/100 aperture for time-domain spectroscopy and imaging

Alexander Macfaden, Univ. College London (United Kingdom); John L. Reno, Igal Brener, Sandia National Labs. (United States); Oleg Mitrofanov, Univ. College London (United Kingdom)

The strong dependence of detected signal strength on aperture size limits the spatial resolution obtainable by THz near-field microscopy techniques employing sub-wavelength apertures. For sub-wavelength apertures (size a) the transmission into the far-field is given by the Bethe dependence of a^3. However, by placing the antenna closer to the aperture, evanescent field components can be detected, allowing performance exceeding the a^3 dependence. A new design for near-field probe to detect terahertz radiation for time-domain spectroscopy is proposed and demonstrated.

By incorporating a distributed Bragg reflector between the antenna and the aperture, optical isolation and confinement superior to that of monolithic devices can be achieved, allowing smaller aperture-antenna separation. We demonstrate detection of a THz signal with 3, 5, and 10µm aperture probes of the new design. The 3µm aperture probe represents a spatial resolution of λ/100 at 1 THz.

The signal strength dependence on aperture size is shown to beat the Bethe dependence, and agree with FDTD simulations. These simulations show the benefit of building thinner devices, but also the requirement to design appropriate antenna geometry to capitalise on the near-field enhancement.

Imaging with the 5µm aperture probe of THz field confinement between two pointed needles separated by a small distance demonstrates further the requirement for thinner devices to image near-field phenomena. We will discuss strategies for reducing further the thickness of the device by optimising the device structure to increase optical confinement in the detection region, while also increasing optical isolation of the detector.

8993-50, Session 9

Ultrafast terahertz dynamics in bulk and nanostructured materials *(Invited Paper)*

Peter U. Jepsen, DTU Fotonik (Denmark); David G. Cooke, McGill Univ. (Canada); Krzysztof Iwaszczuk, Andrew C. Strikwerda, DTU Fotonik (Denmark); Pernille Klarskov Pedersen, Maksim Zalkovskij, Technical Univ. of Denmark (Denmark)

With photon energies in the meV range, electromagnetic radiation at THz frequencies interacts strongly with systems that have characteristic lifetimes in the picosecond range or energetic transitions in the meV range. Examples of such systems include bound electrical charges, free charge plasmas, strongly confined charge plasma, excitons, transient molecular dipoles, phonons in crystalline solids, weakly bonded molecular crystals, relaxational dynamics in aqueous liquids, and hydrated biological matter. Such low-energy interactions can be investigated with spectroscopy in the THz range.

Here we will discuss systems for generation of intense, ultrafast and ultrabroadband pulses of THz radiation and their application in investigations of ultrafast linear and nonlinear dynamics in bulk and nanostructured materials. Tilted pulse front excitation of $LiNbO_3$ generates intense, multi-µJ THz pulses with spectral coverage 0-2.5 THz, and two-color femtosecond air plasmas are used for generation of sub-µJ THz pulses with spectral coverage 1-30 THz.

We will discuss several investigations based on spectroscopy with these THz sources. Firstly, we have investigated the picosecond dynamics of excitons in CdSe nanorods, where we for the first time observe the ultrafast evolution of the 1s-2p internal transitions. Secondly, we investigate the picosecond photoconductivity dynamics of silicon nanoparticles in a glass matrix subsequent to femtosecond optical excitation, with emphasis on the temporal evolution of confinement of the carriers. Thirdly, the nonlinear optical properties of bulk chalcogenide glasses are investigated, with emphasis on the THz-induced Kerr effect. Finally, first investigations of extreme nonlinear optical properties of metallic structures will be discussed.

8993-51, Session 10

Development of bulk AlInAsSb for L/MWIR detector applications *(Invited Paper)*

Stefan P. Svensson, Wendy L. Sarney, Harry S. Hier, U.S. Army Research Lab. (United States); Ding Wang, Dimitri Donetsky, Gela Kipshidze, Leon Shterengas, Youxi Lin, Gregory Belenky, Stony Brook Univ. (United States)

HgCdTe has persisted as the preferred detector material for long wavelength infrared (LWIR) applications for half a century. Its direct bandgap and long minority carrier lifetimes make it a nearly ideal material. It is, however, an expensive technology due to difficult synthesis and the need for dedicated fabrication facilities. Until recently it was assumed that no direct-bandgap III-V compound existed that could absorb light in the entire LWIR band (8-12 micron). We have demonstrated that the bandgap bowing parameter of InAsSb is 0.87 eV, which is considerably larger than previously thought. We have reached photoluminescence wavelengths up to 11.7 micron in bulk InAsSb grown without detectable alloy ordering or strain effects.

Material of this type can be used in IR detector configurations with or without majority carrier blocking barrier layers. Larger bandgaps can be achieved in AlInAsSb, which can be lattice matched to LW InAsSb, albeit with a different Sb/As-ratio. This allows growth of midwave absorber material and/or electron barriers. Diodes with undoped electron barriers commonly exhibit a need for significant bias to overcome unintentional internal electric fields. These are assumed to arise due to unwanted modulation doping from the barrier layer. In order to understand this process we are studying AlInAsSb layers with Al contents from 0-50%. These layers are lattice matched to InAsSb with a bandgap corresponding to 10 micron absorption. The implication of these results for barrier devices (large Al-content) and multicolor devices (low Al-content) will be discussed.

8993-52, Session 10

Infrared material development at Army Research Lab *(Invited Paper)*

Priyalal S. Wijewarnasuriya, U.S. Army Research Lab. (United States)

No Abstract Available

8993-53, Session 10

GaSb-based photodetectors covering short-wave to long-wave IR grown by molecular beam epitaxy

Dmitri Lubyshev, Joel M. Fastenau, Yueming Qiu, Amy W. K. Liu, IQE Inc. (United States); Edwin J. Koerperick, Jon T. Olesberg, Dennis Norton Jr., ASL Analytical, Inc. (United States); Mark J.

Furlong, IQE IR (United Kingdom)

The GaSb-based family of materials and heterostructures provides rich bandgap engineering possibilities for a variety of infrared (IR) applications. Mid-wave and long-wave IR photodetectors are progressing toward commercial manufacturing applications, and growths on 4 inch diameter GaSb as well as 6-in diameter GaAs substrates have been demonstrated. In particular, nBn barrier-type photodetectors have attracted significant interest due to suppression of dark currents and a straight-forward, manufacturable structure design. Improved device performance can be achieved with a device architecture utilizing the 6.1 Å GaSb-base alloys such as InAsSb absorber layers with AlGaAsSb barrier layers, where the barrier material has appropriate band alignment with the absorber to eliminate any current blocking for photo generated carriers, thus reducing electron-related dark currents. Such photodetectors with InAsSb absorbers were demonstrated for cutoff wavelengths in the 4.2~7.0 µm range. Recently, InPSb-based alloy lattice-matched to GaSb has been evaluated as an nBn absorber material for SWIR applications in the 2.8~3.0 µm range. In this paper, we will report on the molecular beam epitaxial (MBE) growths of GaSb-based IR photodetector structures covering the short-wave to long wave IR spectral range. Material properties based on AFM, XRD, cross-section TEM and low temperature photoluminescence characterization will be presented, as well as electrical data from large-area mesa diodes. We will also discuss the feasibility of integrating a SWIR photodetector with similar GaSb-based mid- and long-infrared nBn devices on the same GaSb substrate.

8993-54, Session 10

Multi-wafer growth of GaInAs photodetectors on 4" InP by MOCVD for SWIR imaging applications

Mark J. Furlong, Mark Mattingley, Sung Wook Lim, Matthew Geen, Wynne Jones, IQE IR (United Kingdom)

Photodiodes based on the GaInAs/InP material system responding in the 1.3-1.7 µm wavelength range are of interest in a wide range of applications, from optical power and channel monitors in telecommunication systems through to advanced night vision imaging using large format focal plane type detectors for defence and security applications. Here we report on our results of GaInAs PIN photo detector structures grown on 2", 3" and 4" InP by low pressure Metalorganic Chemical Vapor Deposition (MOCVD) in both a standard (8 x 4") and new large volume format (12 x 2", 3" or 4") reactor configurations. High quality, lattice matched InP/GaInAs epitaxial layers were grown and we demonstrate that when moving from an 8 to 12 wafer configuration, high degrees of thickness uniformity (<3%, FTIR), lattice mismatch (<0.1%, XRD) and compositional uniformity (<2 nm, PL) can be maintained. The surface quality of epitaxial wafers will be assessed by various surface analytical techniques. We also make comparisons with the performance of 3" photodetector structures grown, this demonstrating that MOCVD production processes have been successfully scaled. We conclude by discussing the material requirements for large area infrared focal plane array photodetectors and describe how MOCVD growth technology will address industry's requirements for increasing device sizes with improved performance.

8993-55, Session 10

Growth and characterization of 6" InSb substrates for use in large area infrared imaging applications

Mark J. Furlong, IQE IR (United Kingdom); Gordon Dallas, Greg Meshew, J. Patrick Flint, IQE Inc. (United States); David Small, Rebecca J. Martinez, Andrew Mowbray, IQE IR (United Kingdom)

In this paper we report on an industry first; the commercial growth and characterization of 6" diameter InSb substrates that are suitable for use in the fabrication of MWIR focal plane infrared detectors. Results will be presented on the production of single crystal 6" InSb ingots grown by the Czochralski (LEC) technique, supported by the analysis of bulk material quality by X-ray diffraction (XRD). We will also assess the electrical quality of new 6" InSb crystals and present uniformity information on Hall mobility, resistivity and carrier level from which we will infer comparisons on the relative dark current performance of the material grown. High quality, epitaxy-ready type surfaces have been prepared and we will demonstrate how the key surface quality characteristics of roughness (< 0.5 nm rms), oxide thickness (<20 Å) and flatness (<7 µm TTV) have been maintained across production processes that scale 4" to 6" wafer formats. We conclude by presenting our road map for the development of large area InSb substrates and describe how developments in Czochralski crystal growth and surface finishing technology will support industry's requirements to deliver higher performance, large format IR focal plane array type devices.

8993-56, Session 10

Controlling the transport properties of magnetic devices with magneto-optics *(Invited Paper)*

Jean-Yves Bigot, Michele Albrecht, Mircea Vomir, Institut de Physique et Chimie des Matériaux de Strasbourg (France)

The transport properties of magnetic devices, such as their magneto-resistance, are strongly affected by the presence of magnetic domains and the associated Bloch or Néel domain walls which separate them. These walls generally appear spontaneously in a magnetic field and depend on the particular crystalline structure and shape of the magnetic material. Therefore, to modify the transport properties of such magnetic devices, it is desirable to control the domain walls. Two standard approaches are used: either modifying the shape of the active magnetic nanostructures or using an electric current to displace the walls. Here we propose an alternative way based on magneto-optics. We use laser pulses to pattern domains across ferromagnetic wires. The longitudinal resistivity changes when the domains are written. It is shown to increase linearly when the number of optically-written domains increases, as demonstrated with multi-layers CoPt wires. There are several advantages to this new approach. First, the domains walls can be induced optically in any structure without paying particular attention to the material shape and anisotropy (perpendicular or in plane domains). Second, the process of writing/erasing the domains is fully reversible, which is advantageous for realizing dynamical spin circuits. Third, the process relies on a local heating of the spins, which can be achieved either via an increase of the lattice temperature by using a CW laser or long pulses, or by using femtosecond optical pulses via a combined heating of the charges and spins. In the latter case, it opens the way to realizing.

8993-3,

Single-mode tunable quantum cascade lasers for radio-astronomy *(Keynote Presentation)*

Jérôme Faist, Keita Ohtani, Dana Turcinkova, Christopher B. Bonzon, Cristina Benea, Mattias Beck, Giacomo Scalari, ETH Zurich (Switzerland)

There is a great interest for single frequency, tunable terahertz sources for radio-astronomy. In this purpose, we report very low dissipation quantum cascade lasers operating using a third order grating distributed feedback. Milliwatt optical power level at 4.74THz with 55mA driving current have been achieved. Progress on devices containing monolithic extractor antennas as well as on three terminal tunable devices will also be reported.

8993-57, Session 12

Infrared hyperspectral standoff detection of explosives using external cavity QCL *(Invited Paper)*

Frank Fuchs, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Stefan Hugger, Jan-Philip Jarvis, Verena Blattmann, Quankui K. Yang, Ralf Ostendorf, Wolfgang Bronner, Rachid Driad, Rolf Aidam, Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

We report on imaging standoff detection of traces of explosives using broadly tunable quantum cascade lasers for backscattering spectroscopy. The technique relies on active laser illumination, synchronized with the collection of the backscattered radiation by a high performance infrared camera. We compare our technique with other IR-Laser based active standoff detection methods.

The key component of the IAF technique is an external cavity quantum cascade laser with a tuning range of 300 cm-1 that enables us to scan the illumination wavelength over several of the characteristic absorption features of a large number of different explosives using a single source. For the hyperspectral image analysis we combine an Adaptive Matched Subspace Detection (AMSD) algorithm with an Adaptive Target Generation Process (ATGP). This approach yields high detection performances while keeping the false alarm rates at low level.

We investigated traces of various explosives on different real-world target-materials. For medium distances (< 3 m) particles below 1 µg can be detected. For larger quantities we demonstrate detection distances exceeding to 25 m. The large tuning range of the laser proved to be crucial both for the ability to identify most of the relevant explosives as well as for reliable suppression of cross-sensitivity to other substances.

Due to their high spectral brightness, EC-QCLs are also ideally suited also for the spectroscopic detection of contaminants in water. We present results of an EC-QCL based measurement system providing sensitive detection of contaminants in water.

8993-58, Session 12

Chemical and explosive detections using photo-acoustic effect and quantum cascade lasers

Fow-Sen Choa, Univ. of Maryland, Baltimore County (United States)

Photoacoustic (PA) effect is a sensitive spectroscopic technique for chemical sensing. In recent years, with the development of quantum cascade lasers (QCLs), significant progress has been achieved for PA sensing applications. Using high-power, tunable mid-IR QCLs as laser sources, PA chemical sensor systems have demonstrated parts-per-trillion-level detection sensitivity. Many of these high sensitivity measurements were demonstrated locally in PA cells. Recently, we have demonstrated standoff PA detection of isopropanol vapor for more than 41 feet distance using a quantum cascade laser and a microphone with acoustic reflectors. We also further demonstrated solid phase TNT detections at a standoff distance of 8 feet. To further calibrate the detection sensitivity, we use nerve gas simulants that were generated and calibrated by a commercial vapor generator. Standoff detection of gas samples with calibrated concentration of 2.3 ppm was achieved at a detection distance of more than 2 feet. An extended detection distance up to 14 feet was observed for a higher gas concentration of 13.9 ppm. For field operations, array of microphones and microphone-reflector pairs can be utilized to achieve noise rejection and signal enhancement. We have experimentally demonstrated that the signal and noise spectra of the 4 microphone/4 reflector system with a combined SNR of 12.48 dB. For the 16-microphone and one reflector case, an SNR of 17.82 was achieved. These successful chemical sensing demonstrations will likely create new demands for widely tunable QCLs with ultralow threshold (for local fire-alarm size detection systems) and high-power (for standoff detection systems) performances.

8993-59, Session 12

Advances in broadly tunable QCL external cavity lasers and their use in novel rapid wide bandwidth cavity ringdown spectroscopy

Leigh J. Bromley, Daylight Solutions Inc. (United States); Toby K. Boyson, UNSW@ADFA (Australia); David B. Caffey, Daylight Solutions Inc. (United States); Maria E. Calzada, Loyola Univ. New Orleans (United States); William B. Chapman, Timothy O. Day, Daylight Solutions Inc. (United States); Abhijit G. Kallapur, UNSW@ADFA (Australia); K. Paul Kirkbride, Flinders Univ. (Australia); David S. Moore, Los Alamos National Lab. (United States); Ian R. Petersen, UNSW@ADFA (Australia); Allen Priest, Daylight Solutions Inc. (United States); Dylan R. Rittman, Los Alamos National Lab. (United States); David Ruiz, Daylight Solutions Inc. (United States); Thomas G. Spence, Loyola Univ. New Orleans (United States); Charles C. Harb, The Univ. of New South Wales (Australia)

Molecules with mid-infrared (mid-IR) absorptions are of interest for a wide range of applications. A mid-IR source with broad tuning is highly beneficial in many of these applications, including for probing a range of molecular species with a single device, or for mapping out the multi-peaked absorption profiles of complex molecules. Mid-IR sources based on Quantum Cascade Lasers (QCLs) have become the standard for producing high-power, broadly tunable output in a compact form factor. Increasing the tuning range of QCL-based systems can be achieved either by increasing the gain bandwidth of individual QCL emitters, combining multiple QCLs into a single instrument, or both. Traditionally, the tuning range of continuous wave (CW) QCLs has lagged that of equivalent pulsed devices. In this paper, we report recent advances in broadly tunable QCL external cavity systems, including tuning ranges of >300 cm-1 for single-QCL CW devices and >800 cm-1 for a novel multi-QCL instrument. We also present examples of applications for which broad tuning is advantageous, including a new variant of the Cavity Ringdown Spectroscopy (CRDS) technique. This new technique is able to scan across more than 1400 nm of spectral bandwidth, acquiring and analyzing more than 150,000 spectral data points in less than four seconds.

8993-60, Session 12

Further developments of capillary absorption spectrometers using small hollow-waveguide fibers *(Invited Paper)*

Jim F. Kelly, Robert L. Sams, Thomas A. Blake, Pacific Northwest National Lab. (United States); Jason M. Kriesel, Opto Knowledge Systems, Inc. (United States)

Our objective is to enhance quantification of stable carbon and oxygen isotope ratios to better than 1‰ precision for sample sizes < 1 pico-mole of total carbon. A Capillary Absorption Spectrometer is employed using a proprietary hollow waveguide in conjunction with wavelength and frequency modulation techniques of tunable laser absorption spectrometry. This system has been utilized with laser ablation-catalytic combustion techniques to analyze small resolution (~ 25 ?m spot diameter) ablation events on solids. Previous work used capillaries with 1 mm ID, and while performing fairly well, underwent some residual

modal noise due to multi-mode spatial propagation in the hollow-waveguides [1]. As an IR compatible hollow waveguide's ID is reduced to < 300 ?m, modal noise is reduced significantly for mid-IR operation, but feedback noise with high gain semiconductor lasers can still be problematic. In work with Opto-Knowledge Systems, Inc - OKSI's proprietary small waveguide, we can see better mode filtering and some significant reductions of feedback noise under favorable coupling with a multi-spatial mode QC laser. Our progress to date with this approach of replacing Isotope Ratio Mass Spectrometers will be discussed and compared to other competitive systems.

1. Kelly, J.F., et al., A capillary absorption spectrometer for stable carbon isotope ratio (13C/12C) analysis in very small samples. Review of Scientific Instruments, 2012. 83(2): p 023101-1

8993-61, Session 12

Vibration waveform reproduction and location of OTDR based distributed optical-fiber vibration sensing system

Hui Zhu, Southeast Univ. (China); Chao Pan, Southeast University (China); Xiaohan Sun, Southeast Univ. (China)

In the past decade varieties of OTDR based distributed optical fiber vibration sensing systems (DOFVS) were proposed with the functions of long range detection, multiple vibrations location and non-electromagnetic interference, and have been used in the areas of industries and perimeter security. However, a lot of researches about the current engineering systems fasten on the problem of the vibration location, ignoring the acquirement of vibration waveforms which are actually important signals for distinguishing the kinds produced by the vibration sources outsides. We demonstrate the scheme for both reproducing vibration waveform and locating in the OTDR based DOVFS in this paper.

The scheme for both vibration location and waveform reproduction in the OTDR based DOVFS is shown in Fig.1, in which the upper part is the optical circuit structure. With the help of differential detection of Rayleigh backscattering signals produced by single optical pulse propagating in sensing the fiber, multiple vibrations occurred synchronously can be monitored respectively and immediately. The down part in Fig.1 is the detection module, which can separate the signals received by the photodetector into vibration location pulses and vibration waveforms. Vibration waveforms are reproduced from the detecting pulses transmitted in which the original sensing signals have been included, by denoising selectively, adjusting bias voltage and band-pass filtering. We set up the experimental system and obtain the results in Fig.2 and Fig.3, which show the output signal for locating observed by oscillograph in one pulse period when vibration occurred and vibration waveform reproduced, respectively.

8993-63, Session 13

Nanoplasmonic biosensors and photodetectors *(Invited Paper)*

Ekmel Özbay, Bilkent Univ. (Turkey)

In this talk, we will present our recent work on nanoplasmonic based biosensors and photodetec-tors. 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 of silver nano-cylinder arrays located periodically on a sapphire substrate by E-Beam Lithography (EBL), which provides high resolution and flexibility in patterning. Firstly, the size and period dependency of the LSPR wavelength was studied. Secondly, the surface functionalization studies were carried out on an ar-ray with a selected size and period. Finally, the concentration dependency of the LSPR shifts was observed by changing the avidin concentrations to be sensed in the target solution. The sensing mechanism is based on the detection of refractive index change, due to the binding of biotin that is immobilized on the silver nano-cylinders to the avidin in the target solution, by observing the shifts in the LSPR wavelength. Our results show that such a plasmonic structure can be success-fully applied to bio-sensing applications and extended to the detection of specific bacteria species. A highly tunable design for obtaining double resonance substrates to be used in Surface Enhanced Raman Spectroscopy will also be presented. Tandem truncated nano-cones composed of Au-SiO2-Au layers are designed, simulated and fabricated to obtain resonances at laser excitation and Stokes frequencies. Surface Enhanced Raman Scattering experiments are conducted to compare the enhancements obtained from double resonance substrates to those obtained from single reso-nance gold truncated nano-cones. The best enhancement factor obtained using the new design is 3.86 x10E7. The resultant tandem structures are named after "Fairy Chimneys" rock formation in Cappadocia, Turkey. The integration of plasmonic structures with solid state devices has many po-tential applications. It allows the coupling of more light into or out of the device while decreasing the size of the device itself. Such devices are reported in the VIS and NIR regions. However, mak-ing plasmonic structures for the UV region is still a challenge. Here, we report on a UV plasmonic antenna integrated metal semiconductor metal (MSM) photodetector based on GaN. We designed and fabricated Al grating structures. Well defined plasmonic resonances were measured in the reflectance spectra. Optimized grating structure integrated photodetectors exhibited more than eight-fold photocurrent enhancement.

8993-64, Session 13

Time-resolved and ultra-sensitive vibrational biospectroscopy with mid-infrared plasmonics *(Invited Paper)*

Hatice Altug, Ronen Adato, Serap Aksu, Dordaneh Etezadi, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We demonstrate a plasmonic chip based technology for performing ultra-sensitive infrared (IR) absorption spectroscopy in aqueous solutions, capable of monitoring biomolecule interactions at the sub-monolayer level in real-time. In leveraging engineered plasmonic antennas for IR absorption enhancement, our results represent a dramatic advance over previous studies, being the first demonstration of their use for biologically significant measurements in solution. Such kinetic measurements are fundamentally challenging in traditional IR spectroscopy due to sensitivity limitations and the extremely strong absorption bands of liquid water, which routinely prohibit analysis in aqueous solutions. Our plasmonic system overcomes these challenges, enabling us to monitor in real-time protein and nano-particle binding events at high sensitivity. Compared to traditional label-free approaches our technology is based on molecular bond-specific IR absorption signatures, therefore it even enables observation of minute volumes of water displacement during molecular interactions. These measurements are made possible by the plasmonic enhancement of absorption bands in conjunction with a non-classical form of internal reflection that together boost sensitivity while limiting interference from solution absorption. In comparison with the current state of the art in IR spectroscopy, we reduce the sampling volumes more than three orders of magnitude and eliminate the need for bulky and macroscopic optics. Our ultra-compact chip based technology integrated with microfluidics represents a dramatic advancement in the compatibility of IR absorption spectroscopy with modern and next generation sample preparation and handling techniques. We will also describe a new manufacturing method for low-cost and high-throughput fabrication of these plasmonic sensor substrates.

8993-65, Session 13

Photonic crystal band-edge laser biosensor with silica passivation layer prepared by atomic layer deposition process

Hyungrae Cha, Jeongkug Lee, Seoul National Univ. (Korea, Republic of); Lukas R. Jordan, Univ. of Minnesota, Twin Cities (United States); Sang-Hyun Oh, Univ. of Minnesota, Twin Cities (United States) and Seoul National Univ. (Korea, Republic of); Heonsu Jeon, Seoul National Univ. (Korea, Republic of)

A two-dimensional PC pattern with honeycomb lattice was fabricated in an InGaAsP multiple quantum well (MQW) structure for single mode lasing action at the surface-emitting ?-point band-edge. In order to make a useful and reliable biosensor out of such a PC structure, we employed atomic layer deposition (ALD) method and passivated the entire device surface with a thin layer of silica, which effectively protects the InGaAsP MQWs and preserves optical gain for lasing action. The ALD silica layer also provides a hydrophilic surface suitable for silane chemistry developed for biochemical reactions. We experimentally proved that merely 5-nm-thick ALD silica layer was enough to protect the underlying InGaAsP MQWs from the chemicals known to etch them otherwise. Standard interaction between streptavidin and biotin was employed to confirm sensing capability of our PC laser device. We observed that the band-edge lasing wavelength was shifted by about 1 nm when streptavidin of 100 nM concentration was applied, which is comparable to SPR-based biosensor results in the literature; yet monitoring of peak shift should be much easier and straightforward with a sharp laser peak than with a broad SPR peak. Estimated figure-of-merit (FOM) of our device was as high as 800, which is much higher than those of the traditional SPR sensors. We expect that when integrated with microfluidic channels, our ?-point band-edge laser based biosensors should enable compact real-time parallel sensing and find various sensing applications, such as protein-protein interaction, lipid membrane experiment, and small segment DNA sequencing.

8993-66, Session 13

Plasmonic metamaterials for biosensing applications: from proteins to cells *(Invited Paper)*

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

Plasmonic metamaterials are emerging as a powerful platform for sensing minute amounts of biological materials, in some instances as small as a single molecular monolayer. The basic physical reason for that is their highly spectrally-selective response and very high optical intensity concentration near resonance that enable proximity sensing. This translates into order of magnitude higher signals compared with more traditional surface-enhanced infrared absorption measurements. Because optical resonances of meta-surfaces are determined by their sizes and geometries, they can be readily engineered to match various vibrational fingerprints of proteins, nucleic acids, and other biologically relevant entities. Non-specific bindings can be easily accounted for because of the extra specificity provided by tuning meta-surface resonances to vibrational fingerprints. By fabricating multiple plasmonic pixels, each tuned to different vibrational resonances, it is now possible to develop label-free high-throughput biosensors for monitoring the kinetics of antibody-antigen bindings. Recent experimental results demonstrating how such platform can be used to determine protein orientation on the surface [1] will be presented. Experimental results for several binding assays such as biotin/streptavidin monolayers, mono and bi-layers of binding proteins and peptide, and engineered peptides will be presented.

[1] C. Wu, A. B. Khanikaev, R. Adato, N. Arju, A. A. Yanik, H. Altug, and G. Shvets, “Fano-resonant asymmetric metamaterials for ultrasensitive spectroscopy and identification of molecular monolayers”, Nature Materials 11, 69 (2012).

8993-67, Session 14

Measures for optimizing pulsed EC-QC laser spectroscopy of liquids and application to multi-analyte blood analysis *(Invited Paper)*

Markus Brandstetter, Cosima Koch, Andreas Genner, Bernhard Lendl, Technische Univ. Wien (Austria)

We employed a broadly tunable pulsed external cavity (EC)-QC laser with a spectral tuning range from 1030 cm-1 to 1230 cm-1 and a tuning speed of 166 cm-1/s for direct absorption spectroscopy of aqueous solutions. The laser offered spectral power densities of up to four orders of magnitude higher than available with a conventional FTIR spectrometer. Therefore, a portable demonstration system with a large optical path length transmission flow cell (165 µm) could be realized preventing clogging of the flow cell. In pulsed mode an EC-QC laser provides significantly higher peak power levels than in continuous-wave mode, but pulse-to-pulse intensity variations, intra-pulse mode hops and mechanical imperfections of the scanning mechanism significantly impair the quality of resulting absorbance spectra. This article reports on measures which we found appropriate to reduce the initially high noise level of EC-QC laser absorbance spectra. These measures include a spectral self-referencing algorithm that makes use of the inherent structure of the EC QC laser’s gain curve to correct laser instabilities, as well as Fourier filtering, among others. This enabled us to derive infrared spectra which were finally useful for quantitative analysis in blood plasma samples. Finally, with the appropriate measures in place and using partial least squares regression analysis it was possible to simultaneously quantify 6 blood analytes from a single physical measurement of a 200 µL blood sample. This proves the potential of EC-QC lasers for practical application in clinical point-of-care analysis.

8993-68, Session 14

QCL-based integrated sensors for liquids and gases

Pierre Jouy, Kerstin Hans, Markus Sigrist, ETH Zurich (Switzerland); Markus Mangold, Bela Tuzson, Lukas Emmenegger, EMPA (Switzerland); Philip Waegli, Alexandra Homsy, Lubos Hvozdara, Hans Peter Herzig, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Herbert Looser, FH Aargau Nordwestschweiz - Letzte Aktualisierung (Switzerland); Alexander Wirthmüller, Daniel Hofstetter, Univ. of Neuchâtel (Switzerland); Jérôme Faist, ETH Zurich (Switzerland)

We developped two mid-infrared sensors based on quantum cascade lasers (QCL) in order to detect molecules both in gases and liquids. A 8 cm diameter cylindrical multi reflection cell has been used as well as a quantum cascade detector for the detection of different isotopes of CO2. Precisions down to 0.2 ‰ for C18O2 / C16O2 ratio and to 0.03‰ for C18O2 / C16O2 ratio in 1% CO2 synthetic air were obtained. To avoid interference paterns, an absorption mask was developed. This compact sensor has a footprint of 15x30 cm2. For the liquid sensor, detection of cocaine in saliva was targeted. A microfluidic system is used to extract cocaine from saliva to a transparent solvent. The microfluidic system is bonded on a Si/Ge waveguide. The cocaine concentration is detected through the interaction of the evanescent field of the guided mode and the fluid flowing on top. Real time measurements with 500 ?g of cocaine per milliliter of saliva have been realized. To further push both sensors, we developed independent multi-wavelength distributed feedback (DFB) QCL. In this scheme, two DFB gratings with different periodicity are realized on the same laser ridge. A shallow etching allows independent electrical injection in each DFB. It permits single mode lasing at two different wavelengths through the same optical output. Simultaneous detection of NO at 1900 cm-1 and NO2 at 1600 cm-1 have been obtained. In parallel, we developed a new DFB geometry for highly single mode vertical emission QCLs with perspective of multi species detection.

8993-69, Session 14

Latest improvements in field deployable compound specific isotope analyzer based on quantum cascade lasers and hollow waveguide

Sheng Wu, California Institute of Technology (United States) and Power Environmental Energy Research Institute (United States); Andrei Deev, California Institute of Technology (United States)

One of the important applications of quantum cascade laser sources in the mid-Infrared is field deployable isotope analysis[1, 2]. However, compound specific isotope analysis has been limited to Isotope Ratio Mass Spectroscopy till now.

We first demonstrated that Quantum Cascade lasers could have orders higher coupling efficiency into small bore long HWG than blackbody light sources, and when coupled with capillary GC, the online sensor has potential performance to match Mass Spectroscopy sensors[3]. Here, we give the latest progresses over the past 2 years. First, the latest progress in quantum cascade lasers give us the true room temperature laser source that could work above ambient temperature while still able to pump out over 10mW, this translate into easy alignment and lower power consumption for the system. Second, we improve the performance of the system by introducing mode filtering and isolation optics which result in improved signal to noise ratio.

We present the latest field data of this analyzer at oil fields, and applications for breath analysis with minimal isotope tracers.

1. Kelly, J.F., et al., A capillary absorption spectrometer for stable carbon isotope ratio ([sup 13]C/[sup 12]C) analysis in very small samples. Review of Scientific Instruments, 2012. 83(2): p. 023101-14.

2. Nelson, D.D., et al., New method for isotopic ratio measurements of atmospheric carbon dioxide using a 4.3 mu m pulsed quantum cascade laser. Applied Physics B-Lasers and Optics, 2008. 90(2): p. 301-309.

3. Wu, S., et al., Hollow waveguide quantum cascade laser spectrometer as an online microliter sensor for gas chromatography. Journal of Chromatography A, 2008. 1188(2): p. 327-330.

8993-70, Session 14

Quantum cascade laser-based sensor system for hydrogen peroxide detection

Wei Ren, Wenzhe Jiang, Nancy Sanchez, Rice Univ. (United States); Pietro Patimisco, Rice Univ. (United States) and Univ. degli Studi di Bari (Italy); Vincenzo Spagnolo, Univ. degli Studi di Bari (Italy); Chung-en Zah, Feng Xie, Lawrence C. Hughes Jr., Corning Incorporated (United States); Robert Griffin, Frank K. Tittel, Rice Univ. (United States)

Sensitive detection of hydrogen peroxide (H2O2) is of interest in atmospheric chemistry applications, where it has a significant role as an atmospheric reservoir of HOx and is associated with biomass burning. Furthermore H2O2 can partition into cloud and particle water resulting in the formation of sulfate and organic aerosols. A sensitive sensor for H2O2 is also useful in explosive detection as well as in medical diagnostics, such as oxidative stress in the lungs, early diagnosis and monitoring of asthma, and acute respiratory distress syndrome. A 7.73 µm cw, distributed feedback quantum cascade laser (DFB-QCL) based sensor system for ppb-level hydrogen peroxide detection will be reported. By employing a calibration free 2f wavelength modulation spectroscopy (WMS) model, introduced in 2009 by Rieker et al., it is possible to accurately infer the H2O2 concentration without comparison to a calibrated H2O2 mixture. The model includes both the linear and nonlinear tuning characteristics of the QCL source as well as normalizes the 2f WMS signal with the 1f WMS signal. In order to measure the laser-specific tuning characteristics, a self-designed characterization system, which consists of an etalon with a free spectral range of 0.011 cm-1, two mid-infrared photo detectors, and a simultaneous data acquisition were integrated into the sensor system. To optimize the sensor performance, the influence of modulation parameters was investigated, including the slow ramp signal as well as the superimposed fast sinusoidal signal to perform WMS. To ensure good reproducibility of the derived H2O2 concentrations, the background signal was minimized and a stable source for H2O2 vapor was developed.

8993-71, Session 14

THz signatures of biological macromolecules *(Invited Paper)*

Elliott R. Brown, Wright State Univ. (United States); Edgar A. Mendoza, Redondo Optics, Inc. (United States); W. Zhang, L. Viveros, Matthieu Martin, Wright State Univ. (United States); Yuliya Kuznetsova, A. Neumann, Steven R. Brueck, The Univ. of New Mexico (United States)

With the recent detection of spectroscopic signatures in proteins, all three bio-macromolecular types (polysaccharides, nucleic acids, and proteins) have provided samples displaying THz absorption resonances, which often are surprisingly strong when confined to the nanochannels of a fluidic-chip platform. Some good examples are poly-lactose (lactose monohydrate crystal), Lambda DNA, and protein-ladder solutions. This paper will present examples from all three types, and present insight into what is required to observe a THz vibrational resonance, and why nanochannel-confinement can enhance the spectroscopic signature in spite of strong background absorption by the aqueous environment. A critical issue still under investigation is the surprising narrowness in some of these signatures, approaching a linewidth (~10 GHz) comparable to that observed in the rotational resonance of some polar gas molecules, such as water vapor, at standard temperature and pressure. This suggests that biomolecules are bonding to the sidewalls of the nanochannels, creating a quasi-solid-state behavior in terms of collective excitation and vibrational damping.

8993-72, Session 15

High-sensitivity QEPAS for environmental monitoring *(Invited Paper)*

Aurore Vicet, Tong Nguyen Ba, Yves Rouillard, Quentin Gaimard, Univ. Montpellier 2 (France)

We present in this paper developments of quartz enhanced photoacoustic spectroscopy (QEPAS) with antimonide laser diodes emitting at 2.3 µm and 3.3 µm. Since its invention in 2002, this technique has shown a large range of applications with compact and cheap setups, based on the use of a commercial quartz tuning fork (QTF) as an efficient acoustic transducer excited by a sound wave generated by molecular absorption.

We will show experiments dedicated to environmental purposes, such as methane detection and ethylene control. Ethylene is a molecule of strong importance in fruits and vegetables industry as it is used to evaluate and control the products ripening. Two demonstrators are presented: a laboratory bench and a compact setup. In the compact setup, we have developed a cell including both the laser and the QTF. The detection limits of the demonstrators were evaluated: for example, measurements of methane diluted in dry nitrogen led to a threshold detectivity of 100 ppbv at 3.38 µm.

Some key points of the QEPAS setup will be evaluated using finite elements modelisation.

We have developed some new laser structures to reach long wavelengths, dedicated to those spectroscopic applications. They were

grown by molecular beam epitaxy on GaSb substrates. We will present photonic crystal based lasers inspired by coupled cavities, photonic crystal based DFB lasers and new DFB lasers, based on the Ga(In)AlAsSb/InGaAsSb material system. Some InAs/AlSb quantum cascade lasers have been specially developed as well.

Finally, future trends of these applications will be described.

8993-73, Session 15

THz quartz-enhanced photoacoustic sensor employing a quantum cascade laser source

(Invited Paper)

Vincenzo Spagnolo, Patimisco Pietro, Simone Borri, Angelo Sampaolo, Gaetano Scamarcio, Univ. degli Studi di Bari, CNR-IFN (Italy); Miriam S. Vitiello, Consiglio Nazionale delle Ricerche (Italy); Harvey E. Beere, David A. Ritchie, Univ. of Cambridge (United Kingdom)

High sensitivity THz molecular spectroscopy is a powerful tool both for laboratory purposes and for remote sensing. Many absorption and emission molecular lines of large interest fall in this spectral region, where typical absorption strengths are of the same order of magnitude of those observed in the mid-IR and from three to six order of magnitude stronger than that reported for the microwave region. Nevertheless, the THz region of the electromagnetic spectrum is still largely unexplored, due to limited options for optical components, detectors and tunable and powerful coherent sources. Quantum cascade lasers (QCLs) represent the most promising THz light source and quartz-enhanced photo-acoustic spectroscopy (QEPAS) employing QCLs sources showed high sensitivity in the mid-IR spectral ranges. Since one of the main advantages of the PAS techniques is that no optical detection is required, the extension of the QEPAS technique in the THz range would allow to avoid the use of low-noise but expensive, bulky and cryogenic bolometers.

We report here on the development of a QEPAS sensor working in the THz range. The sensor employs a 3.93 THz QCL and custom-made QTF, having a prongs spacing of ~0.8 mm. For our QEPAS THz sensor demonstration we selected methanol as target gas molecule. To determine the best achievable detection sensitivity of the sensor we performed an Allan variance analysis, measuring and averaging its response. The calculated normalized noise equivalent absorption coefficient NNEA is 2?10^-10 W•cm^-1•Hz^-1/2, comparable with the best result obtained in the mid-IR.

8993-74, Session 15

Cavity and quartz enhanced photo-acoustic mid-IR sensor

Pietro Patimisco, Univ. degli Studi di Bari (Italy); Simone Borri, CNR-IFN UOS Bari (Italy); Gaetano Scamarcio, Univ. degli Studi di Bari (Italy); Vincenzo Spagnolo, Politecnico di Bari (Italy); Iacopo Galli, Giovanni Giusfredi, Davide Mazzotti, Paolo de Natale, Istituto Nazionale di Ottica (Italy) and European Lab. for Non-linear Spectroscopy (Italy)

Since its demonstration, quartz-enhanced photo-acoustic spectroscopy (QEPAS) has emerged as a powerful tool for gas sensing in the near and mid-IR spectral ranges, combining the peculiar compactness and robustness of the set-up, with large dynamic range and fast time response. One of the key features of QEPAS technique is the direct proportionality of the spectroscopic signal to the laser power, and the most direct way to boost its detection sensitivity is therefore to enhance the optical power interacting with the sample.

We report on a novel spectroscopic technique combining QEPAS with cavity-enhanced laser spectroscopy. The potentialities of this technique were preliminarily investigated by comparing the detection sensitivities of standard and cavity-enhanced QEPAS for the detection of CO2 diluted in N2, employing a distributed feedback quantum cascade laser source (QCL) emitting at 4.3 µm. The QCL beam was coupled with a compact (~10x5 cm) bow-tie four-mirror optical resonator (free-spectral-range ~1.7 GHz). The measured finesse is ~800 and the enhancement factor ~500. A standard tuning fork (QTF) was positioned inside the resonator. A locking loop keeps the resonance of the cavity fixed on the laser frequency during its low-frequency spectral scan. A f0/2 current dither is also added to the QCL and the QTF signal was detected at its resonance frequency (f0=32.8 kHz). The detection sensitivity with respect to the standard QEPAS was improved by a factor ~300, comparable to the enhancement factor, down to a 25 ppb sensitivity, corresponding to normalized noise-equivalent absorption in the 10^-10 W•cm^-1•Hz^-1/2 range.

8993-75, Session 15

Fast automotive diesel exhaust measurement using quantum cascade lasers

Johannes Herbst, Raimund Brunner, Armin Lambrecht, Fraunhofer-Institut für Physikalische Messtechnik (Germany)

Step by step, US and European legislations enforce the further reduction of atmospheric pollution caused by automotive exhaust emissions. This is pushing automotive development worldwide. Fuel efficient diesel engines with SCR-technology can impede NO2-emission by reduction with NH3 down to the ppm range. To meet the very low emission limits of the Euro6 resp. US NLEV (National Low Emission Vehicle) regulations, automotive manufacturers have to optimize continuously all phases of engine operation and corresponding catalytic converters. Especially nonstationary operation holds a high potential for optimizing gasoline consumption and further reducing of pollutant emissions. Test equipment has to cope with demanding sensitivity and speed requirements. In the past Fraunhofer IPM has developed a fast emission analyzer called DEGAS (Dynamic Exhaust Gas Analyzer System), based on cryogenically cooled lead salt lasers. These systems have been used at Volkswagen AG's test benches for a decade. Recently, IPM has developed DEGAS-Next which is based on cw quantum cascade lasers and thermoelectrically cooled detectors. The system is capable to measure three gas components (i.e. NO, NO2, NH3) in two channels with a time resolution of 20 ms and 1 ppm detection limits. We shall present test data and a comparison with fast FTIR measurements.

8993-94, Session PWed

Single photon excitation and entanglement transfer using hyperbolic metamaterials

Onur Danaci, Ozgur Mustecaplioglu, Koç Univ. (Turkey)

Spontaneous emission rate of an atom is affected in the presence of absorbing dielectrics, this can be reversed to get single-photon excitation of qubit. According to Choquette et al[1], however, a time-inverted pulse must be generated due to broken symmetry of plasmon-emitter system, hence strong directionality of emission, comparing to an emitter in vacuum. We use Hyperbolic metamaterial of differing layers of Ag/Ti02 with thickness 10/30 nm and the model devised by Newman et al[2]. They estimated greatest rate of high-k emission to far-field for 900nm, where a superstrate with real dielectric constant greater than 30 is needed for outcoupling to vacuum photonic modes and light is emitted to a cone of 34-degree half-angle. For engineering time-inverted pulse, we use this model[1]and use Choquette et al's [2] suggestion of using ring mirror to compensate conical spontaneous emission in HMM. A single photon, conical, time-inverted pulse is sent to excite qubit; two single-photon light modes are sent for qubit-qubit entanglement and checked if there is transfer between qubits similar to Cano et al[3]. Our results indicate that excitation probability is highly directional and converges to unity as it goes by predicted 34-degree half-cone angle, entanglement transfer between qubits is provided.

[1]: Phys.Rev. A 85, 063841 (2012)
[2]: JOSA B, Vol. 30, Issue 4, pp. 766-775 (2013)
[3]: Phys. Rev. B 84, 235306 (2011)

8993-95, Session PWed

Experimental realisation of focusing dual wavelengths by a far-field plasmonic lens

Priyamvada Venugopalan, Xiangping Li, Qiming Zhang, Min Gu, Swinburne Univ. of Technology (Australia)

Surface plasmons (SPs) are electromagnetic waves bound to a metal/dielectric interface having a much shorter effective wavelength than the incident light. Plasmonic lens which are capable to excite and focus such propagating SPs are intended to produce super-resolution much above the diffraction limit. Many kind of plasmonic lens structures have been developed like single and multiple ring metallic structures, spiral metallic structures etc [1]. However, the reported plasmonic lenses are confronting by obstacles of low throughput efficiency, incapability of far-field and broad-band focusing, which limit their potential applications. In this paper, we report the experimental demonstration of sub wavelength far-field focusing with large field enhancement by a far-field plasmonic lens which is composed of a single annular slit and a groove structure [2]. A radially polarised beam at a wavelength of 632.8 nm is loosely focused on to the rear plane of the plasmonic lens which excites the SPs in all directions to enhance the throughput efficiency or field enhancement. Also, we report the simultaneous focusing of two different wavelengths by the same plasmonic lens structure to a single focal plane, thereby realising a dual wavelength far-field plasmonic lens. The focal field distribution is characterised by a scanning near-field optical microscope (SNOM). Our results lead to the potential application of such a far-field plasmonic lens in super-resolution imaging and recording.

Acknowledgement:

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[1] Fu, Y. and X. Zhou., "Plasmonic Lenses: A Review," Plasmonics 5(3), 287-310 (2010).

[2] Zhang, M., J. Du., Shi, H., Yin, S., Xia, L., Jia, B., Gu, M., Du, C., "Three-dimensional nanoscale far-field focusing of radially polarized light by scattering the SPPs with an annular groove." Opt. Express 18(14), 14664-14670 (2010).

8993-5,

Monolithic QCL design approaches for improved reliability and affordability *(Keynote Presentation)*

Kwok Keung Law, Naval Air Warfare Ctr. Weapons Div. (United States)

Many advances have been made recently in mid-wave infrared and long-wave infrared quantum cascade lasers (QCLs) technologies, and there is an increasing demand for these laser sources for ever expanding Naval, DOD and homeland security applications. We will discuss in this presentation a portfolio of various Naval Air Warfare Weapons Division's current and future small business innovative research programs and efforts on significantly improving QCLs' performance, affordability and reliability.

8993-6,

Near-infrared OPO in an AlGaAs/AlOx waveguide *(Keynote Presentation)*

Cécile Ozanam, Marc Savanier, Univ. Paris 7-Denis Diderot (France); Loïc Lanco, Laboratoire de Photonique et Nanostructures, CNRS-UPR20 (France); Xavier Lafosse, Lab. de Photonique et de Nanostructures (France); Alessio Andronico, Ivan Favero, Sara Ducci, Giuseppe Leo, Univ. Paris 7-Denis Diderot (France)

Within the ambitious quest for an electrically pumped version of the optical parametric oscillator, we demonstrate the first integrated near-infrared OPO in III-V semiconductor waveguide. This nonlinear device is based on a selectively oxidized GaAs/AlAs heterostructure, the same "AlOx" technology that is at the heart of VCSEL fabrication.

The heterostructure and waveguide design allows for type-I form-birefringent phase matching, with a TM00 pump around 1 um and TE00 signal and idler around 2 µm. Thanks to the high non-resonant ?(2) of GaAs, the relatively weak guided-wave optical losses, and the fabrication of unconventional monolithic SiO2/TiO2 dichroic Bragg mirrors (6 bi-layers deposed onto non-uniform end facets), we observe a threshold of 210 mW at degeneracy in the continuous-wave regime, with a single-pass-pump doubly resonant scheme.

Further improvement can be achieved by adopting a double-pump-pass scheme and, in a more fundamental way, by further optimizing the waveguide optical losses. The latter are induced by a not entirely mastered AlAs oxidation process and are of two distinct types: Rayleigh-like scattering at signal and idler wavelength ($\propto \leq$ 1cm-1), due to the interface roughness between GaAs and AlOx layers; and absorption at pump wavelengths ($\propto \approx$ 3cm-1), due to volume defects in the GaAs layers adjacent to the aluminum oxide.

This result marks a milestone for integrated nonlinear photonics and represents a significant step toward the goal of an electrically injected coherent light source on chip.

We acknowledge the financial support of the SEAM Labex of Sorbonne Paris Cité, under the DOLPHIN project.

8993-76, Session 16

Widely-electrically-tunable plasmonic antennas with graphene *(Invited Paper)*

Yu Yao, Mikhail A. Kats, Patrice Genevet, Harvard School of Engineering and Applied Sciences (United States); Nanfang Yu, Harvard School of Engineering and Applied Sciences (United States) and Columbia Univ. (United States); Yi Song, Massachusetts Institute of Technology (United States); Raji Shankar, Harvard School of Engineering and Applied Sciences (United States); Jing Kong, Massachusetts Institute of Technology (United States); Marko Loncar, Harvard Univ. (United States); Federico Capasso, Harvard School of Engineering and Applied Sciences (United States)

Graphene is emerging as an optical material which can be dynamically tuned by electrostatic doping. However, integration of graphene into optical and optoelectronic devices is limited due to its small thickness and the resultant weak interaction with light. By combining metal and graphene in a hybrid plasmonic structure, it is possible to enhance graphene-light interaction and thus achieve in situ control of the optical response.

Here we demonstrate that graphene can be integrated into the nano-gaps of coupled plasmonic antennas to achieve broad tuning of plasmonic antennas. Full wave simulation and circuit model analysis

was used to design the hybrid plasmonic structure and understand the coupling between the plasmonic modes of the metallic antennas and the graphene. In our experiment, a CVD (chemical vapor deposition) single layer graphene was first transferred onto a silicon oxide layer on doped silicon substrate (back gate). Then Au plasmonic structures were patterned onto the graphene sheet, followed by the fabrication of metal contact on graphene and back gate. Reflection spectra of the plasmonic structures were taken at various gate voltages using a Fourier transform infrared (FTIR) spectrometer equipped with a mid-infrared microscope. The reflection peak wavelength of the hybrid metal-graphene plasmonic structure can be tuned electrically over 1100 nm (18% of the resonance frequency) at mid-infrared (MIR) wavelengths (6-7 µm). The time response of our device was measured to be shorter than 30 ns, which can be further decreased to the picosecond scale. This study confirms that hybrid metal-graphene structures are promising elements for high speed electrically controllable optical and optoelectronic devices.

8993-77, Session 16

Graphene for transparent conductor applications *(Invited Paper)*

Vinod E. Sandana, Graphos (France)

Transparent conductors are widely used in opto-electronic devices such as LEDs, LCDs, screens/displays, solar cells etc. Due to their combination of good electrical conductivity and optical transparency, Transparent Conducting Oxides (TCOs) are often adopted. Indium Tin Oxide (ITO) is the most commonly used TCO. However, indium has some significant drawbacks including toxicity issues (which are hampering manufacturing), an increasing rarification [1] and resulting price increases. Thus alternative materials solutions are actively being sought. This review will discuss the performance and perspectives of graphene for use in transparent conductor applications with a particular emphasis on the perspectives of a much neeeded breakthrough in p-type transparent conductors.

[1] Rapport JRC Commission Européenne: « Critical Metals in Strategic Energy Technologies, Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies » (2011)

8993-78, Session 16

Atom chips for quantum sensing with cold thermal atoms *(Invited Paper)*

Sylvain Schwartz, M. Ammar, M. Dupont-Nivet, Landry Huet, Jean-Paul Pocholle, Thales Research & Technology (France); C. Guerlin, J. Reichel, Lab. Kastler Brossel (France); Peter Rosenbusch, Observatoire de Paris (France); Isabelle Bouchoule, Christoph I. Westbrook, Lab. Charles Fabry de l'Institut d'Optique (France)

We will discuss the possibility of building a matter wave interferometer using thermal (i.e. non condensed) cold atoms with reduced mean-field effects. Cold atoms trapped in the vicinity of an atom chip serve for quantum sensing of acceleration and gravity. To maintain a satisfactory level of coherence, a high degree of symmetry is required between the two interferometer arms. We will give a quantitative analysis, and describe the experimental protocol we are developing for this purpose. The latter is based on internal state labeling. Two parallel coplanar waveguides deposited on the atom chip are used to selectively address the two hyperfine states through microwave dressing.

8993-79, Session 16

A tunable omni-directional sensing platform: strong light-matter interactions enabled by graphene

Feng Liu, Univ. of Pennsylvania (United States) and Shanghai Normal Univ. (China); Ertugrul Cubukcu, Univ. of Pennsylvania (United States)

In this theoretical work, we report on voltage-controllable hybridization of electromagnetic modes arising from strong interaction between graphene plasmons and molecular vibrations. Compared with the strong light-matter interaction platforms based on noble metals, graphene offers much tighter plasmonic field confinement thus smaller effective mode volume and higher quality-factor due to longer carrier relaxation time in midinfrared regime, leading to Rabi splitting and hybridized polaritonic modes at 3 orders of magnitude lower molecular densities. Electrostatically tunable carrier density in graphene allows for dynamic control over the interaction strength. In addition, the flat dispersion band arising from the deep confinement of the polaritonic modes gives rise to the omni-directional excitation. Our approach is promising for practical implementations in infrared sensing and detection.

8993-80, Session 16

Graphene active plasmonics and their applications to terahertz lasers and sensors

Taiichi Otsuji, Akira Satou, Tohoku Univ. (Japan); Takayuki Watanabe, Tohoku Univ (Japan); Alexander Dubinov, Institute for Physics of Microstructures (Russian Federation); Vyacheslav Popov, Institute of Radio Engineering and Electronics (Russian Federation); Stephane Albon Boubanga Tombet, Tohoku Univ (Japan); Vladimir Mitin, Univ. at Buffalo (United States); Victor Ryzhii, Tohoku Univ. (Japan)

[Invited] Graphene is a one-atom-thick planar sheet of carbon atoms that are densely packed in a honeycomb lattice. The gapless and linear energy spectra of electrons/holes lead to nontrivial features such as the negative dynamic conductivity in the terahertz (THz) spectral range, which may lead to a new type of THz lasers. The two-dimensional Dirac Fermion systems in graphene yield unique plasmonic properties; the dispersion relation of the gated plasmons in graphene take a linear dependence on wave vector and a 1/4-power dependence on carrier density. Starting from the semi-classical Boltzmann's transport equations, one can lead to a set of hydrodynamic equations, giving rise to a new insight for the plasmon dynamics for both heavily doped unipolar and undoped or optically excited bipolar graphene. The former case exhibits a strong damping for any plasmons but non-ionic acoustic sound-like waves are predominated whereas the latter cases are predominated by the majority carriers' plasmons. We theoretically discovered and experimentally manifested that when graphene carrier populations are inverted by optical or electrical pumping the excitation of graphene plasmons by the THz photons results in propagating surface plasmon polaritons with giant gain in a wide THz range. Furthermore, when graphene is patterned in a micro- or nano-ribbon array by grating gate metallization, the structure acts as an active plasmonic metamaterial, providing a super-radiant plasmonic lasing with giant gain as well as ultrahigh sensitive detection at the plasmon modes in a wide THz frequency range.

8993-81, Session 16

Electrical tunability of soft THz parametric resonance by hot electrons in graphene *(Invited Paper)*

Samwel Sekwao, Jean-Pierre Leburton, Univ. of Illinois at Urbana-Champaign (United States)

Recently, we predicted the onset of a soft parametric resonance (SRP) for hot carriers interacting with optic phonons ??_OP in a constant electric field Fo,, at ω=ηω_F, where ω_F=eF_0 v_f/??_OP [1]. In this talk, we show that SRP is not substantially modified with temperature, whereas the parameter n~0.56 is practically independent of the DC field Fo, which makes SPR tunable in the THz range with a sizeable variation of F0 [2]. Our model based on the linearization of the time-dependent Boltzmann transport equation (BTE) predicts a secondary resonance at ω~ω_F, emerging from a weak shoulder in the T=300K ac current when the temperature decreases to T=77K and lower. These two resonances behave differently as scattering at low energy strengthens.

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1) Samwel Sekwao and J.P. Leburton, Phys. Rev. B 87, 155424 (2013)

2) Samwell.Sekwao and J.P. Leburton, Appl. Phys. Lett. (in press)

8993-82, Session 17

Plasmon-induced emission and broadband absorption with a plasmonic crystal *(Invited Paper)*

Hugo Frederich, Clotilde Lethiec, Univ. Pierre et Marie Curie (France); Fangfang Wen, Rice Univ. (United States); Julien Laverdant, Lab. de Physique de la Matiére Condensée et Nanostructures (France); Catherine Schwob, Univ. Pierre et Marie Curie (France); Traian Popescu, Ludovic Douillard, CEA-IRAMIS (France); Laurent Coolen, Agnès Maître, Univ. Pierre et Marie Curie (France)

Even if surface Plasmon Polariton (SPP) offers the opportunity to accelerate efficiently spontaneous emission of nanoemitters located close to a metallic surface, they induce loss of radiation., as they are not coupled to far-field radiative modes. As metallic gratings radiate SPP modes in far field, they can be used both to enhance the fluorescence and to absorb light over a wide spectrum with applications in fields such as bio-imaging, light-emitting diodes (LED), photovoltaics or single-photon sources.

We fabricated a plasmonic crystal of centimetric size, by evaporating gold on an artificial silica opal used as a periodic template. By illuminating it by white light, we coupled to SPP a broad continuum of coupled wavelengths inducing perfect complete absorption over the visible spectrum. This illustrates a crystallographic arrangement at the microscopic scale and disorder at the macroscopic scale. [1]. Complementary photo-emission electron microscopy (PEEM) measurements demonstrated the coupling of propagating light modes to SPP and localized plasmon modes.

We then deposited colloidal CdSe/ZnS nanocrystals on plasmonic crystal and observed a p-polarized wavelength-dependent increase of emission which evidences excitation of plasmon modes by nanocrystals and re-emission of plasmons to far field p-polarized radiation.

We quantized the extraction and re-emission of SPP, and showed a real improvement of the fluorescence intensity. This method provides an interesting tool for designing light-extracting devices.

References:

[1] H. Frederich, F. Wen, J. Laverdant, L. Coolen, C. Schwob, A. Maître, Isotropic broadband absorption by a macroscopic self-organized plasmonic crystal, Optics Express 19, 24424(2011).

8993-83, Session 17

THz near-field microscopy of graphene structures *(Invited Paper)*

Oleg Mitrofanov, Univ. College London (United Kingdom) and The Ctr. for Integrated Nanotechnologies (United States); Wenlong Yu, Georgia Institute of Technology (United States); Robert J. Thompson, Univ. College London (United Kingdom); Yuxuan Jiang, Georgia Institute of Technology (United States); Igal Brener, Sandia National Labs. (United States) and The Ctr. for Integrated Nanotechnologies (United States); Wei Pan, Sandia National Labs. (United States); Claire Berger, Walter A. de Heer, Zhigang Jiang, Georgia Institute of Technology (United States)

At THz frequencies, graphene properties, particularly surface plasmon properties, depend very sensitively on the Fermi level, providing a useful platform for THz devices. Direct experimental detection and investigation of THz surface plasmon waves in graphene require near-field microscopy methods. We will discuss THz near-field microscopy of epitaxial graphene mesas and ribbon arrays, and observed effects of surface waves excitation at the edges of graphene structures and confined plasmon mode excitation in the arrays.

In the near-field microscopy with the integrated sub-wavelength aperture THz near-field probe, three possible contribution to the detected signal are identified: the confined plasmon mode (in ribbons); the surface plasmon wave that can be excited at the pattern edges as well as the incident THz wave that can pass through graphene. Near-field signatures of these contributions will be discussed.

The experimental results demonstrate that graphene ribbon arrays can modify local transmission properties in the near-field substantially, depending on the orientation of the ribbon with respect to the polarization of the THz wave and on the doping level.

The observed properties of graphene suggest promising applications for sensing and for THz devices. The technique of THz near-field microscopy also opens the possibility for non-invasive probing of local THz properties and for investigations of surface plasmon waves in graphene with sub-wavelength spatial resolution.

8993-84, Session 17

Plasmonic resonance absorption spectra in mid-infrared in an array of graphene nanoresonators *(Invited Paper)*

Don C. Abeysinghe, Joshua Myers, Nima Nader Esfahani, Joshua R. Hendrickson, Justin W. Cleary, Dennis E Walker Jr., Air Force Research Lab. (United States); Kuei-Hsien Chen, Academia Sinica (Taiwan); Li-Chyong Chen, National Taiwan Univ. (Taiwan); Shin Mou, Air Force Research Lab. (United States)

Graphene has remarkable optical properties that it is highly transparent while owning large optical absorption coefficient. However, from an optical sensing point of view, it is less attractive due to the low interband optical absorbance resulting from its thinness. An alternative method to achieve optical absorption/ sensing is to utilize the tunable resonant absorption by plasmons in the two-dimensional electron gas (2DEG) of grating-gated field effect transistors (FETs), which is known for a variety of semiconductor systems, giving promise of frequency-agile Infrared/ THz image sensors and spectrometers. Graphene-based plasmonics shows highly tunable and sharp plasmon THz resonance at room temperature while all other semiconductor 2DEG systems generally have plasmon resonance at much lower temperatures (< 77 K.) In addition, graphene has the capability to operate at higher frequencies (shorter wavelength in mid-infrared) due to higher sheet carrier density. As a result, graphene grating-gated detectors have the potential to be the next-generation frequency-agile infrared detectors. We investigate the dc transport of both CVD graphene (grown on Cu) and epitaxial graphene (grown on SiC) with Hall measurement, by which we obtain important parameters such as Hall mobility and sheet carrier density helping us estimate the plasmon resonance frequency and the absorption spectrum. Furthermore, to complement the dc transport characterization, optical transmission/reflection measurements are carried out in Fourier transform infrared spectrometers (FTIRs) to obtain the infrared ac conductance. From that, the carrier density, carrier mobility, sheet resistivity, intraband scattering rate, and graphene layer number can be inferred. Last, we observe graphene plasmon resonances in far-infrared (~ 100 cm-1) by optical transmission measurements through graphene ribbon grating structures.

8993-85, Session 17

Electrical readout of thermo-plasmonically actuated nanomechanical structure by graphene strain gauge sensor

Fei Yi, Alexander Y. Zhu, Jason C. Reed, Hai Zhu, Ertugrul Cubukcu, Univ. of Pennsylvania (United States)

Plasmonic absorbers are resonant metallic nanostructures that can localize the freely propagating radiation and produce very high optical near field intensities while dissipating electromagnetic energy efficiently as heat due to the free carrier absorption in metals. This high optical absorption has enabled the investigation of such structures as nanoscale heat sources in many applications. Along this line, we successfully demonstrated that by integrating plasmonic absorbers, nanomechanical structures with extremely high mass, force, and displacement sensitivities can also be highly responsive to infrared radiation, leading to novel applications such as thermal optomechanical infrared detection. However, an effective readout of the mechanical actuation of these nanomechanical structures is the key to their implementation in sensing applications. Graphene, a monolayer of carbon atoms with large piezoresistive effect, has recently been demonstrated to be a promising material for strain gauge sensors. When integrated on nanomechanical structures, graphene can be a non-disruptive and highly sensitive electrical readout of the mechanical deflection. Inspired by this, we demonstrate a thermal optomechanical infrared detector which consists of a bilayer cantilever with an integrated plasmonic absorber and a graphene strain gauge sensor. The incoming infrared power is converted into heat by the plasmonic absorber and thermomechanically deflects the bilayer cantilever. The mechanical deflection is then transduced into electrical output signals through the piezoresistive effect of the integrated graphene strain gauge sensor. We expect this approach to lead to highly compact optically controlled nanomechanical systems enabling unprecedented functionality in biomolecular and toxic gas sensing and on chip mass spectroscopy.

8993-86, Session 17

Scanning single-emitter fluorescence lifetime imaging

Andreas W. Schell, Philip Engel, Oliver Benson, Humboldt-Univ. zu Berlin (Germany)

Single quantum systems are ideal probes for the local electromagnetic environment. Their single system nature gives rise to a high resolution ¬- in space as well as in the time domain, since any ensemble averaging is avoided. Its photostability and ability to emit photons even at room temperature makes the nitrogen vacancy center (NV center) in nanodiamond an excellent probe. Its position can be manipulated with an atomic force microscope (AFM) in a controlled manner to obtain maps of its decay rate [1].

Here, we employ a single NV center glued to the tip of an AFM as a scanning fluorescence lifetime probe. We demonstrate three-dimensional quantum emitter fluorescence lifetime imaging microscopy (QE-FLIM) by scanning various structures, such as silver nanowires or gold nanospheres [2]. The possibility to pre-characterize the probe at known structures and compare the results to theory enables for quantitative measurement of the local density of optical states (LDOS) at the nanoscale. Our scanning scheme collects data in all three spatial dimensions, which makes a correction for topography artifacts possible and even allows for the identification of buried structures. Future applications of our technique may range from special topics like engineering of single photon sources or improving light trapping in solar cells to broader fields like materials science and biotechnology.

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[2] A. W. Schell, P. Engel, and O. Benson, arXiv:1303.0814 (2013)

8993-87, Session 17

Plasmonic sensing with metal nanohole array fabricated using nanospherical-lens lithography

Yi-Kai Huang, Chang-Han Wang, Han Li, Min-Huan Wang, Yun-Chorng Chang, National Cheng Kung Univ. (Taiwan)

Surface plasmon resonance (SPR) is collective electron oscillation along the metal-dielectric interface, whose light scattering spectrum is very sensitive to the dielectric environment and is widely used in ultrasensitive chemical and biological sensing applications. The periodic-aligned nanohole arrays have been reported to demonstrate ultrasensitive SPR sensing.

In this study, fabrication of metal nanohole array is demonstrated using Nanospherical-Lens Lithography (NLL). A close-packed single-layered nanosphere arrayis assembled on top of an unexposed photoresist. Nanospheres are used as nanoscale spherical lens to focus the incident UV light from a commercial UV lamp. The focus UV light exposed the underneath photoresist thin film and revealed cylindrical hole arrays after developing. The angled Cr deposition will result in Cr nanohole arrays on top of the photoresist and the subsequent oxygen plasma treatment will clean the unexposed photoresist hole. Ag or Au nanohole arrays can be obtained after subsequent glancing-angle deposition. The size and shape information of the nanohole arrays will be analyzed by SEM. SPR of the nanohole arrays are measured by transmission spectroscopy. We will varying several parameters, including the hole sizes and periodicity, to study the response to the SPR spectrum. We will also test several configurations, including nanodisk-in-well, in an attempt to maximize the sensitivity of the metal nanohole array SPR sensors.

8993-89, Session 18

100 Mcount/s InGaAs/InP single-photon detector *(Invited Paper)*

Carmelo Scarcella, Gianluca Boso, Fabio Acerbi, Alessandro Ruggeri, Adriano Della Frera, Alberto Tosi, Politecnico di Milano (Italy)

Recently there has been considerable effort to develop photon-counting detectors for the near-infrared wavelength range (up to 1700 nm). However, a practical detector, which can be employed in many real applications and has both high count rates and low noise, is still not available. Here we show a novel technique to operate InGaAs/InP single-photon avalanche diodes (SPADs) in a free-running equivalent mode at high count rate. The photodetector is enabled with a 915 MHz sinusoidal gate signal: by keeping the SPAD gate signal unlocked from the synchronization reference of the optical waveform to be reconstructed, a free-running equivalent mode is obtained, that we called gate-free.

An extensive experimental characterization has shown how the SPAD performance improves compared with a classical square-wave gating scheme, especially for non-periodic high-throughput applications. The resulting single-photon detector achieves a maximum count rate of 100 Mcount/s, an afterpulsing probability below 0.3 %, a photon detection efficiency of 3 % at 1550 nm, a temporal resolution of 150 ps (Full-Width Half Maximum) and a dark count rate below 2000 count/s (the SPAD is cooled at 220 K). This approach is therefore a new state of the art for high throughput single-photon counting applications in the near-infrared range up to 1700 nm and can be used to measure signals at high count rate, in continuous wave or with slow time decays, where standard gated detectors would not be suitable.

8993-90, Session 18

Ultra-sensitive nano-injection photon detectors *(Invited Paper)*

Hooman Mohseni, Northwestern Univ. (United States)

We present recent breakthroughs in sensitivity of Nano-injection detectors in the short wavelength infrared (SWIR) region. Improved device design and processing has led to over three orders of magnitude reduction in the device dark current density, while a very large internal gain (~1000) can be achieved at a device bias of a few volts. When hybridized with conventional readout integrated circuits (ROIC), the device internal gain effectively reduces the ROIC noise to a fraction of 1 electron rms. Compared with linear gain avalanche detectors based on HgCdTe, the nano-injector internal dark current is four orders of magnitude smaller. The extremely small dark current, combined with the high internal gain, allows single-photon detection at thermoelectrically accessible temperatures. This can lead to a significant impact on many applications including medical imaging, night vision, quantum computing, and astronomy.

8993-92, Session 18

Integrated electronics for time-resolved array of single-photon avalanche diodes

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

The modern systems for single-photon timing applications typically present a trade-off between number of channels and performance: the higher the number of channels is, poorer the obtained performance are. Moreover the overall system counting rate is typically limited by the transfer speed of the time measurement digitalized data towards the pc.

In this work we present the integrated electronics necessary to develop photon timing systems featuring a large number of channels in conjunction with high performance.

The electric signal coming from a custom technology SPAD is read by a gigahertz bandwidth trans-impedance stage, directly reading the SPAD avalanche current and achieving high temporal resolution and low crosstalk between the different channels.

The pick-up circuit output is fed to a routing logic: the signals coming from a large photo-detector array are routed towards a lower number of time-measurement blocks, consisting of an array of time-to-amplitude converters (TAC). This part of the circuit, by means of a reconfigurable logic, allow to route all the SPADs to each TAC, without fixed connections between the two arrays.

This innovative architecture achieves extremely high performance in terms of time resolution and linearity (comparable with the state-of-art single channel systems), since the lower number of TACs allows a larger area and a higher power dissipation for the single converter, and sets a limit only to the overall system count rate, that is still limited by the transfer rate towards the pc , while the single channel rate is not influenced by the system.

8993-93, Session 18

Time-resolved optical spectrometer based on a monolithic array of high-precision TDCs and SPADs

Davide Tamborini, Bojan Markovic, Laura Di Sieno, Davide Contini, Andrea Bassi, Simone Tisa, Alberto Tosi, Franco Zappa, Politecnico di Milano (Italy)

We present a compact time-resolved spectrometer suitable for optical spectroscopy from 400 nm to 1 µm. The detector consists of a monolithic array of 16 high-precision Time-to-Digital Converters (TDC) and Single-Photon Avalanche Diodes (SPAD). The instrument has 10 ps resolution and reaches 70 ps (FWHM) timing precision over a 160 ns dynamic range with a Differential Non-Linearity (DNL) better than 1.5 % LSB. The detection module provides a synchronization output (e.g. to trigger a laser), a STOP input and an USB 2.0 link for PC interfacing. The module is composed of three electronic boards for: i) timing measurement; ii) FPGA processing; iii) power supply (from a 5 V DC input). The core of the timing board is the application-specific integrated chip composed of 16 pixels with 250 µm pitch, fabricated in a 0.35 µm CMOS technology. Each pixel has a 20 µm active area diameter SPAD and an independent TDC. In front of this array a monochromator is used to focused different wavelengths into different pixels.

The spectrometer has been used for fluorescence lifetime spectroscopy. A single mode laser (at 650nm) is focused in a cuvette containing a fluorescence solution on 20 µm spot. The fluorescence spot is imaged to the entrance of the imaging spectrometer and the signal is spectrally separated at the detector. Spectral resolution of 5 nm over an 80 nm bandwidth is achieved. Spectral and lifetime spectroscopy of Nile blue is demonstrated.

Conference 8994: Photonic and Phononic Properties of Engineered Nanostructures IV

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8994-1, Session 1

Integrated silicon photonics systems with gain *(Invited Paper)*

William Fegadolli, Se-Heon Kim, Sameer Walavalkar, Andrew Homyk, Axel Scherer, California Institute of Technology (United States)

Addition of active gain material into silicon photonics has been a challenging goal that has recently been realized in various ways. In this presentation, we will provide an overview of the traditional methods of wafer-bonding of laser material to silicon as well as explore new alternatives that enable silicon to become an opto-electronic material. We will also show optical spectroscopy systems that have been constructed by integrating silicon photonics components.

8994-2, Session 1

Passive and active tuning of optically-resonant nanostructures *(Invited Paper)*

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

Optically resonant plasmonic and high index dielectric nanostructures form the basis of nanophotonic devices and circuits. There is a long history of spectrally tuning their optical resonances by changing the size, shape, and dielectric environment of these nanostructures. In this presentation, I will discuss ways in which these resonances can be tuned passively by electrical doping and anneal treatments as well as actively by electrical gating.

8994-3, Session 1

Enabling nanophotonics with plasmonics and metamaterials *(Invited Paper)*

Vladimir M. Shalaev, Urcan Guler, Gururaj V. Naik, X. Meng, Mikhail Y. Shalaginov, Alexei Lagutchev, Evgenii E. Narimanov, Alexander V. Kildishev, Alexandra Boltasseva, Purdue Univ. (United States)

Manipulating and controlling photons on nanoscale needed for the nanophotonic circuitry and other important applications requires novel plasmonic metamaterials with unique properties. Recent progress in the development of optical metamaterials allows unprecedented control over the flow of light on the nanoscales. Metamaterials (MMs) are rationally designed artificial materials with versatile properties that can be tailored to fit almost any practical need and thus go well beyond what can be obtained with "natural" materials. We review the exciting field of optical metamaterials and discuss the recent progress in developing tunable and active MMs, nanolasers, artificial optical magnetism, semiconductor-based and loss-free negative-index MMs, and a new means for engineering the photonic density of states with MMs. New plasmonic materials with superior properties based on transparent conducting oxides and ceramics will be also discussed. Finally, we review a new approach for controlling light by using meta-surfaces. Similar to the surface science that in the past revolutionized the physics and open up a family of new phenomena and applications unattainable with 3D systems, we envision that metasurfaces can make a difference for the fields of metamaterials and transformation optics as well as for the science of light in general.

8994-4, Session 1

Cavity optomechanics: quantum coherent coupling of light and mechanical motion *(Invited Paper)*

Tobias J. Kippenberg, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

No Abstract Available

8994-5, Session 2

Recent progress in high-power single-mode quantum cascade lasers *(Invited Paper)*

Manijeh Razeghi, Northwestern Univ. (United States)

Quantum cascade lasers have been widely adopted in a variety of applications. For many applications, not only the output power, but also the beam quality and single mode property play decisive role in the system. Manipulation of the spectral and spatial beam quality is achieved through integration of photonic components with the quantum cascade gain medium. A new type of lasers termed as [beta]-type distributed feedback ([beta]-DFB) lasers is proposed. Compared with the more complicated photonic crystal distributed feedback (PCDFB) lasers, the [beta]-DFB laser offers a cost-effective alternative for single mode power scaling.

8994-6, Session 2

Development of metal organic vapour phase epitaxy for re-grown photonic crystal surface emitting lasers

Benjamin J. Stevens, Luke Shepherd, Richard J. E. Taylor, David T. D. Childs, Kristian M. Groom, Salam Khamas, Jay Sarma, Richard A. Hogg, The Univ. of Sheffield (United Kingdom)

Photonic crystal surface emitting lasers (PCSELs) have desirable characteristics such as controllable beam shaping, polarisation control, and power/area scalability. PCSELs realised by a single epitaxial overgrowth offer advantages over wafer fused devices in terms of heat extraction, current injection, and possible reliability issues. Regrowth allows the removal of the fused interface and free surfaces. Furthermore, high coupling coefficients may be achieved with suitable waveguide design for all-semiconductor PCSELs.

Our overgrowth technology allows the realisation of high refractive index contrast gratings by using GaAs and InGaP alloys. Through the use of careful selective etching, aluminium containing layers are never exposed during the overgrowth procedure, but are utilised in the device design. Thin GaAs layers, in conjunction with a carefully controlled temperature profile, help prevent a phosphorus : arsenic interchange during the metal organic vapour phase epitaxy overgrowth procedure. In order to achieve high grating infill (void free) along with good planarization in high aspect ratio structures we discuss the role that the V:III ratio plays and illustrate this with TEM images. We will go on to describe the effect that the overgrowth parameters have upon device performance. We will discuss strategies for device design in order to maximise coupling coefficient for a range of materials systems and emission wavelengths.

8994-7, Session 2

Enhanced transmission in photonic crystals microcavity filters in ridge-waveguide format

Aju S. Jugessur, The Univ. of Iowa (United States)

The design and applications of one- or two-dimensional photonic crystal (PhC) microcavity filters [1-3] have been widely investigated and reported over the last several years. The functionality of these devices can be tailored to suit any specific application such as optical filters [2, 4], sensors [5,6] and optical memory [7]. However, the coupling of light into these miniature devices has always been a challenge, in particular, when light transits the waveguide region to the photonic crystal structures. This modal transition results in scattering losses leading to low optical transmission. In this work, 2-D photonic crystal microcavity structures with mode-matching features [4] embedded in ridge waveguides have been designed using 2-D FDTD modeling tool and fabricated on GaAs/AlGaAs substrate using Electron Beam Lithography (EBL) and Reactive Ion Etching (RIE). The ridge-waveguide format enables easy integration with other photonic device components in a planar configuration and suitable for dense integrated photonic circuits. In this work, a similar technique is applied to two-dimensional PhC microcavity filters and an increase in optical transmission by a factor of 5 is obtained by the addition of the mode-matching features. This work will present a detailed analysis and results demonstrating the application of mode-matching methods to 2-D photonic crystal microcavity filters embedded in ridge waveguides, for increased transmission. Fully developed versions of these microcavity filters with enhanced transmission could be tailored for a wide range of photonic device applications, particularly suitable, for optical filters and sensors.

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8994-8, Session 2

High-performance photonic crystal membrane reflectors by magnetically-guided metal-assisted chemical etching

Yichen Shuai, The Univ. of Texas at Arlington (United States); Karthik Balasundaram, Parsian K. Mohseni, Univ. of Illinois at Urbana-Champaign (United States); Deyin Zhao, The Univ. of Texas at Arlington (United States); Hongjun Yang, The Univ. of Texas at Arlington (United States) and Semerane, Inc. (United States); Xiuling Li, Univ. of Illinois at Urbana-Champaign (United States); Weidong Zhou, The Univ. of Texas at Arlington (United States)

Based on Fano resonance principles in photonic crystals, high performance broadband reflectors can be realized with 100% reflection. Over the last few years, high performance membrane reflectors have been demonstrated on various semiconductors, fabricated using dry etching techniques, along with the demonstrations of innovative lasers on Si, GaAs, and InP substrates. On the other hand, high aspect ratio nano-columns and air-holes have also been realized, through a completely wet metal-assisted chemical etching (MacEtch) process. Such wet processes can lead to the formation of large area scalable high quality nanoscale structures, with direct or arbitural shaped topologies, which is critical for the formation of large area 2D and 3D nanoscale-strutures, for high performance photonic crystal membrane reflectors, filters, and metamaterials. Periodic nanohole arrays were first defined through electron-beam lithography patterning of a metal tri-layer stack of Au (20 nm)/Ni (10 nm)/Au (5 nm). MacEtch was then performed in a solution of hydrofluoric acid, hydrogen peroxide, and deionized water under the influence of an external magnetic field. The magnetic field helps to ensure uniform and vertical drilling of holes in the active device area, such that delamination and detouring of the discrete metallic catalyst disks are avoided during MacEtch. Applying an innovative magnetic field guided MacEtch process, we report here high performance membrane reflectors on SOI with controlled sidewall vertical etching and high reflection around 1550 nm.

The work was partially supported by US ARO (W911NF-09-1-0505) and by US AFOSR MURI program (FA9550-08-1-0337) at the Univeristy of Texas at Arlington, and by DOE Division of Materials Sciences under Award Numbers DEFG02-07ER46471 through the Frederick Seitz Materials Research Laboratory at the University of Illinois.

8994-9, Session 3

Inhibited coupling hollow-core photonic crystal fiber *(Invited Paper)*

Fetah A. Benabid, Frederic Gérôme, L. Vincetti, Benoit Debord, Meshaal Alharbi, Thomas D. Bradley, XLIM Institut de Recherche (France)

We review the recent progress on the enhanced inhibited coupling in kagome hollow-core photonic crystal fiber by introducing negative curvature in the fiber-core shape. We show that increasing the hypocycloid contour curvature leads to a dramatic decrease in transmission loss and optical overlap with the silica surround and to a single modedness. Fabricated hypocycloid core hollow core photonic crystal fibers with a transmission loss in the range of 20-40 dB/km and for a spectral range of 700nm-2000nm have now become typical.

8994-10, Session 3

Transient dynamic distributed strain sensing using photonics crystal fibres

Biswajyoti Das, D. Roy Mahapatra, Gopalkrishna M. Hegde, Indian Institute of Science (India); Sathya V. Hanagud, Georgia Institute of Technology (United States)

Photonic crystal fibres (PCFs) are a class of one-dimensional photonic crystals that have potential for multidimensional and multifunctional sensing beyond what a conventional optical fibre can offer. They can be used to sense thermo-mechanical strain by either the index-guided method or by the photonic bandgap method. Static strain, which is measured simply by resonant wavelength shift, has been extensively studied. The need for strain sensors capable of accurately measuring strain in adverse conditions, high strain rate ballistic impact or shock wave loadings call for a new and efficient way to design and integrate photonic device. Recent studies show great potential in using PCFs for dynamic strain sensing using Rayleigh and Brillouin scattering. We consider a simple 1D PCF and analytically obtain the dynamic strain estimate. To simulate the dynamic responses of the PCF subjected to a non-uniform strain wave we make use of the perturbation theory and the coupled mode theory. A method has also been proposed to decouple the longitudinal/ bending strain from the lateral compressive strain induced on the fibre. For solving the inverse problem of determining the strain as a function of space and time, a parametric study has been done

considering output signal due to a mixed-frequency reference signal. To compute the effect of high strain impact or a shock wave, a shock like modulation of the dielectric has been considered. Experimental investigations with a micro-shock wave induced strain gradients on a metal alloy surface are reported and results are correlated with the analytical model.

8994-11, Session 3

Merged photonic crystal slot waveguide: confining slow modes in tiny volumes

Matthieu Roussey, Petri A. Stenberg, Arijit Bera, Seppo Honkanen, Markku Kuittinen, Univ. of Eastern Finland (Finland)

In the past decades the photonic crystal structures have shown their potential to reduce the size of optical components. More recently, the slot waveguides have appeared as a wonderful tool to confine and guide light in regions 20 times smaller than the wavelength. We propose to combine the two nanostructures by directly patterning the rails of a silicon slot waveguide. In addition, this structure is fully filled with a nonlinear material (titanium dioxide) using the atomic layer deposition (ALD). In addition, a cavity is created in the middle of the structure in order to obtain a resonance mode in the center of the photonic band gap. The response of the structure leads to a slow light mode propagating in an 80 nm-wide slot waveguide. The consequence is a huge enhancement of the nonlinear properties of titanium dioxide filling the slot, which may pave the way to new kind of nanostructures for integrated optics. The design of the structure has been performed using the 3D finite difference time domain method. The slow light effect in this merged photonic crystal slot waveguide has been theoretically investigated. The fabrication is realized with electron beam writing combined with the ALD, which offers us an accurate control of the geometrical parameters of the device at the nano-scale. The transmission spectrum and the propagation losses of the device have been measured with a good agreement with the theoretical predictions. A wide range of applications to the device exists from telecom (modulators, filters…) to sensors (functionalization, addressing…).

8994-12, Session 3

Inducing and harnessing stimulated Brillouin scattering in photonic integrated circuits *(Invited Paper)*

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

We review recent progress in inducing and harnessing Stimulated Brillouin Scattering (SBS) in integrated photonic circuits, with applications such as narrow-linewidth lasers, slow- and fast-light, microwave signal processing, Brillouin dynamic gratings and non-reciprocal devices.

8994-13, Session 4

Active acoustic metamaterials with programmable effective density and elasticity using a fractional derivative controller *(Invited Paper)*

Amr M. Baz, Univ. of Maryland, College Park (United States)

A class of active acoustic metamaterial (AAM) is presented. The proposed AAM consists of an acoustic transmission line connected in parallel to an array of Helmholtz resonators that are provided with actively controlled boundaries. In this manner, the AAM is in effect an assembly of periodic cells, each of which consists of a Helmholtz resonator connected in parallel to two sections of the transmission line. The two sections meet the Helmholtz resonator at its neck. The local control action at each Helmholtz resonator of a unit cell is generated by using a Fractional Derivative (FD) controller that relies in its operation on the measurement of the flow resulting from the deflection of the resonator boundary and the flow rates inside the two transmission line sections before and after the resonator. Such a single local control action is shown to be capable of controlling the local effective density and elasticity of each unit cell.

A lumped-parameter model is developed to model the dynamics and control characteristics of the AAM under different gains and exponents of the FD controller. The model is exercised to demonstrate the ability of the FD controller in generating metamaterials with desirable distributions of the effective density and elasticity over broad frequency ranges as compared to conventional Proportional and Derivative (PD) controllers.

With such capabilities, the development of AAM with FD control action may provide viable means for generating desirable spatial distributions of density and elasticity over broad frequency band using a small number of control actuators.

8994-14, Session 4

Quasi-two-dimensional acoustic metamaterials *(Invited Paper)*

Daniel Torrent, Univ. Politècnica de València (Spain); V. M. Garcia-Chocano, R. Gracia-Salgado, F. Cervera, Univ. Politécnica de Valencia (Spain); José Sánchez-Dehesa, Univ. Politècnica de València (Spain)

We will show how to engineer quasi-two-dimensional artificial structures that acoustically behave as positive, double negative or density-near zero acoustic metamaterials. The scattering units consist of a cavity drilled in one surface of the 2D waveguide and they have an inner structure whose geometrical parameters can be selected in order to obtain the chosen dynamical behavior. We have theoretically studied the possible applications of these structures. Also, we will report the practical realization of several samples as well as their experimental characterization.

8994-15, Session 4

Design and fabrication of a gradient-index phononic quartz plate lens *(Invited Paper)*

Tsung-Tsong Wu, Meng-Jhen Chiou, National Taiwan Univ. (Taiwan); Yu-Ching Lin, Takahito Ono, Tohoku Univ. (Japan)

This paper presents results on the numerical and experimental studies of focusing and waveguiding of Lamb waves in an AT-cut quartz gradient-index phononic crystal (GRIN PC) plate lens which is attached by a linear phononic plate waveguide. The band structures of square-latticed AT-cut quartz phononic crystal plates with different filling ratios are analyzed firstly using the finite element method. The anisotropic properties of the lowest anti-symmetric Lamb mode are discussed. Then, the design of an AT-cut quartz based GRIN PC plate lens is provided. The effect of the gradient coefficient on the focusing characteristics of the GRIN PC plate lens is also given. In the design of the linear waveguide, the propagation modes in square-latticed PC plates with different widths are studied, and then, the results are served for the experimental design.

In the micro-fabrication, the deep reactive ion etching (Deep-RIE) process with a laboratory-made etcher was utilized to fabricate both the GRIN PC plate lens and the linear phononic waveguide on an 80 µm thick AT-cut quartz plate. Interdigital transducers were fabricated directly on the quartz plate to generate the plate waves and a vibrometer was used to detect the wave fields. The measured results on the focusing and waveguiding are in good accordance with the numerical predictions.

8994-16, Session 4

Funneled focusing of planar acoustic waves utilizing the metamaterial properties of an acoustic lens

Ezekiel Walker, Arup Neogi, Arkadii A. Krokhin, Univ. of North Texas (United States); Miguel M. Rojas, Delfino R Contreras, Univ. Autónoma del Estado de México (Mexico)

Metamaterial acoustic lenses are acoustic lenses that take advantage of the negative index of refraction that arise due to the antiparallel nature of the wave propagation and group velocity in some periodic arrangements. Studies, both theoretical and experimental, have clearly shown the focusing ability of these metamaterial phononic crystals with the caveat that the focused acoustic waves are sourced by an approximate point source emission. In this study, we present a theoretical and experimental demonstration of two phononic lenses that utilize the negative index of refraction available in their second bands to funnel and focus acoustic waves from a plane-wave source.

The base of each phononic crystal is composed of 1.6 mm diameter stainless steel rods in a square lattice arrangement with lattice constant 2 mm. COMSOL 4.2, an FDTD simulation program, is used to calculate the bandstructure and simulate the acoustic behavior of each lens; MATLAB is used in combination with Multiple Scattering Theory (MST) to calculate the equifrequency surface. An Olympus Panametrics V301 plane-wave immersion transducer is used as the wave source, and the transmitted field is mapped using an in-house made hydrophone and qualitatively confirmed using another V301 transducer.

Results show good agreement between theory and experiment. Lens A focuses in a funnel-like manner by focusing the acoustic waves along the optical axis laterally, but not axially, almost acting as an acoustic phaser. Lens B exhibits the standard focusing both axially and laterally.

8994-17, Session 5

Prospects of diamond defect centers as quantum light sources *(Invited Paper)*

Oliver Benson, Humboldt-Univ. zu Berlin (Germany)

No Abstract Available

8994-18, Session 5

ICP-etched diamond microstructures for photonics and lasers *(Invited Paper)*

Erdan Gu, H. Liu, Jennifer E. Hastie, Alan J. Kemp, Martin David Dawson, Univ. of Strathclyde (United Kingdom)

Diamond is a remarkably versatile optical material with a host of applications in areas including lasers, light-emitting diodes (LEDs), nonlinear optics and quantum technology. Many of these applications place very high demands on the processing tolerances of the diamond and in the formation of precisely engineered structures on the micro- and nanoscale. Here, we review implications of controllable and versatile microstructure fabrication in single-crystal diamond using inductively-coupled plasma dry etching for a variety of such applications. ICP etching is shown to permit surface preparation/smoothing to promote hybrid bonding of diamond to other materials such as semiconductor laser and LED semiconductor heterostructures, and to substrates and cladding layers for guided wave optics applications. We will illustrate these applications by examples in semiconductor disk laser technology, gallium nitride LEDs transfer printed onto diamond, and in diamond waveguide systems. The removal in this process of surface damage caused by mechanical polishing also has implications for the growth of high quality homoepitaxial diamond films and observation of color center emission. The fabrication of high-quality microlenses in diamond for light extraction and beam control applications in LEDs and in confocal cavity and monolithic structures for laser and nonlinear optics applications is also described; these have implications in areas such as LED-based microsystems technology, compact optically-pumped semiconductor lasers and diamond Raman lasers and Raman wavelength converters.

8994-19, Session 5

Photonic and phononic crystal cavities in diamond *(Invited Paper)*

Janine Riedrich-Möller, Laura Kipfstuhl, Felix Guldner, Christoph Becher, Univ. des Saarlandes (Germany)

The deterministic coupling of single quantum emitters to photonic crystal (PhC) cavities is considered an important step towards integrated solid-state devices for quantum information processing. In this context, color centers in diamond, e.g. nitrogen- (NV) or silicon-vacancy (SiV) centers have recently attracted significant interest due to their extraordinary properties like long spin coherence times or narrow bandwidth emission, respectively. Coupling of color centers to optical cavities can be accomplished by using PhC cavities that consist of a periodic array of air holes directly milled in a single crystal diamond membrane as these cavities offer tiny mode volumes for strong emitter–cavity coupling as well as scalable architectures for integrated photonic devices.

We here present two routes for the deterministic coupling of single color centers to diamond PhC cavities: in the first approach we fabricate cavities directly at the predetermined position of single Silicon-Vacancy (SiV) centers in a single crystal diamond membrane. The cavities can be aligned both to the emitter's position and dipole orientation. We observe a large Purcell enhancement of the spontaneous emission and a reduction of the SiV center spontaneous emission lifetime. In a second approach, we investigate the deterministic implantation of NV centers into PhC cavities with high spatial precision using a nano-implantation technique.

The very same photonic structures in diamond that confine light at very small scales, e.g. 1D PhC or "nanobeam cavities," turn out to also confine acoustical fields thanks to the periodic arrangement of materials with different velocities of sound. This additional confinement gives rise to optomechanical nano-resonators offering strong phonon-photon coupling and integration of acoustic and optical functionalities on the same chip. The unique material properties of diamond allow for very high mechanical resonance frequencies in the few 10 GHz range. We present FDTD and FEM simulations indicating high optical (Qopt = 107) and acoustical (Qacoust= 106) quality factors as well as large optomechanical coupling coefficients in the MHz range. We discuss strategies for fabrication of such devices.

8994-20, Session 6

Diamond nanostructures for optomechanics and quantum optics *(Invited Paper)*

Paul Barclay, Univ. of Calgary (Canada)

Diamond based nanophotonic devices promise to dramatically impact experiments in quantum nanoscience by providing an efficient means to optically control quantum systems. We have designed novel diamond based waveguides for efficiently collecting emission from embedded nitrogen vacancy centers. These device can be fabricated from bulk diamond, and efficiently coupled to optical fiber taper waveguides. We have also developed schemes for optically modulating the electronic state of NV centers using diamond based mechanical nanostructures. This talk will present these schemes and report on on-going efforts to demonstrate these devices experimentally.

8994-21, Session 6

Diamond photonic devices for quantum-optical networks *(Invited Paper)*

Zhihong Huang, Charles Santori, Victor M. Acosta, Hewlett-Packard Labs. (United States); Andrei Faraon, California Institute of Technology (United States); Raymond G. Beausoleil, Hewlett-Packard Labs. (United States)

We will discuss devices that could serve as building blocks for integrated diamond photonics. Diamond appears promising for quantum information applications because it hosts a defect, the nitrogen-vacancy center, that has long-lived electronic spin coherence and capability for optical manipulation and readout at the single-defect level. However, one challenge in this system is that, in bulk diamond the spectrally narrow zero-phonon-line (ZPL) NV emission accounts for only a few percent of the total emission. Thus, much effort has been made to develop optical micro-cavities which enhance the intensity and collection efficiency of the ZPL NV emission. We will discuss the microring resonators and photonic crystal microcavities for Purcell enhancement, and grating couplers to enhance the collection efficiencies.

In order to create NV centers near a diamond surface for quantum information and magnetometer applications, we have used the helium ion microscope to demonstrate a new method for NV center creation in diamond. Near-surface NV centers can be created with spatial resolution below 0.6 ?m. We studied the density, creation efficiency, and spectral linewidths at optical and microwave frequencies for NV centers produced using various helium ion implantation doses. The optical linewidths are narrower than those of similar nitrogen-vacancy centers produced using nitrogen ion implantation.

Finally, we discuss a diamond optical switch that could be used to reconfigure a quantum network.. This thermally controlled switchcouples two waveguides through a microring resonator (10?m-diameter) on a 200nm-thick diamond membrane. Quality factors of Q=3000 are measured with free spectral range of FSR=2.4nm and linewidth of ??=0.2nm. The switching is achieved through variation in the refractive index of ring resonator produced by changing its temperature. By heating the microring from 300 to 400K, 0.4nm switching range can be achieved. In addition, the small footprint of the microring opto-thermal switch is suitable for large scale integration.

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8994-22, Session 6

Diamond photonics and applications: frequency combs, cavity QED, and optomechanics *(Invited Paper)*

Marko Loncar, Harvard School of Engineering and Applied Sciences (United States)

Diamond possesses remarkable physical and chemical properties, and in many ways is the ultimate engineering material - “the engineer’s best friend!” For example, it has high mechanical hardness and large Young’s modulus, and is one of the best thermal conductors. Optically, diamond is transparent from the ultra-violet to infra-red, has a high refractive index (n = 2.4), strong optical nonlinearity and a wide variety of light-emitting defects. Finally, it is biocompatible and chemically inert, suitable for operation in harsh environment. These properties make diamond a highly desirable material for many applications, including high-frequency micro- and nano-electromechanical systems, nonlinear optics, magnetic and electric field sensing, biomedicine, and oil discovery. One particularly exciting application of diamond is in the field of quantum information science and technology, which promises realization of powerful quantum computers capable of tackling problems that cannot be solved using classical approaches, as well as realization of secure communication channels. At the heart of these applications are diamond’s luminescent defects—color centers—and the nitrogen-vacancy (NV) color center in particular. This atomic system in the solid-state possesses all the essential elements for quantum technology, including storage, logic, and communication of quantum information.

In this talk I will review recent advances in nanotechnology that have enabled fabrication of nanoscale optical devices and chip-scale systems in diamond that can generate, manipulate, and store optical signals at the single-photon level. Examples include a room temperature source of single photons based on diamond nano wires and plasmonic appertures, as well as single-photon generation and routing inside ring and photonic crystal resonators fabricated directly in diamond. In addition to these quantum applications I will present our recent work on diamond based on-chip frequency combs, as well as diamond nanomechanical resonators.

8994-23, Session 7

Optical properties of graphene: from the THz to the UV *(Invited Paper)*

Tony F. Heinz, Columbia Univ. (United States)

No Abstract Available

8994-24, Session 7

On-chip graphene optoelectronic devices for high-speed modulation and photodetection *(Invited Paper)*

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

Graphene exhibits remarkable electro-optical properties, including broadband absorption, ultrahigh carrier mobility, and potential compatibility with silicon complementary metal-oxide semiconductor (CMOS) technology. These properties make graphene appealing as the active material in electro-optic modulators and photodetectors with broadband response, high-speed operation, low power consumption, and ease of fabrication. Here we present our recent advances in integrating graphene with silicon-on-insulator buried waveguides and photonic crystal cavities. By coupling graphene to an optical cavity, we demonstrated an efficient electro-optic modulator that features a contrast of 10 dB and a switching energy of 300 fJ. Several high-speed modulators are also tested, showing a speed up to 0.57 GHz. In addition, we implemented a graphene photodetector on a silicon waveguide. A 53-um-long graphene sheet couples to the evanescent field of the waveguide mode, resulting in more than 60% absorption of the input light. We demonstrated a responsivity of 0.108 A/W, data transmission of 12.5 Gbps, and response time in excess of 20 GHz. Our results, together with recent work from other groups, show the great promise of graphene as the active electro-optic material in silicon photonic integrated circuits.

8994-25, Session 7

Graphene plasmonics *(Invited Paper)*

Tony Low, Phaedon Avouris, IBM Thomas J. Watson Research Ctr. (United States)

Recent years have seen rapid growth in the research of graphene-based plasmonics, motivated by its unique linear energy dispersion, two-dimensionality, electrostatic tunability, long-lived collective excitations and extreme light confinement. In this talk, I will review our recent study of the basic properties of graphene plasmons in nanostructures, such as its plasmonic dispersion, phonon hybrid modes, and its relative damping pathways. Identified applications space in the terahertz to mid-infrared regime will also be discussed e.g. modulators, polarizers, infrared photodetectors, light harvesting devices, enhanced surface spectroscopy and molecular sensing, among many others. Looking beyond the horizon, the yet unexplored general class of two-dimensional materials offer exciting opportunities beyond graphene plasmonics. We motivate this notion with graphene's immediate cousin, its Bernal stacked bilayer, showing uniquely different and novel plasmonic effects.

8994-26, Session 8

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

Luca Dal Negro, Boston Univ. (United States)

The ability to tailor light-matter interactions using metal-dielectric nanostructures is at the heart of nanoplasmonics and nano-optics technologies. Efficient approaches for nanoscale electromagnetic field enhancement, concentration and manipulation over desired spatial-spectral bandwidths and angular ranges are enabled by the exquisite control of propagating and non-propagating electromagnetic fields that is possible by the engineering of resonant optical nanomaterials.

In particular, recent advancements in the design, fabrication and characterization of periodic and aperiodic metal-dielectric arrays of nanoparticles supporting localized surface plasmon excitations offer unique opportunities to demonstrate novel functionalities and optical devices that leverage photonic-plasmonic coupled resonances. The manipulation of photonic-plasmonic coupling in nanomaterials has recently led to engineering broadband linear and nonlinear optical nano-antennas, switchers, nanoscale energy concentrators, biosensors, and resonant nano-cavities for deep sub-wavelength light sources and photodetectors with plasmon-enhanced emission/absorption rates.

In my talk, I will present our recent results on the design, nanofabrication and characterization of sub-wavelength field localization in metallic and metal-dielectric nanostructures with enhanced optical cross sections for applications to light emission, energy conversion, optical sensing, and nonlinear nano-optics using the widespread silicon materials/processing platform [1-14]. In particular, I will discuss nonlinear and polarization switchable optical nanoantennas, Si-compatible plasmonic ring active nanocavities for high density integration of ultra-small light sources, and the manipulation of Orbital Angular Momentum (OAM) of light using diffractively coupled plasmonic nanostructures and aperiodic geometry. Finally, our recent work on the development of metal-free resonant materials for plasmonic field concentration and manipulation will also be presented in the context of enhanced light sources and omnidirectional optical absorbers.

8994-27, Session 8

Engineering optical properties of colloidal quantum dots in metallic nanostructures

Jayson Briscoe, Sang-Yeon Cho, New Mexico State Univ. (United States)

We report on the successful demonstration of extraordinary optical transmission (EOT) assisted photoluminescence (PL) of CdSe/CdS colloidal quantum dots (QDs). We experimentally demonstrate engineering of fundamental optical properties of QDs such as the suppression of inherent homogenous and inhomogenous broadening processes of QDs. This is achieved by coupling spontaneously emitted photons (SEPs) from the QDs into resonant electromagnetic waves in an engineered metallic nanostructure. QDs were encapsulated between a subwavelength 2-D nanohole array (NHA) and a distributed Bragg reflector (DBR). The NHA was designed to convert SEPs at surface normal incidence into surface plasmon polariton (SPP) modes and to locate its EOT peak within a forbidden band of the DBR. This design provides spectral and angle selective optical feedback to the nanostructure, maximizing the interaction between SEPs and the SPP mode. Experimental results demonstrate spectral narrowing of 22nm and a red-shift of 7nm around the center wavelength, indicating a modification of the spontaneous emission profile of the QDs. Further spontaneous emission control can be achieved by changing the plasmonic resonance conditions through modifying the period of the NHA.

8994-28, Session 8

Optical characterization of plasmonic membranes and examples of their applications

L. Andrea Dunbar, Rolf Eckert, Branislav D. Timotijevic, Ross P. Stanley, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

There are two main challenges for plasmonic components at visible wavelengths, metallic losses and fabrication costs. Fabrication is expensive due to the sub-micron feature sizes required at these wavelengths. At mid-infrared wavelengths metal losses are usually lower and the feature size increases to greater than a micron. This means that photolithography can be used as an inexpensive up-scalable fabrication method, opening access to marketable plasmonic component at infra-red wavelengths.

Here we design, fabricate and characterize plasmonic components for mid infrared applications. Photolithography is used to fabricated micron hole arrays in ultra-thin (<500nm) metallic membranes. A FTIR is used to optically characterize these plasmonic structures by measuring their polarization and angular (theta and phi) dependant transmission. Good agreement is found between experimental measurements and a modal expansion model. Design rules enable the structures to be used for a diverse range of applications.

We demonstrate these membranes as optical filters. The membranes at normal incidence show large transmissions (90%) with an excellent extinction with low transmission over several microns wavelength range. Angularly integrated transmission is also investigated where they are shown to be very effective as angularly independent filters. A wide range of applications from multispectral imaging to photovoltaic filters is foreseen.

The membranes can also be used as excellent surfaces for chemical sensing. Normally chemical sensing is made with ATR or high angle reflectivity to increase the interaction length. These membranes demonstrate an enhanced interaction in normal transmission setup. A factor of 10 greater absorption of a monolayer of perfluorooctyltrichlorosilane (FOTS) was measured when compared to high angle reflectivity at 75°.

8994-29, Session 8

Efficient coupling of InGaAs quantum dots to propagating surface plasmons in lithographically defined Au-waveguides on GaAs

Michael Kaniber, Gregor Bracher, Nicolas Coca-Lopez, Konrad Schraml, Max Bichler, Jonathan J. Finley, Technische Univ. München (Germany)

Gold waveguides with width w=1-5µm and lengths l=10-50µm are defined by a combination of electron beam lithography and thermal evaporation on a GaAs substrate with an embedded single layer of InGaAs quantum dots grown by molecular beam epitaxy. Applying low-temperature confocal microscopy enables us to optically study the coupling of near-surface (<25nm) single quantum dots to surface plasmon polariton modes propagating at the Au-dielectric interface. The strongly confined plasmon fields at the waveguides edges lead to a selective excitation at the remote waveguide end, enabling single quantum dot spectroscopy even on medium density (30-50 per µm?) quantum dot samples. Probing the spontaneous emission dynamics of plasmon-excited quantum dots shows a reduction of the exciton lifetime of >2x for quantum dots located at the waveguide edges compared to the intrinsic value ~1ns. Photon correlation measurements exhibit pronounced photon antibunching (g(2)(0)<0.5) when probing a plasmon-excited quantum dot at the remote waveguide edge. Those experimental findings will be corroborated by simulations clearly demonstrating that even the coupling of quantum light from a near-by emitter to the propagating plasmon mode in such systems is feasible. The study and understanding of the coupling of optically active InGaAs quantum dots to plasmonic waveguides is an important step towards future on-chip quantum circuits.

8994-31, Session 8

Design optimization and fabrication of plasmonic nano sensor

Salah El Zohary, Univ. of Tokushima (Japan); Abdulilah Azzazi, The American Univ. in Cairo (Egypt); Hiroyuki Okamoto, Anan National College of Technology (Japan); Toshihiro Okamoto, Masanobu Haraguchi, Univ. of Tokushima (Japan); Mohamed A. Swillam, The American Univ. in Cairo (Egypt)

We propose a novel design for a high sensitive sensor based on a plasmonic square resonator. The detection performance of our device has been numerically verified by (FDTD) finite-difference time-domain simulations. The spectral sensitivity obtained found to be 700 nm/RIU, where RIU is the refractive index unit. Our proposed sensor was found to have a detection limit in the order of 10 to the negative sixth. The plasmonic sensor was fabricated using (FIB) focus ion beam milling. The proposed sensor consists of a trench channel plasmonic waveguide. Its width is about 100 nm, and a square resonator with length of 2000 nm. The gap between the waveguide and the square resonator is about 20 nm.

Our design leads to an ultra compact sensor suitable for on-chip sensing applications associated with a high sensitivity.

8994-32, Session 9

Broadband three-dimensional plasmonic metamaterials at optical frequencies *(Invited Paper)*

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

A broadband metamaterial capable of negatively refracting light across the entire visible and near-infrared spectrum would enable unprecedented manipulation of light, but has to date remained elusive. In this presentation, we introduce the design and three-dimensional characterization of metamaterials with optical properties that are largely insensitive to the wavelength, orientation and polarization of incident light. First, we use transformation optics to design the metamaterial constituents. Our approach begins with an infinite plasmonic waveguide that supports a broadband but dark (i.e, not easily optically accessed) negative index mode. Conformal mapping of this waveguide to a finite split-ring-resonator-type structure transforms this mode into a bright (i.e, efficiently excited) resonance composed of degenerate electric and magnetic dipoles. A periodic array of such resonators exhibits negative refractive indices at optical frequencies in multiple regions exceeding 200 nm in bandwidth, confirmed through simulations of plane wave refraction through a metamaterial prism. Then, we introduce a novel tomographic technique, cathodoluminescence (CL) spectroscopic tomography, to probe the metamaterial resonator in three dimensions with nanometer-scale resolution. In this technique, two-dimensional CL maps of the three-dimensional nanostructure are obtained at various orientations. Next, a filtered back projection is used to reconstruct the CL intensity at each wavelength. The result of this CL spectroscopic tomography is the first three-dimensional map of optical properties with nanometer-scale spatial and spectral resolution. Our results illustrate the power of transformation optics for new metamaterial design and provide a foundation for high-resolution, three-dimensional visualization of light-matter interactions in novel materials systems and devices.

8994-33, Session 9

Experimental and modelling results for plasmon soliton waves

Gilles Renversez, Institut Fresnel (France); Wiktor Walasik, Institut Fresnel (France) and ICFO - Institut de Ciències Fotòniques (Spain); Mélinda Olivier, Univ. de Rennes 1 (France) and Univ. Pardubice (Czech Republic); Yaroslav V. Kartashov, Institute of Spectroscopy (Russian Federation); Virginie Nazabal, Univ. de Rennes 1 (France); Petr Nemec, Univ. Pardubice (Czech Republic); Mathieu Chauvet, FEMTO-ST (France)

Merging the fields of plasmonics and optical solitons attracted a lot of attention in the last decades. Devices supporting plasmon-soliton waves propagating along metal/nonlinear dielectric interfaces may be of interest for sensor applications as they offer an alternative way to couple light with plasmons. The first description of 1D stationary solution composed of a spatial soliton part coupled with a plasmonic wave was given 30 years ago. More recently, several articles have been published on this research topic of plasmon-soliton coupling (Feigembaum & Orenstein, 2007)(Bliokh et al., 2009)(Davoyan et al., 2009)(Milian et al, 2012)(Marini et al, 2013).

Nevertheless, up to now, no experimental results have been published on this issue of soliton-plasmon coupling. The main reason is that for the already proposed structures the required induced nonlinear refractive index change (or peak power) is too high compared to the one attainable for real materials used in integrated optics.

In this work, we describe our new results that concern both the modelling and the experimental sides.

For the modelling part, we are now able to study metal/nonlinear dielectric/linear dielectric structures using three complementary numerical approaches that allow us to get a complete description and understanding of these photonic strutures.

For the Finite Element method we developped 2D results can also be obtained starting from Maxwell's equations.

The propagation of finite duration light pulse is now also studied using FDTD simulations that complete our previous 'modal' approaches of the study of soliton-plasmons coupling.

Our recent experimental results dealing both fabrication issues based on chalcogenide glasses and plasmon soliton characterization using a powerful OPO laser source are promising. An other type of realistic physical system where such a soliton plasmon coupling occur will also be described.

8994-34, Session 9

CMOS-compatible metallic nanostructures for visible and infrared filtering

Ujwol Palanchoke, Salim Boutami, Jérome Hazart, CEA-LETI-Minatec (France)

Metal-Insulator-Metal (MIM) and Insulator-Metal (IM) sub-wavelength arrays were studied to perform filtering in Visible (VIS) and Near-Infrared (NIR) respectively [1]. Most image sensors use infrared cut-off filter to allow correct color rendering. However, enhanced imaging with rich texture detail could be achieved with joint processing of visible and near infrared data. Therefore we investigated the MIM sub wavelength pattern using silicon nitride (SiN) core and aluminum metal for visible color filtering, and IM sub wavelength array with the same materials for near-infrared filtering. The study was made using Rigorous Coupled Wave Analysis (RCWA). Transmission as high as 50 % was observed for VIS-filters, while that for NIR filters, maximum transmissions of 60% and 80% were observed in 800nm – 900nm and 900nm – 1500nm wavelength ranges respectively. Metallic absorption in Infrared is significantly reduced using IM structure. Enhancement in Infrared transmission by factor of 1.5 (atleast), was observed upon using IM structure instead of MIM structure. Effect of rounded patch corners on transmission spectra was also investigated. Blue shift in transmission spectra was observed with increase in roundness of the patch corners. Angular tolerance of ± 20° in incidence was observed for the arrays studied.

Reference:

[1] U. Palanchoke, S. Boutami and J. Hazart, “Dispositif de filtrage spectral dans les domaines visible et infrarouge”, FR patent 12 57823 (2012).

8994-35, Session 9

Efficient plasmonic energy conversion to an electrical signal using a plasmon field effect transistor

Hossein Shokri Kojori, Univ. of Miami (United States); Juhyung Yun, Univ. at Buffalo (United States); Younghun Paik, Univ. of Miami (United States); Joondong Kim, Kunsan National Univ. (Korea, Republic of); Wayne A. Anderson, Univ. at Buffalo (United States); Sung Jin Kim, Univ. of Miami (United States)

Plasmonics is considered as one of the solutions for the next generation electronics due to its high speed operation and integration capability with current electronics. This plasmonic electronics concept needs a bridge device to convert plasmonic signals into electrical signals. We have successfully demonstrated a novel plasmon field effect transistor that converts plasmonic energy into electrical signal efficiently. The measured spectral response reflects the plasmonic absorption of gold nanoparticles and shows an efficient amplification with higher gate voltage bias. We believe that this new device has a great potential for wideband detector, imaging device, sensing applications and plasmonic electronics.

8994-36, Session 10

The sub-nanoscale optical response of plasmonic materials *(Invited Paper)*

John B. Pendry, Imperial College London (United Kingdom)

In optics we generally describe a material by its electrical permittivity. Sometimes the permittivity is dispersive and depends strongly on frequency, as is the case for metals, but usually it is assumed to be independent of wave vector. This assumption works well on the scale of the wavelength of light, but current experiments on nanostructured materials challenge this assumption. Theorists are still debating the correct model permittivities observed at the sub nanoscale. I shall discuss the theories, how they can be implemented to calculate optical properties, and how they also have consequences for the Van der Waals interactions and heat transfer between nanoparticles.

8994-37, Session 10

Calculating van der Waals interactions between plasmonic nanoparticles using transformation optics

Rongkuo Zhao, Yu Luo, Antonio I. Fernandez-Dominguez, John B. Pendry, Imperial College London (United Kingdom)

van der Waals force is the electromagnetic interaction between instantaneous quantum fluctuation-induced charges. It plays an important role in colloidal stability and crystallization, surface adhesion and friction, and nanoparticle self-assembly. Exact calculation of van der Waals forces between closely spaced plasmonic nanoparticles with ``singular” separations is extremely difficult both numerically and analytically because of the strong concentration of the electromagnetic fields at the nearly touching nanometric gap between them. Transformation optics is capable of mapping a small volume into any desired length scale and enables us to shed physical insight into the intricate behavior of electromagnetic fields in extremely small gaps. Through transforming two closely spaced spheres with a ``singular” gap into an annulus which possesses higher symmetry and less ``singular”, we recently developed a powerful formalism to calculate the spectra of singular and near singular structures [J. B. Pendry, A. I. Fernández-Domínguez, Y. Luo, and R. Zhao, Capturing photons with transformation optics, Nat. Phys., doi:10.1038/nphys2667 (2013)]. Applied it to study the van der Waals interactions, we [R. Zhao, Y. Luo, A.I. Fernández-Domínguez, and J.B. Pendry, Description of van der Waals Interactions Using Transformation Optics, Phys. Rev. Lett. 111, 033602 (2013)] have not only obtained fast convergence of exact calculations, but also obtained very accurate analytical approximations. It can be used directly by a broad range of people from all disciplines without requiring special knowledge. Our generic method can also be applied to the study of near field radiative heat transfer and non contact van der Waals frictions.

8994-38, Session 10

Complex DNA plasmonics

Na Liu, Max-Planck Institut für Intelligente Systeme (Germany); Baoquan Ding, National Ctr. for Nanoscience and Technology of China (China)

The rapid growth of complex plasmonic nanaomaterials calls for intelligent nanomanufacturing platforms, which offer a new level of sophistication in structural design and a greater control over individual components in space. In the past decade, structural DNA technology has emerged as a rich field of study for patterning plasmonic materials on the nanoscale. One of the grand challenges facing the development is rational assembly of anisotropic plasmonic nanoparticles into three-dimensional (3D) architectures, which exhibit well-defined optical functionalities. So far, most of the successful examples have been based on isotropic spherical building blocks. Here we demonstrate a 3D plasmonic chiral colloid, which is synthesized through deterministically grouping of two twisted gold nanorods (AuNRs) on DNA origami. Due to strong near-field coupling, these twisted rods exhibit gigantic circular dichroism (CD) at optical frequencies. Given the unique regiospecificity of DNA base pairing, the handedness of the plasmonic chiral colloid can be programmably switched through position tuning of the two AuNRs on the DNA origami with nanoscale accuracy. In addition, the anisotropic character of the AuNRs affords the first experimental evidence of chiral molecule induced orientational chirality. This is implemented by orientationally controlling the interaction of a single AuNR with the well-aligned DNA helices on the origami. Our experimental results agree well with theoretical predictions. This work will leverage the library of DNA as designer motif to synthesize arbitrary 3D plasmonic nanomaterials with tailored optical response. These DNA templated plasmonic assemblies may ultimately enable intelligent photonic devices and smart diagnostic systems, which will spur the methodological perspective of DNA far beyond its genetic role in nature.

8994-39, Session 10

Cylindrical channel plasmon resonance for single-molecule sensing

Brandon Terranova, Alyssa Bellingham, Sylvia Herbert, Adam K. Fontecchio, Drexel Univ. (United States)

Quasi-3D nanoplasmonic structures are investigated, and the interaction of cavity and surface plasmon modes in Au cylindrical channels is discussed. By fastidious choice of geometrical parameters, it is shown that hybrid surface plasmon resonances (SPR) inside the channels are established and are highly sensitive to changes in the local dielectric environment. In this study, cylindrical channels are added to the surface of gold nanopillars whose geometry otherwise permits SPR. The inclusion of the channels creates a plasmonic waveguide supporting whispering gallery mode cylindrical channel plasmons, which result from the coupled hybridized field. Numerical simulations reveal the possibility of single-molecule sensitivity of these cylindrical channel nanopillars (CCNP) by demonstrating near-IR wavelength shifts in the detected reflectance from a modeled array of CCNPs in various dielectric environments. The reported sensitivity of this metamaterial provides a platform for SPR single-molecule studies and exhibits potential for label-free biological and chemical sensing.

8994-40, Session 11

Highly-local enhancement of the spontaneous emission of InGaAs quantum dots and CdSe nanocrystals using plasmonic bowtie nanoantennas

Konrad Schraml, Matthias Spiegl, Mathias Kammerlocher, Gregor Bracher, Benedikt Mayer, Kai Müller, Max Bichler, Jonathan J. Finley, Michael Kaniber, Walter Schottky Institut (Germany)

Metallic nanoparticles are capable of strongly localizing electromagnetic fields incident from the far field and, thereby, enhance strength of light-matter interactions over extreme sub-wavelength dimensions. Here, we present the simulation, fabrication and optical investigation of lithographically defined gold bowtie nanoantennas on GaAs and SiO2 substrates containing near surface proximal quantum emitters. We observe a 5x enhancement of the local emission intensity form InGaAs quantum dots embedded in GaAs as well as a 4x increase for CdSe nanoclusters implanted in SiO2. Furthermore, we present studies of the nonlinear optical properties of GaAs and gold to quantify the electric field enhancement in these hybrid systems.

Our results demonstrate that the surface plasmon resonance can be tuned from 600-1000 nm on glass and 900-1500 nm on GaAs, by controllably changing the size of the triangles and the antenna feed-gap. High quality nanostructures with feed-gaps and tip radii that are sub ~10 nm are realized leading to expected electric field enhancement factors up to 10E4. This pronounced enhancement leads to strongly increased nonlinear responses for such hybrid system. We observe in particular second harmonic generation from the GaAs samples and two-photon photoluminescence in the gold nanostructures on SiO2. Furthermore, the field enhancement results in strongly modified spontaneous emission dynamics for embedded InGaAs quantum dots and CdSe nanocrystals located in the feed-gaps. The exquisite control of the optical properties of plasmonic nanostructures afforded by lithography combined with near surface QDs promises unique properties for future applications in nanoscale optics such as efficient quantum light sources or novel photovoltaics concepts.

8994-41, Session 11

Controllable emission of quantum dots coupled to magneto-electric Mie-type resonances of subwavelength all-dielectric nanoantennas

Isabelle Staude, Manuel Decker, The Australian National Univ. (Australia); Nche T. Fofang, Sheng Liu, Jason Dominguez, Sandia National Labs. (United States); Andrey E. Miroshnichenko, Dragomir N. Neshev, The Australian National Univ. (Australia); Ting-Shan Luk, Igal Brener, Sandia National Labs. (United States); Yuri S. Kivshar, The Australian National Univ. (Australia)

Recent experimental observations of strongly directional light scattering based on interference between electric and magnetic Mie-type modes supported by high-index all-dielectric nanoparticles [1,2] suggest a novel approach towards highly directional nanoantennas [3]. However, previous works so far concentrated on directional far-field scattering effects, while the direct coupling of nano-emitters to such all-dielectric optical nanoantennas remains largely unexplored. Here we investigate experimentally and numerically how the emission properties of near-infrared PbS quantum dots (QDs) are influenced by coupling to tailored electric and magnetic modes supported by silicon nanodisks.

In experiment we fabricate silicon nanodisks covered with a thin polymer layer containing QDs. A systematic variation of the nanodisk aspect ratio allows us to tune the spectral positions of the electric and magnetic resonances both with respect to each other and to the QD emission wavelength. We perform micro-photoluminescence (PL) spectroscopy measurements of the coupled system, showing that the QD emission properties are strongly modified by the presence of the silicon nanodisk antennas, and that the spectral PL line shape is strongly dependent on the nanodisk aspect ratio. Our results demonstrate that the role of high-index all-dielectric nanoparticles is not limited to creating highly directional effects, but that they can furthermore significantly modify the emission properties of spectrally matched QDs.

[1] S. Person et al., Nano Lett. 13, 1806 (2013).

[2] Y.-H. Fu et al., Nat. Commun. 4, 1527 (2013).

[3] A. E. Krasnok et al., Opt. Exp. 20, 20599 (2012).

8994-42, Session 11

Nano antenna elements for controlling optical phase

Yuval Yifat, Zeev Iluz, Michal Eitan, Amir Boag, Jacob Scheuer, Yael Hanein, Tel Aviv Univ. (Israel)

Diffractive optical elements are widely used for various optical applications such as lenses, computer generated holograms, as well as beam shifters and shapers. The diffractive components rely on a structure which alters the phase and amplitude of an incident beam to obtain the required far field pattern.

Recent years have seen widespread use of nanoantennas – nanoscale plasmonic elements which resonate at the optical frequencies of the electromagnetic spectrum. These elements have been used to interact and control the incident optical radiation making them ideal candidates for diffractive optical applications.

In this work we demonstrate the use of nano-antenna arrays fabricated on a dielectric substrate over a reflective surface to control the phase of the reflected optical beam. We designed nano-antenna cells each of

which is composed of a dipole and a patch of various sizes. Thanks to the coupling between the elements, altering the dimensions of the cell elements allows us to alter the relative phase reflected from the cells. Thus, we created modular phase elements which span continuously the range between 0 and 360 degrees.

In this talk we will demonstrate how we can use these unit cells to design several optical elements. We both numerically and experimentally designed a beam deflector array modeled after a blazed grating that allows high efficiency beam reflecting at high angles. We also show a numerical comparison between a regular parabolic mirror and one made from nano-antenna elements. Finally, we will demonstrate the possibility to create arbitrary wave forms from the nano-antenna cells.

8994-43, Session 11

Wavelength and polarization selective photodetection using coupled plasmonic nanoantennas

Jayson Briscoe, Sang-Yeon Cho, New Mexico State Univ. (United States)

In this presentation we report on our investigation of a new photodetector which exploits unique optical properties of coupled metallic nanostructures to achieve wavelength and polarization selective photodetection for multispectral and polarimetric imaging. Specifically, we integrate an orthogonally-coupled plasmonic nanoantenna on the active region of a Schottky diode. The coupled nanoantenna exhibits wavelength selective near-field enhancement due to the excitation of resonant surface plasmon (SP) modes within the structure. The enhanced near-field around the antenna generates electron-hole pairs (EHPs) in the diode. EHPs created by the SP modes are collected by an applied electric field within the depletion region of the Schottky diode. The resonance of plasmonic nanoantennas can be engineered by changing their geometry and orientation for a specific wavelength range or polarization.

Near-field characteristics of the coupled antenna were investigated by performing 3-D finite-element-method based electromagnetic simulations. The coupled antenna consists of two orthogonally oriented nanorods with matching dimensions of 140nm in length and a radius of 20nm. When the geometrical symmetry of the coupled antenna is broken, resonant mode splitting occurs in its near-field. According to the simulation results, mode splitting of 36nm with an antenna displacement of 10nm was observed. Initial results of the coupled antennas demonstrate highly tunable resonant mode splitting. Furthermore, there exists a strong relationship between plasmonic antenna resonance and physical factors such as geometry, material, and symmetry.

8994-44, Session 11

Photophysical study of plasmonic propagation in nanoparticle chains

Alexandre Grégoire, Samuel Ouellet, Olivier Ratelle, Denis Boudreau, Univ. Laval (Canada)

In the last decade, the field known as plasmonics, the interaction of electromagnetic radiation with conduction electrons at metallic interfaces or in metallic nanostructures, has seen a tremendous growth in interest from the research community. One of these applications is the surface plasmon waveguide, being investigated as a means to confine electromagnetic fields within optical nanostructures smaller than the wavelength of light. As an alternative to solid linear nanostructures, a chain of plasmonic nanoparticles can also be used, via the excitation of one end of the chain, to propagate a traveling wave of surface charges. This is made possible by the strong inter-particle plasmon coupling which induces multiple plasmons resonances and leads to a lossless propagation phenomenon known as dark plasmons. Experimentally, plasmonic nanoparticles lend themselves well to the fabrication of plasmonic waveguide via the self-assembly of nanoparticles into linear structures with very small inter-particle separation. In the present work, we are developing facile and rapid bottom-up techniques to fabricate nanoparticle chain waveguides for the study of plasmonic propagation. One technique is the use of wrinkled PDMS stamps to fabricate large one-dimensional nanoparticle assemblies. Combining this technique with the use of tunable, metal-dielectric, core-shell nanoparticles allows the fabrication of linear assemblies with adjustable inter-particle separation. By combining single particle microscopy/spectroscopy (epifluorescence, dark-field scattering, fluorescence lifetime microscopy) with transmission electron microscopy, we are able to gather optical and structural information from isolated nanoparticle assemblies in order to derive interesting structure-properties correlations - in particular the interaction between propagating dark plasmons with the emission behavior from nearly fluorophores. We will also present results on the use of a fluorescence-based far-field microscopy technique called bleach imaged plasmon propagation (BLIPP) to visualize plasmon polariton propagation along nanoparticle chains.

8994-45, Session 11

Application of plasmonic subwavelength structuring to enhance infrared detection

David W. Peters, Paul S. Davids, Jin K. Kim, Darin Leonhardt, Thomas E. Beechem III, Stephen W. Howell, Taisuke Ohta, Joel R. Wendt, John A. Montoya, Sandia National Labs. (United States)

Nanoantennas are an enabling technology for visible to terahertz components and may be used with a variety of detector materials. We have integrated subwavelength patterned metal nanoantennas with various detector materials for infrared detection: midwave infrared indium gallium arsenide antimonide detectors, longwave infrared graphene detectors, and shortwave infrared germanium detectors.

Nanoantennas offer a means to make infrared detectors much thinner, thus lowering the dark current and improving performance. The nanoantenna converts incoming plane waves to more tightly bound and concentrated surface waves. The active material only needs to extend as far as these bound fields. In the case of graphene detectors, which are only one or two atomic layers thick, such field concentration is a necessity for usable device performance, as single pass absorption is insufficient. The nanoantenna is thus the enabling component of these thin devices. However nanoantenna integration and fabrication vary considerably across these platforms as do the considerations taken into account during design.

We will discuss the motivation for these devices and show the design steps for the three material systems. We will also offer an overview of the fabrication processes required to make these subwavelength structures on at times complex underlying devices. Finally, we will present characterization results of our structures.

8994-64, Session PWed

Observing transverse Anderson localization in random air line based fiber

Minghan Chen, Ming-Jun Li, Corning Incorporated (United States)

The concept of Anderson localization has been applied to electromagnetic waves for decades and strong photon localization effect has been observed in many two-dimensional systems including optical lattice and optical fibers. Among different types of optical fibers, both fibers with and without air hole were investigated. Air hole based fiber has significant higher refractive index contrast than other fibers which allow much lower filling factors in order to observe Anderson localization.

In a previous research, Anderson localization was observed near the fiber edge with an air filling fraction of 5.5%. At the fiber center region with only 2.2% air filling factor, Anderson localization disappeared. However, we observed Anderson localization in fibers with much lower air filling fraction.

In our experiments, random air line fibers with 150, 250 and 350 µm diameters were fabricated and characterized by scanning electronic microscopy (SEM). Average air line diameters were 177, 247 and 387 nm for 150, 250 and 350 µm diameter fibers, respectively. Air filling factors were also measured at fiber center, middle and edge regions. Beam profiles were imaged into a charge couple device (CCD) and Anderson localization was observed. Unlike the previous research in which Anderson localization was only observed at the fiber edge due to non-uniform air line distribution, we observed Anderson localization within the entire fiber area including regions with air filling factors (~1.06%) significantly lower than the previous investigation. This is because with smaller air line diameter our fiber has higher air lines density than the previous report.

8994-65, Session PWed

Fabrication and evaluation of active spectral filter with metal-insulator-metal structure for visible light communication

Kensuke Murai, National Institute of Advanced Industrial Science and Technology (Japan); Yasushi Oshikane, Fumihiko Yamamoto, Osaka Univ. (Japan); Shoichi Mochizuki, National Institute of Advanced Industrial Science and Technology (Japan); Kou Hattori, Osaka Univ. (Japan); Toshiyuki Mihara, National Institute of Advanced Industrial Science and Technology (Japan); Motohiro Nakano, Osaka Univ. (Japan)

Visible light communication with LED is an important ICT technology for the ubiquitous network society. However visible light communication has the speed limit in the conventional blinking LED method. Therefore an active spectral filter would be useful in order to input information signals onto the LED spectrum. Plasmonic spectral filter based on a metal-insulator-metal (MIM) structure is one of the candidates of such active filter.

We have designed the MIM structure for the visible light communication by the calculation of the optical reflection. The metal should be the plasmonic material such as gold or silver. The MIM structure shows the very narrow absorption dip as functions of the wavelength and the incident light. However very precise thicknesses of the metal and the insulator layers are requested for the designed structure. For example, the thickness of the metal layer (M1) decides the depth of the absorption dip. And the thickness and the flatness of the insulator layer decide the spectral position and the spectral width of the absorption dip, respectively. Since the absorption dip had been decided by the underneath layers, real-time monitoring of the MIM structure would be required in order to see the thickness and the flatness of the deposition of each layer. Design of reflection optics is also important in order to establish the active device.

We will explain our progress of fabrication of the active devices with the plasmonic spectral filter with explaining several cadidate materials and with evaluating their photonic and electrical properties.

8994-66, Session PWed

Efficient harmonic generation in double-near-zero-permittivity slabs

Maria A Vincenti, Domenico de Ceglia, National Research Council (United States) and U.S. Army Aviation & Missile Research, Development & Engineering Ctr. (United States); Michael Scalora, U.S. Army Aviation & Missile Research, Development & Engineering Ctr. (United States); Joseph W. Haus, Univ. of Dayton (United States) and National Research Council (United States) and U.S. Army Aviation & Missile Research, Development & Engineering Ctr. (United States)

Materials exhibiting near-zero-permittivity (NZP) have been investigated mostly for their peculiar linear properties. A TM-polarized plane wave incident on a NZP slab produces a singular electric field component, which may be exploited to boost nonlinear processes. In fact, if the NZP condition is achieved thanks to the presence of a plasma resonance, harmonic generation is simply favored by the extremely large field enhancement of the pump that derives from the continuity of the displacement field component normal to the boundary. Plasma resonances may be found in natural materials and artificial materials alike, where absorption losses may be compensated by including active media in their lattice. We demonstrate that the simultaneous enhancement of the pump and harmonic fields triggered by the NZP condition dramatically improves nonlinear processes when compared to either a single plasma resonance scenario, or to nonlinear crystals commonly used for harmonic generation. We show that in presence of relatively small losses and an implicit, almost perfect phase-matching condition, pump depletion is achieved for material lengths smaller than the pump wavelength and irradiance values in the MW/cm2 range, without resorting to other resonant photonic mechanisms.

8994-67, Session PWed

Phase-resolved unidirectional scattering in all-dielectric silicon nanodisks

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

Interference of optically-induced electric and magnetic resonances in high-index all-dielectric nanoparticles offers unique opportunities for tailoring directional scattering and engineering the flow of light [1,2]. In particular, it has been suggested theoretically that the interference of electric and magnetic optically-induced modes in individual subwavelength silicon nanodisks can lead to the suppression of resonant backscattering and enhanced resonant forward scattering of light [3] when both electric and magnetic resonances overlap spectrally. Then the transmittance approaches unity, corresponding to resonant forward scattering, while the resonance characteristics can still be extracted from the phase information of the transmitted light. We fabricate metasurfaces composed of square lattices of silicon nanodisks and overlap electric and magnetic resonances by a variation of the nanodisk aspect ratio. We use a dedicated phase-resolved transmittance setup to measure the transmittance phase and amplitude of the silicon nanodisks in the regime of resonant forward scattering and compare our findings with numerical calculations. We show that backward scattering can be suppressed and forward scattering can be enhanced at resonance for the particular case of overlapping electric and magnetic resonances and show that this effect is based on the interference of electric and magnetic modes of the silicon nanodisks with the incident wave. We also show the potential of this approach for high-transmittance phase modulators and dispersion engineering.

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8994-68, Session PWed

On the performance improvement of transmitted Bessel beams emitted from sub-wavelength annular aperture coupled with periodic grating

Chun-Hung Weng, Ming-Han Chung, Chih-Kung Lee, National Taiwan Univ. (Taiwan)

The lens spatial resolution and depth of focus depends on the numerical aperture and the incident light beam wavelength. Traditionally, smaller focal size leads to short depth of focus, which may hinder the system integration advancement. The paper investigates the possibility to break free the limitation associated with small focal size and short depth of focus. It was discovered by T. W. Ebbesen that periodic aperture on metallic film may improve the transmission and confine the divergent angle of the emitting light beams beyond the prediction of the Bethe's theory. We developed subwavelength annular aperture (SAA) first and then used tapered hollow micro-tube to mimic the function of SAA so as to generate Bessel beam in the far-field region. High aspect ratio microstructures were fabricated using the above-mentioned techniques. In addition, coupling annular aperture and periodic grating to further advance the high aspect ratio fabrication technique was also explored. Firstly, to maximize the transmission in specific wavelength, the pitch of grating was modulated. More specifically, we manipulated the periodic grating to search the maximum transmission efficiency in specific waveband. Secondly, in order to improve the depth of focus, we changed the grating slit to induce proper phase delay. These studies were all verified by FDTD simulations and some experimental verification.

8994-69, Session PWed

Chiral plasmonics: route towards strong and broadband chiro-optical response

Greshma Nair, Haobijam J. Singh, Murugesan Venkatapathi, Ambarish Ghosh, Indian Institute of Science (India)

Recent advances in nanotechnology have paved way to various techniques for designing and fabricating novel nanostructures incorporating noble metal nanoparticles, for a wide range of applications. The interaction of light with noble metal nanoparticles (NPs) can generate strongly localized electromagnetic fields (Localized Surface Plasmon Resonance, LSPR) at certain wavelengths of the incident beam. In assemblies or structures where metal nanoparticles are placed in close proximity, the plasmons of individual metallic NPs can be strongly coupled to each other via Coulomb interactions. By arranging metallic NPs in a chiral (e.g. helical) geometry, it is possible to induce collective excitations, which lead to differential optical response of the structures to right- and left circularly polarized light (e.g. Circular Dichroism - CD). Earlier reports in this field include novel techniques of synthesizing metallic nanoparticles on helical scaffolds made from DNA, certain proteins etc. In our present work, we have developed new ways of fabricating chiral complexes made of metallic NPs, which demonstrate a very strong chiro-optical response in the visible region of the electromagnetic spectrum. We have also tried to develop the theory behind the enhanced optical activity observed in plasmonic chiral nanostructures. Using DDA simulations, we studied the conditions responsible for large and broadband chiro-optical response and generating highly twisted electromagnetic fields. Hence, such systems with very strong chiro-optical activity can be used for various biomedical sensing applications such as the sensing of proteins and other chiral bio-molecules.

8994-70, Session PWed

Acousto-optic interaction induced photonic band gaps in silicon slab waveguides

Tzy-Rong Lin, National Taiwan Ocean Univ. (Taiwan); Jin-Chen Hsu, National Yunlin Univ. of Science and Technology (Taiwan); Chiang-Hsin Lin, National Taiwan Ocean Univ. (Taiwan); Jheng-Hong Shih, National Taiwan Ocean University (Taiwan)

We demonstrate that the photonic band gaps in silicon slab waveguides are generated through the acousto-optic (AO) interaction. By exciting the acoustic eigenmodes of slab waveguides, the refractive indices and interfaces of silicon slab can be modulated periodically to perturb the guided optical waves and open up the photonic band gaps. We find that the occurrence of the strong forbidden effect to form the band gaps is due to nonlinear interactions between the guided optical and acoustic modes. Using the finite-element method, we calculate the photonic band structures of TE-like waves and TM-like waves under the perturbation of the lowest three plate eigenmodes, respectively. The results show that the fundamental symmetric acoustic slab mode can create Bragg photonic band gaps of tunable width. With generating an acoustic-wave amplitude of 1.0 % of the slab thickness, photonic band gaps from 70.76 – 71.09 THz for TE-like and 95.59 – 95.8 THz for TM-like are demonstrated. We also analyze the transmission coefficient for optical waves propagating in the slab waveguide experienced 500 periods of acoustic waves, and the results shows that transmission coefficients of 0.152 for TE-like and 0.219 for TM-like are achieved, which can also be adjusted by changing the acoustic intensity and the periods of the acoustic waves. We also show that the perturbed transmitted optical field near the band-gap frequencies experiences strong photon-phonon exchange, causing a nonlinear AO interaction that depends on acoustic properties. Applications include the design of optomechanical and AO devices and micro and nanolasers.

8994-71, Session PWed

Effective focusing method using simple Au double block with surface plasmon

Hong-Gyu Ahn, Seung-Han Park, Yonsei Univ. (Korea, Republic of)

We studied effective focusing method using nano double block. In this study, We used Au nano block with surface plasmon and finded that focusing with double block was higer than focusing with doule slit. Changing block seperation and block size, We optimized that conditions and compared FDTD simulation to NSOM scan result.

8994-72, Session PWed

Anderson localized modes in a disordered glass optical fiber

Salman Karbasi, Seyed Rasoul Hosseini, Univ. of Wisconsin-Milwaukee (United States); Karl W. Koch, Corning Incorporated (United States); Thomas Hawkins, John Ballato, Clemson Univ. (United States); Arash Mafi, Univ. of Wisconsin-Milwaukee (United States)

A beam of light can propagate in a time-invariant transversely disordered waveguide because of transverse Anderson localization. We developed a disordered glass optical fiber from a porous artisan glass (satin quartz).

The refractive index profile of the disordered glass optical fiber is composed of a non-uniform distribution of air voids which can be approximated as longitudinally invariant. The fill-fraction of air voids is higher at the regions closer to the boundary compared with the

central regions. The experimental results show that the beam radius of a localized beam is smaller at the regions closer to the boundary than the one at the central regions. In order to understand the reason behind these observations, the fully vectorial modes of the disordered glass fiber are calculated using the actual scanning electron microscope image of the fiber tip. The numerical calculations show that the modes at regions closer to the boundary of the fiber are more localized compared with the modes at the central regions. Coupling of an input beam to the less-localized modes with large tails at the central regions of the fiber results in a large beam radius. In comparison, a beam of light launched at the regions close to the boundary couples to the highly compact modes of the fiber and results in a small localized beam radius. We will show how the disorder distribution as well as the fiber boundary play important roles in shaping the mode profiles and setting the localization radius.

8994-73, Session PWed

Plasmonic emission enhancement from Er3+-doped tellurite glass via negative-nanobowtie

Victor A. Garcia Rivera, Univ. de São Paulo (Brazil); Yannick Ledemi Sr., Younès Messaddeq, Ctr. d'Optique, Photonique et Laser (Canada) and Univ. Laval (Canada); Euclydes Marega Jr., Univ. de São Paulo (Brazil)

Metallic negative-nanobowtie is a new suitable structure for development of antennas that can be integrated on wide number of devices, especially in optical communications. Such feature is achieved due the presence of surface plasmon polariton (SPP) that provides a great charge density on nearby region from its tips creating hot spot. Considerable studies have described theoretical and experimentally the influence of gap between tips and the corner angles on radiation emission, once this parameter may improve the local field, as such length decrease. In optical regime, the emission enhancement is due the quantum-plasmonic interaction create from tips region (localized local field) and the transitions levels. Nevertheless, metallic negative-nanobowtie with absence of gap deserve attention special, because in addition to present similar properties from regular case as previously mentioned, can also interacts with different systems, like gain materials. One of remarkable class of such material is rare earth ions, not only by the enhancement on measured intensity, but also its easiness to implement it on glasses, which constitute the main type of substrate adopted on plasmonic structures. In this work we performed the analysis of effects due implementation of Er3+ ions into tellurite glass over a pattern of negative-nanobowtie on absence of gap between its tips, fabricated by focused ion beam (FIB) technique from gold (Au) films with 200 nm thickness. The bowties are vertically excited by an argon laser (Ar) which wavelength is 488 nm and were performed to verify the dependence of nanobowtie's geometry over the electric field along its symmetry axis.

8994-74, Session PWed

Growth of ZnO nanowire array on a fiber end face and reflection modification

Igor V. Melnikov, Mikhail Y. Nazarkin, Andrey A. Machnev, Alexei S. Shuliatyev, Dmitry G. Gromov, National Research Univ. of Electronic Technology (Russian Federation)

The small uniform diameter ≤ 100 nm along with low absorption and large refractive index in the visible of wide-gap semiconductor nanowires have opened several avenues for pursuing sub-wavelength optical devices. Among others, ZnO continues to be of particular interest, not only for studies of fundamental solid-state physics but for application to optical waveguides. The practical implementation of ZnO nanowires requires a detailed understanding of coupling external light into the guiding modes of the nanowire whose diameter is much smaller than the corresponding vacuum wavelength. This report presents measurements of broadband light propagating through a single-mode optical silica fiber that has an end facet modified by a deposited array of ZnO nanowires.

The procedure exploited to create an array of ZnO nanowires on a tip of a single-mode optical fiber is based on a standard technological procedure. In order to provide required level of the surface quality, the magneto-sputtering of 300-nm ZnO film is executed immediately after the fiber (SMF-28 Corning) cleaving. This film works as a catalyst for ZnO nanowires to grow and also provides proper adhesion and ordering for the structure to be created in the next step, where low-temperature chemical deposition is used to create an array of ZnO nanowires. In the solution, there is a concentration of 0.01 M of Zn(NO3)2*6H2O and 0.4 M of NaOH, and pH of this solution is equal to 13.2. The solution is kept for ten minutes a water bath heated to 80º?, and the end facet of the fiber is immersed into it afterwards and kept there for twenty minutes, correspondingly. The fiber with ZnO nanowires grown on its end facet, is cleaned in a deionized water and then air-dried. The length of the nanowire is equal 800 nm, diameter varies from 40 to 50 nm, and surface density is 5x1010 cm2, correspondingly.

In the next step, the transmission and reflection spectra of the fiber that comprises a bundle of ZnO nanowires grown on its cleaved facets, are studied using experimental setup depicted in Fig. 1. The output of the Er3+ broadband source MPB EBS-7210 is launched into one piece of SMF-28 followed by a circulator and another length of the SMF-28 that has ZnO nanowires on its facet and is connected by means of an adapter to the optical spectrum analyzer AQ6370 by Yokogawa. The circulator is introduced into the set-up in order the reflection spectrum to be analyzed simultaneously.

The reflection spectra are measured for the clean cleaved facet, facet with a seed layer of ZnO on its cleaved surface, and with ZnO nanowires that are being grown on this cleaved facet, correspondingly, and the reflection spectrum is given in Figs. 3 and 4. It is readily seen a profound asymmetry in the reflection spectrum that does not match the transmission one hence making a temptation to claim an observation of surface polaritons excited along the ZnO nanowires. Further basic measurements that are again the spectral measurement but with tilt and variable spacing introduced between the nanowires and collecting fiber confirm this assumption.

In conclusion, measurements of the transmission and reflection spectra of the single-mode optical fiber that end facet is modified by a disordered (but yet controllable) array of ZnO nanowires, exhibit spectral asymmetry of the reflection due to the excitation of surface polaritons that propagate along the surface of the nanowire. The behavior reported here is of interest for the implementation of new sub-wavelength optical waveguides.

8994-75, Session PWed

High absorption and polarization-independent thin-film absorber with gold nanorod array

Guangyao Su, Deng Xiao, Zhaoyu Zhang, Peking Univ. Shenzhen Graduate School (China)

A metal-insulator-metal (MIM) structure is proposed for high efficient absorption of non-polarized incident light. The top 35 nm gold layer is patterned into a two dimensional nanorod array. The bottom layer is also a gold layer with thickness of 100 nm. The two layers are separated by 100 nm SiO2 layer. The period in x direction (parallel to the long axis of nanorods) is marked as W1 and the period in y direction (perpendicular to nanorods) W2. Finite difference time domain (FDTD) method is adopted for numerical simulations. First, the absorption for structure with one single nanorod whose length is 300 nm and width is 40 nm in the center of the lattice is investigated. Two absorption peaks were observed and their trends which are corresponding to surface plasmon polaritions (SPPs) mode and localized surface plasmon resonances (LSPRs) mode have been studied as the changing of W1 or W2. The absorption rate is much sensitive to these two parameters. Then, polarization independent absorber is designed by combining two perpendicular nanorods in one lattice,. Moreover nanorods with different lengths in adjacent lattices are

arranged periodically can lead to two or more absorption peaks. Finally the paper optimizes the absorber with three absorption peaks (absorption rate over 90%) in wavelength from 1.2um to 2.2um which are polarization independent. Extending the similar design into optical wavelength or terahertz absorber can also be expected base on this work.

8994-76, Session PWed

2D impedance-matched zero-index metamaterial

Philip A. Munoz, Yang Li, Shota Kita, Orad Reshef, Marko Loncar, Eric Mazur, Harvard School of Engineering and Applied Sciences (United States)

The index of refraction in metamaterials can be tuned over a wide range, including recent efforts to realize very low (near zero) values. However, these efforts have primarily focused on “single zero” metamaterials, which take advantage of the low index at a photonic band edge. This behavior is accompanied by a divergent impedance, resulting in high reflectivity and inefficient transmission. We investigate the nature of this discontinuity and show that it can be removed by carefully tuning the electric and magnetic response of the metamaterial. We present a design for a 2D zero-index metamaterial based on this concept. The metamaterial is entirely dielectric, which results in low-loss transmission at the design wavelength of 1.55um. The design consists of periodic, sub-wavelength silicon pillars, which exhibit both electric and dielectric Mie resonances. By tuning the radius and pitch of the pillars, the resonances can be tuned to achieve low-loss zero index with minimal impedance mismatch. This behavior is confirmed using finite-difference time domain (FDTD) methods. The pillar array is incorporated in a slab waveguide to demonstrate propagation over large areas, and to incorporate the metamaterial with existing integrated photonics. This design is amenable to standard nanofabrication techniques. We will focus on the design and numerical optimization of the zero-index metamaterial, and also present preliminary experimental results.

8994-46, Session 12

Integrated nanophotonic isolator without magnetism: angular-momentum biased metamaterials *(Invited Paper)*

Dimitrios Sounas, Andrea Alù, The Univ. of Texas at Austin (United States)

Non-reciprocal devices, such as isolators and circulators, are indispensable parts of optical systems, in order for example to protect sources from unwanted reflections or isolate a receiver from a transmitter both connected to the same channel. To date, non-reciprocity is almost exclusively achieved by means of magneto-optic effects, occurring in certain magnetic materials when biased with a static magnetic field. However, lattice incompatibility between magneto-optic materials and semiconductors and the need of a static magnetic bias, usually produced by bulky magnets, make magneto-optical devices hard to integrate. Magnetic-free non-reciprocity can be achieved with non-linear structures [1] or spatiotemporally modulated waveguides [2]-[4], however such approaches work for a limited range of input signal intensities and/or are electrically large, due to the weak nature of electro- and acousto-optical effects.

Inspired by the Onsager-Casimir principle, we propose a novel way to break non-reciprocity, by biasing a circular resonator, or an array of them, with the angular momentum vector. Spatiotemporal modulation is induced by a signal with finite angular momentum applied to the ring resonators [5], removing the degeneracy between counter-propagating azimuthal resonant states and producing non-reciprocity. By appropriately selecting the angular momentum of the modulation signal and the quality factor of the ring, strong non-reciprocity can be obtained with low modulation amplitude and frequency. Incorporating the modulated ring in channel-drop-filter configurations optical isolators with more than 30 dB of isolation, almost zero transmission loss and a footprint in the order of the wavelength can be realized. The spatiotemporal modulation can be efficiently implemented in the form of a discrete stepwise profile, realizable via a series of pin junctions, with as few as 3 steps per ring, being able to produce giant non-reciprocity at the subwavelength scale without the need of magnetic effects.

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8994-47, Session 12

Dirac-cone based negative/zero/positive refractive index metamaterials

Yang Li, Philip A. Munoz, Shota Kita, Orad Reshef, Marko Loncar, Eric Mazur, Harvard School of Engineering and Applied Sciences (United States)

By carefully tuning the geometric and material parameters of a photonic crystal, a Dirac-cone can be formed at the center of the Brillouin zone due to the accidental degeneracy, which means one monopole eigenstate and two double-degenerate dipole eigenstates have the same eigenfrequency. Considering that the photonic crystal can be treated as a homogeneous bulk metamaterial in the vicinity of the Dirac-point since the homogenization criteria, effective wavelength ?_eff inside a medium is much larger than the lattice constant, is met since ?_eff close to infinite at the zone center, we can see that: 1) in the vicinity below the Dirac-point, the backward wave implies negative effective refractive index (n_eff); 2) at the Dirac-point, k=0 results in n_eff=k/?=0; and 3) in the vicinity above the Dirac-point, the forward wave induces positive n_eff. This negative/zero/positive refractive index associates with a very low loss since it is far away from the Mie resonance, around which the effective constitutive parameters show a peak of loss. And, since effective permittivity ?_r^eff and effective permeability ?_r^eff of Dirac-cone based metamaterials approach zero simultaneously and linearly at the Dirac-point, effective characteristic impedance ?_eff of such a metamaterial is a finite value so as to provide a good impedance matching to free space. According to the aforementioned theory, we designed a Dirac-cone based metamaterial consisting of 2D square array of silicon pillars operating around 1.55 ?m. Its negative/zero/positive refractive index is demonstrated analytically, numerically, and experimentally.

8994-48, Session 12

Transmission in a 1D split-ring resonator metamaterial containing a nonlinear barrier: soliton modes

Arthur R. McGurn, Western Michigan Univ. (United States)

The transmission properties of electromagnetic waves in a 1d split ring resonator meta-material containing a nonlinear barrier are studied

theoretically. Within the barrier the split ring resonators contain a Kerr nonlinear dielectric media and outside the barrier the split ring resonators contain a linear dielectric media. The focus of the study is on the transmission maxima (resonant transmissions) through the barrier studied as a function of the barrier dielectric media. The resonant transmissions are associated with the excitation of resonant modes in the barrier, and these resonantly excited barrier modes can in many instances be associated with various bright, dark, and grey solitons. The excitation of the modes is studied as a function of the dielectric media of the barrier and the dispersion of the wave incident on the barrier. Soliton modes are found to appear in the system at a lower critical value of the Kerr nonlinearity of the barrier media. In other case, solitons arise through the breakup of modes evolving from the modes of the linear media barrier limit as nonlinearity is applied and allowed to increase.

8994-49, Session 12

The negative refraction under out-of-plane incident condition: an experimental study

Silvia Romano, Consiglio Nazionale delle Ricerche (Italy); Edoardo De Tommasi, Istituto per la Microelettronica e Microsistemi (Italy); Anna Chiara De Luca, Ivo Rendina, Consiglio Nazionale delle Ricerche (Italy); Stefano Cabrini, The Molecular Foundry (United States) and Lawrence Berkeley National Lab. (United States); Vito Mocella, Consiglio Nazionale delle Ricerche (Italy)

The study of negative refraction effect in photonic crystals is an important topic of research and both theoretical studies and experiments have focused the attention on it. In photonics, such effects have a limited number of experimental demonstrations, mainly under out-of-plane incidence conditions.

In this paper we show experimental evidence about the negative refractive behavior of a 2D lattice in silicon through the detection of resonances phenomena coupled with an out-of-plane incident wave vector. Localized plasmon-like modes and guided mode resonances are detected in the reflectivity spectrum of PhC slab [6].

It is demonstrated that a dielectric photonic crystal (PhC) can be described by a Lorentz resonator [1] and this can be related to the negative index properties of the PhC. Using this feature, the phenomena are discussed with a new approach, adding more information about the resonance coupling [2, 3, 4, 5]. The strong confinement of the radiation in addition to the field enhancement make these phenomena a very appealing alternative to plasmonic substrates, avoiding the limits of absorption losses in metals.

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8994-50, Session 12

ENZ waveguide of Al-doped zinc oxide for telecommunication applications

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

Epsilon-near-zero (ENZ) metamaterials are an interesting class of structures for novel applications at optical and microwave frequencies. It is possible to improve previously well-known optical systems utilizing the properties of such artificial materials. Since waveguides are widely employed, we investigate the incorporation of an ENZ material into a waveguide structure in order to suppress dispersion associated with the interaction of light with material in the core, guiding layer. An ideal material for the core is air, since it has minimum interaction with light. However, in dielectric waveguides, the core has to possess a higher index than the cladding, even though, for example in communication fiber, that difference is best kept very small to maintain single mode operation. ENZ metamaterials can provide a mechanism for such air-core waveguides by introduction of a cladding medium exhibiting a refractive index less than unity. The metamaterial for such an application can be constructed by inclusion of suitable nanostructures in a host medium. The material for these nanostructures must be chosen such that they introduce lowest possible optical attenuation to optical signals.

We study the application of aluminum zinc oxide (AZO), a transparent conducting oxide, as the candidate material for ENZ waveguides. For this purpose, we design a metamaterial cladding layer with ENZ properties derived from nanoparticles of AZO, and investigate the resulting loss and dispersion of guided optical signals. To analyze the propagation characteristics of an AZO-ENZ waveguide system, we use a finite element method for fullwave simulation of lightwaves at optical telecommunication wavelengths.

8994-51, Session 13

Flat optics based on metasurfaces *(Invited Paper)*

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

No Abstract Available

8994-52, Session 13

Multispectral imaging with silicon nanowires and wafer-scale metasurfaces for single-molecule Raman scattering *(Invited Paper)*

Kenneth B. Crozier, Harvard Univ. (United States)

We present recent studies in which the engineering the interaction between light and nanoscale materials has been pursued for applications in image sensors and in spectroscopy. In the first, we demonstrate a compact multispectral imaging system that uses vertical silicon nanowires to realize a filter array. Multiple filter functions covering visible to near-infrared (NIR) wavelengths are simultaneously defined in a single lithography step using a single material (silicon). Nanowires are then etched and embedded into polydimethylsiloxane (PDMS), thereby realizing a device with eight filter functions. By attaching it to a monochrome silicon image sensor, we successfully realize an all-silicon multispectral imaging system. In the second study, we demonstrate a metasurface that achieves the near-perfect absorption of visible-wavelength light and enables the Raman spectroscopy of single molecules. Our metasurface is fabricated using thin film depositions, and is of unprecedented (wafer-scale) extent.

8994-53, Session 13

Coupling between a metasurface and intersubband transitions in a quantum well explained via classical electrodynamics

Salvatore Campione, Univ. of California, Irvine (United States); Alexander Benz, John F. Klem, Michael B. Sinclair, Igal Brener, Sandia National Labs. (United States); Filippo Capolino, Univ. of California, Irvine (United States)

Strong coupling between an engineered optical transition in a semiconductor heterostructure (e.g., quantum well) and a metasurface resonance (i.e., bare cavity) has been enabled by the use of near-field coupling. It has been shown that different resonator geometries may lead to different Rabi splitting, although a justification to this phenomenon has not yet been provided in a quantitative manner. Here we aim at demonstrating which physical parameter leads to strong coupling, providing a quantitative explanation to the resonator shape dependence, by also resorting to the quasi-static (electrostatic) expression for point dipoles located at the interface between an isotropic and an anisotropic medium. In particular, by using the electrostatic approximation, we propose a circuit network model that recovers the energy and spectral properties of a metasurface/quantum-well system with the least number of parameters. We compare the circuit network model results to both full-wave and experimental results, found in good agreement, proving the correctness of the proposed model. We are then able to show that there is a clear dependence of the Rabi splitting on the resonator shape. Our model allows for the identification of the key parameters that affect strong coupling. Strongly-coupled systems are of key importance for the design of novel devices at mid-infrared frequencies (~10 ?m) such as optical switches, modulators, filters, and phase shifters, which are of large need for the next generation optoelectronic devices.

8994-54, Session 13

Stokes parameter sensor using an integrated cavity array metasurface

Isroel Mandel, David T. Crouse, The City College of New York (United States)

Polarimetric sensing has been shown to have numerous applications in imaging such as enhancing the contrast of an image and the shape of the source object. There is increasing interest in developing a sensor that is able to measure all the Stokes parameters of an incident beam without a reduction in image resolution. We propose a cavity array metasurface polarization sensor capable of determining the complete elliptical polarization state of an incident beam allowing for the Stokes parameters to be calculated within a single pixel. The metasurface consists of a metal film with periodically patterned cavities filled with an absorbing dielectric. Each unit cell of the periodic array contains three different cavities with each cavity interacting in a different manner with the incoming beam, absorbing the radiation. The absorption in each of the three cavities depends on the incident polarization state and phase of the incident beam. An isolated measurement of the absorption in each cavity within the unit cell is possible with separate collection of photogenerated carriers. This will enable the elliptical polarization state of an incident beam to be measured. In this work, we describe the elements of the metasurface sensor and numerically characterize its optical response to elliptically polarized light.

8994-55, Session 14

Control thermal radiation with nanophotonic structures *(Invited Paper)*

Shanhui Fan, Stanford Univ. (United States)

Nanophotonic structures provide important new opportunities for controlling thermal radiation. In this talk, we show that one can use photonic structure to enhance thermal radiation power to far field from a finite-sized macroscopic blackbody emitter. We also discuss our recent progress aiming to achieve daytime radiative cooling using nanophotonic design.

8994-56, Session 14

Near-infrared cut-off filters based on CMOS nanostructures for ambient light sensors and image sensors

Stephan Junger, Nanko Verwaal, Wladimir Tschekalinskij, Norbert Weber, Fraunhofer-Institut für Integrierte Schaltungen (IIS) (Germany)

Silicon based photodiodes provide spectral response in the visible wavelength range (VIS) but also in the near-infrared (NIR) for wavelengths up to 1100 nm. For ambient light sensors (ALS) that approximate the response of the human eye and image sensors with high color reproducibility the sensitivity in the NIR is unwanted as it impairs the sensing performance. Typically, external thin film filters are applied as near-infrared cut-off filters in front of the photodiode or image sensor, adding cost and complexity. We demonstrate plasmonic nanostructures - subwavelength hole arrays and nanodisk arrays - fabricated directly using an extended CMOS (complementary metal–oxide–semiconductor) process on top of photodiodes. As opposed to post processing techniques like electron beam lithography or focused ion beam milling, this approach is suitable for high volume fabrication. Several CMOS test chips with photodiodes and filter designs in one and two metal layers were simulated, processed, and evaluated with respect to spectral sensitivity. The filter transmission is tailored by varying the lateral geometry of the nanostructures at constant thickness of the metal layers. These monolithic sensors with photodiodes and plasmonic filters on a single chip enable ambient light sensors and color sensors as well as CMOS image sensors with pixel level NIR-blocking filters for color vision with high quality. Additional pixels without any filter can be used on the same chip, providing high sensitivity in the visible and especially near-infrared wavelength range. Image sensors with simultaneous acquisition of VIS and NIR images address emerging applications, e. g. surveillance systems, automotive, industrial, and medical applications.

8994-57, Session 14

Flexible optical-infrared metafilter

Jean-Baptiste Brückner, Institut Materiaux Nanoelectronique de Provence (France); Vincent Brissonneau, Commissariat à l'Énergie Atomique (France); Abdelkerim Ferchichi, LTM CNRS (France); Judikaël Le Rouzo, Ludovic Escoubas, Institut Matériaux Microélectronique Nanosciences de Provence (France); Christophe Dubarry, Commissariat à l'Énergie Atomique (France); Cécile Gourgon, LTM CNRS (France); Jean-Jacques Simon, Institut Matériaux Microélectronique Nanosciences de Provence (France); Gérard Berginc, Thales Optronique S.A.S. (France)

We present a flexible optical filter showing very broad antireflective properties from visible to near infrared region and simultaneously a mirror behavior in the mid wavelength infrared range (MWIR: 3 to 5 μm) and long wavelength infrared region (LWIR: 8 to 15 μm). As it acts as a selective thermal emitter, a huge interest is found in the field of thermophotovoltaics, but it can be useful as well in the stealth domain where optical signature reduction from the optical to LWIR region is an important matter. It may also be mentioned that undesired radiation from antennae could be reduced as well with such properties.

Numerical studies on metallic perforated metallic screens and antireflective silicone cones gratings inspired us to fabricate a novel and flexible optical filter. Indeed, by combining the antireflective properties from gradual changes in the effective refractive index and cavity coupling from cones gratings, and the interesting optical behavior of a tungsten layer, we have obtained a very promising wavelength filter. As the process is cheap, fast, needing only a few steps, and offers a high resolution, nano-imprint technology was used to replicate inverted cones patterns on a flexible polymer coated afterwards with a thin tungsten film. The spectral response characterizations made by spectrometry from visible to middle infrared, have confirmed the promising theoretical computations.

8994-58, Session 14

An all-dielectric broadband high-transmission efficiency circular polarizer

Arvinder S. Chadha, Deyin Zhao, Weidong Zhou, The Univ. of Texas at Arlington (United States)

Optical circular polarizers find their use in a variety of applications like displays, optical communication, photography, sensors and spectroscopy. Cholesteric liquid crystals (CLC) and a combination of linear polarizer with a quarter-wave plate are the commonly used methods to generate circularly polarized light. The performance of the CLCs is limited by the crystals birefringence and poor photo-chemical stabilities. The linear polarizer absorbs 50% of the incident light and the optical efficiency is halved. More recently metal helix structures demonstrated broadband circular dichroism, however, the metal absorption leads to low transmission efficiency and poor polarization suppression ratio (PSR), which is defined as the ratio of the transmitted light intensity of one state of the circularly polarized light to the other state of the circularly polarized light.

The dielectric helical structures comprising of hexagonal lattice exhibited polarization gaps with circular dichroism. More recently circular dichroism using photoresist is demonstrated experimentally. However, the device performance is largely limited by the low index contrast between the photoresist and the background. So it is preferable to have semiconductor based dielectric structures for higher index contrast and integration with other passive/active devices for integrated optics on chip. In this paper we propose an all-dielectric circular polarizer consisting of silicon helix on glass substrate. We show that the proposed structure provides extremely high polarization suppression ratio above 2,300:1 with almost 100% transmission over a wide range of incident angles. Complimentary structure consisting of air helix holes in silicon membrane is also investigated, which provides 500 nm polarization bandgap with PSR of 10. We also investigated the influence of the helix period, pitch, radius, wire radius, number of turns, scalability, lattice arrangement, angle of incidence and refractive index of the helix and surrounding medium on the polarization gap and the circular dichroism.

The work was partially supported by US ARO (W911NF-09-1-0505) and by US AFOSR MURI program (FA9550-08-1-0337).

8994-59, Session 15

Recent advances of three-dimensional optical photonic crystal: light trapping and manipulation *(Invited Paper)*

Shawn-Yu Lin, Rensselaer Polytechnic Institute (United States); Mei-Li Hsieh, Rensselaer Polytechnic Institute (United States) and National Chiao Tung Univ. (Taiwan); Ping Kuang, James A. Bur, Rensselaer Polytechnic Institute (United States)

In this talk, we will describe two recent experimental advances in three-dimensional photonic-crystal at optical and visible wavelengths. The first is the realization of anomalous light-refraction, an acutely negative refraction, in a 3D simple-cubic photonic-crystal for light trapping. The second is the observation of quasi-coherent thermal emission in a 3D metallic photonic-crystal.

8994-60, Session 15

Mechanical free optical technology for nanostructures inspection

Maxim Ryabko, Samsung Advanced Institute of Technology (Korea, Republic of); Sergey N. Koptyaev, Alexander Shcherbakov, Alexey D. Lantsov, Samsung Advanced Institute of Technology (Russian Federation); Sangyoon Oh, SAIT-Russia (Russian Federation)

We present a novel all optical technology for nanoscale pattern inspection. The approach is based on utilization of chromatic aberration of the objective lens and tunable light source. This combination allows capturing the set of defocusing images without mechanical scanning of either tested sample or image sensor. Similar to TSOM technology, further processing of through-focus images and comparison with simulation library allow us to define geometrical and material parameters of nano structure. Being free of mechanical scanning, the method provides higher throughput and lower noise level in comparison with TSOM technology.

In our work tunable light source is based on monochromator scheme. LED (470 nm central wavelength, 30 nm spectrum width) is used as a broadband light source. Experimental setup utilizes bright field microscope scheme with Kohler illumination. The tunable light source provides ±10 nm defocusing range for aspherical objective lens (NA=0.55 F=1.45 mm) and achromatic tube lens, which is enough for accurate inspection of nanostructures with characteristic size of few dozen nanometers.

Defocused images are simulated using the finite-difference time-domain (FDTD) method. Simulated defocused light intensity distributions are obtained by a light field expansion to plane waves and their subsequent free space propagation and optical imaging system transformation to compose diffraction patterns for different focus offsets.

The proposed method is tested with calibrated lines (height 50 nm, length 100 ?m, width range 40-150 nm with 10 nm step) on top of monocrystalline silicon substrate produced by NTT Advanced Technology Corporation, and it shows accuracy about several nanometers.

8994-61, Session 15

Magnetoelectric coupling in cylindrical inclusions

Diana Strickland, Southwest Research Institute (United States); Andrea Alù, The Univ. of Texas at Austin (United States); Arturo Ayon, The Univ. of Texas at San Antonio (United States)

The polarizability of cylindrically shaped particles lies at the heart of nanoparticle spectroscopy, antenna theory, and classical microscopic theories of a composite material's electromagnetic properties. In this paper we provide a brief overview of the first theory providing the complete, fully dynamic polarizability tensor for circular cylinders, with emphasis on the discovery of significant bianisotropic elements. These magnetoelectric coupling coefficients are shown to be associated with strong spatial dispersion, and may become significant even for relatively small dielectric cylinders at oblique incidence. The results caution against neglecting the bianisotropic tensor elements, even in the long wavelength limit.

8994-62, Session 15

A quantum tunneling theory for nanophotonics

Joseph W. Haus, Univ. of Dayton (United States); Domenico de Ceglia, U.S. Army Aviation & Missile Research, Development & Engineering Ctr. (United States) and National Research Council (United States); Maria A. Vincenti, National Research Council (United States) and U.S. Army Aviation & Missile Research, Development & Engineering Ctr. (United States); Michael Scalora, U.S. Army Aviation & Missile Research, Development & Engineering Ctr. (United States)

Nanoplasmonics has emerged as a discipline with a broad range of activities and applications. There are many research directions often using surface plasmon polaritons including: nanoantennas for concentrating the field or controlling the radiation of electromagnetic energy, sensing at the nanoscale, enhanced nonlinear optical phenomena, such as harmonic generation and surface enhanced Raman scattering. The electromagnetic enhancement effects rely on a classical description of the materials and structures that works well for many experimental situations. Further gains are considered possible as the separation of the metal structures is reduced to the nanometer scale. Limitations of the classical description have to be examined when dimensions reach this scale.

We adopted the successful description of electron tunneling in metal-insulator-metal (MIM) structures that is built on a foundation of quantum mechanical calculations [1,2]. We apply a photon-assisted tunneling analysis [3,4] to describe the response of MIM structures to electromagnetic waves. The theory is a successful description of superconductor detectors, as well as normal metal MIM structures for high bandwidth photodetection. It has also been studied for its energy harvesting potential.

In our Quantum Conductivity Theory (QCT) we extract a set of linear and nonlinear conductivities based on calculations for MIM structures. The conductivities are incorporated into the electromagnetic simulations of the nanoscale models. Results are compared well to published quantum plasmonic calculations. Our theory describes optical phenomena with different insulators and metal combinations without a fit parameter.

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8994-63, Session 15

Fluorescence quenching metrology of graphene and 2D nanostructures

Maziar Ghazinejad, California State Univ., Fresno (United States); Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

We demonstrate an industrial-scale metrology technique for graphene and other 2D nanostructures that relies on Fluorescence Quenching Phenomena. Our technique can accurately characterize the number of the layers and defects, and visualize chemically doped/undoped regions across a large graphene landscape by utilizing the fluorescence quenching rates of graphene atomic planes. Reactive ion plasma etching allows us to develop patterns of p-type graphene that are doped with fluorine. We employ 4-(dicyanomethylene)-2-methyl-6-(4-dimethylaminostyryl)-4H-pyran (DCM) as the fluorescent agent. The emission of DCM is quenched to a different extent by fluorinated and pristine graphene, which provides the fluorescence-imaging contrast essential for this metrology. Fluorescence images of dye-coated graphene distinctly reveal the difference between the doped and as-grown regions. The regions with pristine graphene appear darker on the fluorescence images than the regions with fluorinated graphene, enabling large-scale mapping of the functionalized regions in CVD grown graphene sheets. Steady-state and time-resolved absorption and emission spectroscopy are used to comparatively characterize the photophysical properties of the dye when immobilized in PMMA films coating bare glass, pristine graphene, and fluorinated graphene. We observe that a three-fold increase in the in the rate constant of non-radiative decay is the principal reason for the DCM fluorescence quenching for the graphene regions of the samples. The spectral overlaps reveal the propensity for energy transfer from DCM to graphene, causing the increase in the rates of non-radiative deactivation of the photo excited dye. Fluorescence Quenching phenomenon can be employed to address the chronic need for a microscopy based graphene metrology.

Conference 8995: High Contrast Metastructures III

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8995-1, Session 1

High-contrast grating for flat optics

Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

High contrast grating (HCG) is a new class of optical grating with many distinct features that are not found in conventional gratings. These features include broadband ultra-high reflectivity, broadband ultra-high transmission, or very high quality-factor resonance, for optical beam surface-normal or in oblique incidence to the direction of grating periodicity. Furthermore, these features can be designed with simple top-down guidelines. The extraordinary features originate from a special near-wavelength regime that HCG operates at and from a large index contrast between the grating and its surrounding media. With many extraordinary properties, HCG establishes a new platform for planar optics and integrated optics. We report recent advances in theoretical analysis and device applications of high contrast gratings (HCG), including monolithic, continuously tunable vertical cavity surface-emitting lasers (VCSEL) and tunable detectors for high-speed wavelength-division mulplexed data-center networks and a single-layer mirrorless high-Q cavity for gas sensing. In addition, a new interesting phenomenon in HCG for light incident at an oblique angle will be discussed with potential applications for compact waveguides and switches.

8995-2, Session 1

High-index contrast/photonic crystal gratings: a wealth of new photonic functionality *(Invited Paper)*

Pierre Viktorovitch, Xavier Letartre, Ecole Centrale de Lyon (France); Badhise Ben-Bakir, CEA-LETI-Minatec (France); Sylvie Menezo, CEA-LETI (France)

High index contrast / Photonic Crystal membrane (HCG) resonators can be exploited to perform an arbitrarily adjustable molding of light at the wavelength scale: they can process free-space as well as wave-guided optical modes along a variety of addressing configurations and transfer functions, where the spectral, spatial, polarization, phase, group delay… characteristics can be resolved accurately and adjusted at will.

The physics of HCG resonators will be revisited based on a simple analytical approach and intuitive arguments, thus providing direct routes for design rules. Specifically, such desired functionalities as wavelength tuning, beam shaping, efficient light coupling to wave-guides, polarization selectivity, will be emphasized. Practical implementation of these functionalities will be presented in the case of VCSEEL (Vertical Cavity Surface Edge Emitting Laser) devices, where silicon HCG resonators are used as reflectors and are heterogeneously integrated with III-V semiconductor gain material, along a CMOS compatible technological approach.

8995-3, Session 1

High-refractive-index gratings for spectroscopic and laser applications *(Invited Paper)*

Uwe D. Zeitner, Frank Fuchs, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Ernst-Bernhard Kley, Friedrich-Schiller-Univ. Jena (Germany); Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Gratings are essential components in different high performance optical set-ups such as spectrometers in space missions or ultra-short pulse-laser applications. The technology used for the realization of such gratings at the Fraunhofer IOF is based on a highly efficient electron-beam lithography and reactive ion-etching processes for the transfer of the grating structures into fused silica substrates. However, the comparable low refractive index of the SiO2 may result in serious performance limitations related to the achievable diffraction efficiency or bandwidth of the gratings. A way out would be gratings patterned in high refractive index materials such as Ta2O5, TiO2 or Al2O3. Unfortunately, these materials can typically not be patterned with the required quality by common etching processes.

To overcome this limitation we developed novel grating fabrication technologies which are based on a combination of the conventional lithography with an Atomic-Layer-Deposition (ALD) process known from semiconductor industry. For that the basic structure of the grating is first realized in a fused-silica substrate or a SiO2-layer. This template is then functionalized by an ALD-coating in a specific pre-defined manner. The new approach opens up a huge variety of new options for the realization of gratings whose fabrication would otherwise be far out of our lithographic capabilities.

The potential of the technique will be demonstrated by different examples of gratings for ultra-short laser-pulse compression and space based spectroscopic instruments.

8995-4, Session 2

Narrowband absorption enhancement and broadband circular polarizers using high-contrast gratings *(Invited Paper)*

Ekmel Özbay, Ahmet E. Akosman, Bilkent Univ. (Turkey); Mehmet Mutlu, Bilkent Univ. (Turkey) and Stanford Univ. (United States)

Using high contrast gratings based on silicon on sapphire wafers, it is possible to achieve enhanced absorption and broadband circular polarizers. Two high-contrast grating structures, which are suspended in free-space, and composed of silicon ridges and free-space grooves, are designed to achieve an enhancement factor of 1310 at 1.06 micron wavelength. The same silicon on sapphire wafer is also used for a broadband circular polarizer. The experimental bandwidth of the polarizer is measured to be 33%, which is in reasonably good agreement with the theoretically calculated bandwidth of 42%.

8995-5, Session 2

Controlling the spatial flow of light using photonic gauge field induced by temporal modulations *(Invited Paper)*

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

In dielectric structures undergoing temporal refractive index modulation, the phase of the modulation can be used to create a gauge field for photons. Here we show that such a gauge field can be used to provide significant capabilities for controlling the spatial flow of light. As examples we show that proper gauge configurations can be used to achieve beam focusing, one-way mirrors, and negative refractions.

8995-6, Session 2

Efficient and broadband blazing with artificial dielectrics *(Invited Paper)*

Philippe Lalanne, Institut d'Optique d'Aquitaine (France)

No Abstract Available

8995-7, Session 2

Low-loss propagation in semiconductor AlxGa1-xAs waveguides

Latef M. Blbas, Farah A. Abed, Erbil Technical Institute (Iraq)

The electric fields within the slab waveguide are used to calculate the transmission coefficient of the dominant modes, the lowest loss in the region around 1550 nm. This study demonstrates the feasibility of obtaining semiconductor waveguide as a low-loss, single-mode transmission and useful for designing a waveguide filter.

8995-8, Session 2

Design and fabrication technique development of 3D high-contrast metastructure cage waveguides *(Invited Paper)*

Weimin Zhou, Gerard Dang, Monica Taysing-Lara, U.S. Army Research Lab. (United States); Tianbo Sun, Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

Previously, we developed a new type of 3D cage-like high-contract metastructure hollow-core waveguide that showed "slow-light" effect at 1550nm operation wavelength with reasonable low propagation loss. The challenge is to fabricate such 3D cage waveguide by four high-contrast gratings (HCG)s, with square hollow-core, on a Si wafer using relatively simple and practical technique. In this presentation, we review our design and development of different fabrication techniques that allow us to create this 3D structure from the 2D surface using precision under-cut technique by cycled plasma dry etch of deep trenches with controlled trench width variation while etching down. The fabrication precision, tolerance, and uniformity are critical for reducing the propagation loss and reach the optimized "slow-light" regime. We are also looking for different operation wavelength. One of the applications for such a waveguide is chemical gas sensing, because the cage form provide an open form of high-Q cavity that can be integrated with a light source and detector. However, it is desirable to perform the chemical sensing in THz regime that has less busy spectrum for easy chemical identification. Therefore, we are developing a new fabrication technique for the THz metastructure cage waveguide on Si wafers. The waveguide is built with entire wafer thickness (600-800?m) using a modified "SCREAM" method which involves deep Si etch to form the HCG as cladding, SiO2 coating of the HCG, etching the hollow core with isotropic undercut etch, etc. We will discuss the details of these fabrication techniques, compare them in our experimental results.

8995-10, Session 3

Investigation on the angular dependent reflectance of coupled high-contrast gratings

Stefanie Kroker, Thomas Käsebier, Friedrich-Schiller-Univ. Jena (Germany); Ernst-Bernhard Kley, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

During the past years high contrast gratings (HCGs) based on silicon have been attracting large interest in applied and fundamental science, as well. Their broadband performance with respect to geometric parameters, wavelength or angle of the incident light enable the realization of high reflectance or filters and beam steering devices. In this contribution we discuss configurations of stacked silicon HCGs. The high-index gratings are separated by a low-index grating made of silicondioxide. If the thickness of this separating grating layer is sufficiently small the HCGs are coupled via their near-fields. This coupling is dependent on the geometric grating dimensions and the illumination conditions. Hence, altering the wavelength or incidence angle it is possible to either benefit from the optical performance of two HCGs acting as an asymmetric Fabry-Perot etalon or one single HCG with enhanced grating thickness. This effect can be exploited to realize reflective or transmissive filters with tailored optical properties. We experimentally demonstrate the coupling effect on a stack of two HCGs exhibiting a pronounced coupling for an incidence angle of about 70°, a wavelength of 1550 nm and transverse-magnetic polarization. The investigated structure allows for a nearly angular independent high reflectance.

8995-11, Session 3

GaAs/AlOx high contrast gratings for 980 nm VCSELs

Marcin Gebski, Maciej Dems, Technical Univ. of Lodz (Poland); Jian Chen, Wang Qijie, Dao Hua Zhang, Nanyang Technological Univ. (Singapore); Tomasz Czyszanowski, Technical Univ. of Lodz (Poland)

In order to obtain low threshold VCSELs high reflectivity mirrors are crucial in their designs. Typically used Distributed Bragg Reflectors (DBR) provide reflectivity over 99.8 % in the spectral range of 75 nm. It has been shown in the recent years that High Contrast Gratings (HCG), if properly designed, provide extremely large polarization discrimination as well as 150 nm spectrum of high reflectivity which makes them superior to DBRs and potentially opens a way to the next generation HCG based VCSELs. We present numerical simulations of the 980 nm HCG VCSEL top mirror. We determine the maximal fabrication error and the absorption of HCG that still allow to meet the criteria of VCSEL top mirror. We perform the statistical analysis of manufacture inaccuracy based on Gaussian distribution with standard deviation ? as inaccuracy measure varying from 0 nm to 50 nm. We show that σ= 35 nm reduces the reflectivity to the level of 99% which is the typical reflectivity of the output mirror of 980 nm VCSELs. Additionally we have found that reduction of the reflectivity is linear and very slow varying with the change of the absorption. The results show that absorption as large as 500 cm-1 in HCG stripes allows to reach 99% of reflectivity while typical absorption for GaAs is assumed to be equal to 10 cm-1.

This work is jointly supported by Polish NCR&D and Singapore A*STAR (grant no. 122 070 3063) project: 'A Novel Photonic Crystal Surface Emitting Laser Incorporating a High-Index-Contrast Grating'.

8995-12, Session 3

High-contrast gratings for long-wavelength laser integration on silicon *(Invited Paper)*

Corrado Sciancalepore, Ecole Centrale de Lyon (France); Antoine Descos, Damien Bordel, Hélène Duprez, CEA-Leti, Minatec, Photonics on CMOS Labs (France); Xavier Letartre, Ecole Centrale de Lyon (France); Sylvie Menezo, CEA-LETI (France); Badhise Ben-Bakir, CEA-LETI-Minatec (France)

(Invited Talk) Silicon photonics is increasingly considered as the most promising way-out to the relentless growth of data traffic in today's telecommunications infrastructures, driving an increase in transmission rates and computing capabilities. This is in fact challenging the intrinsic limit of copper-based, short-reach interconnects and microelectronic circuits in data centers and server architectures to offer enough modulation bandwidth at reasonable power dissipation. In the context of the heterogeneous integration of III-V direct-bandgap materials on silicon, high-contrast metastructures optics enables the efficient implementation of optical functions such as laser feedback, input/output (I/O) to active/passive components, and optical filtering in the silicon architectures, while III-V layers provide sufficient optical gain, resulting in silicon-integrated laser sources characterized by enhanced wall-plug efficiency, low power-consumption, and reduced system architecture footprint. The invited talk will introduce the audience to the latest breakthroughs concerning the use of high-contrast gratings (HCGs) for the integration of III-V-on-Si vertical-cavity surface-emitting lasers (VCSELs) as well as Fabry-Perot edge-emitters (EELs) in the main telecom bands around 1.55 um. The strong near-field mode overlap within HCG mirrors can be exploited to implement unique optical functions such as on-chip optical routing as well as dense wavelength division multiplexing (DWDM): a 16-lambda 100-GHz-spaced channels VCSEL array is demonstrated. On the other hand, high fabrication yields obtained via molecular wafer bonding of III-V alloys on silicon-on-insulator (SOI) conjugate excellent device performances with cost-effective high-throughput production, supporting industrial needs for a rapid research-to-market transfer.

8995-17, Session 3

1550-nm wavelength-tunable HCG VCSELs *(Invited Paper)*

Christopher Chase, Yi Rao, Michael Huang, Bandwidth10 (United States); Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

We demonstrate wavelength tunable VCSELs using high contrast gratings (HCGs) as the top output mirror on VCSELs, operating at 1550 nm. Tunable HCG VCSELs with a ~24 nm mechanical tuning range and 2 mW output power were realized. Error-free operation of an optical link using directly-modulated tunable HCG VCSELs transmitting at 1.25 Gbps over 10 channels spaced by 100 GHz and transmitted over 25 km of single mode fiber is demonstrated, showing the suitability of the HCG tunable VCSEL as a low cost source for WDM communications systems.

8995-13, Session 4

GaN-based surface-emitting lasers using high-contrast grating *(Invited Paper)*

Tien-Chang Lu, Shing-Chung Wang, Tzeng-Tsong Wu, Shu-Hsien Wu, Yu-Cheng Syu, National Chiao Tung Univ. (Taiwan)

High contrast gratings (HCGs) have been utilized for manipulating various functional devices in recent years. In our recent works, we have demonstrated the GaN-based HCG as an optical reflector in the blue region and developed GaN-based surface-emitting lasers using HCG. The GaN membrane high contrast grating (HCG) reflectors have been fabricated and investigated. The structural parameters including grating periods, grating height, filling factors and air-gap height were calculated to realize high reflectivity spectra with broad bandwidth by the rigorous coupled-wave analysis and finite-difference time-domain method. Based on the optimized simulation results, the GaN membrane HCG reflectors were fabricated by the e-beam lithography and focused-ion beam process. The fabricated GaN-based membrane HCG reflectors revealed high reflectivity at 460 nm band with large stopband width of 60 nm in the TE polarization measured by using the micro-reflectivity spectrometer. The experimental results also showed a good agreement with calculated ones. Secondary, GaN-based surface-emitting lasers (SELs) using HCG with AlN/GaN distributed Bragg reflectors were reported. The device exhibited a low threshold pumping energy density of approximately 0.56 mJ/cm2 and the lasing wavelength was at 393.6 nm with a high degree of polarization of 73% at room temperature. The specific lasing mode and polarization characteristics agreed well with the theoretical modeling. The low threshold characteristics of our GaN-based SELs using HCG facilitated by the Fano resonance can serve as the best candidate in blue surface emitting laser sources.

8995-15, Session 4

Fano resonance membrane reflector surface-emitters and filters on silicon *(Invited Paper)*

Weidong Zhou, The Univ. of Texas at Arlington (United States); Zhenqiang Ma, Univ. of Wisconsin-Madison (United States)

Based on Fano resonance principle in 2D air hole photonic crystal slabs, we have demonstrated high performance broadband membrane reflectors and optically pumped membrane reflector vertical-cavity surface- mitting lasers (MR-VCSELs) on silicon. In this invited talk, we will report our recent progress in the development towards electrically-pumped MR-VCSELs at 1550 nm, including efficient electrical injection configurations, thermal-management, and cavity design for emission control. Additionally, based on multi-layer stacked and lattice-shifted Fano resonance filters, we have designed and demonstrated very high Q (>1e5) surface-normal optical filters, with unique cavity and optomechanic characteristics. In this talk, I will review the design, fabrication, and characterization of these membrane structures, for surface-normal operation and 3D multi-functional integrated photonic systems. The work was supported by US AFOSR, ARO and NSF.

8995-16, Session 4

High-contrast silicon grating built on fiber tip for acoustic detection

Tao Ling, Cheng Zhang, L. Jay Guo, Univ. of Michigan (United States)

High contrast gratings (HCGs) have been demonstrated for many promising applications, such as broadband reflector, a single layer high-Q cavity, and forming vertical-cavity surface-emitting lasers. Besides, hybridizing the polymer materials with HCG devices could open new opportunities and impart new functionalities to the photonic devices by exploiting the unique properties of the polymer materials, such as large opto-elastic effect. Furthermore, direct integration of photonic device on fiber tip can facilitate various applications in remote sensing, optical fiber communication and point-of-care detection. In this work, we developed a high-Q HCG on fiber tip as an ultrasonic sensor. The HCG is filled with polymer which makes it sensitive to acoustic pressure. By using a novel transfer and bonding process, a polymer filled high contrast silicon nanograting resonator has been successfully transferred onto the fiber tip with preserved functionalities and performance. High Q factor ~10^4 as well as sensitive acoustic response has been demonstrated. Further improving the Q factor as well as the coupling efficiency from fiber to silicon grating cavity has been studied. The demonstration of the fiber tip based passive silicon photonic device platform could open doors to novel applications including remote opto-strain monitoring, intravascular ultrasound imaging and bio-photonic probes.

8995-9, Session 5

Engineering of angular dependence of high-contrast grating mirror for transverse mode control of VCSELs

Fumio Koyama, Tokyo Institute of Technology (Japan)

We present our recent activity on highly angular-dependent high contrast grating (HCG) for the transverse mode control of VCSELs. The modeling and the experiment show the design flexibility of HCG to manage the angular dependence of HCG. The optimized angular dependent HCG functions as a spatial frequency filter. While the transverse angle for each transverse mode is different, a fundamental mode has the smallest transverse angle and high-order modes show larger angles. Thus we are able to select only a fundamental mode using the highly angular dependence of HCG. This advantage of this proposed method is to avoid all the higher-order modes. This would come from the special frequency filtering thanks to the highly angular dependence. We carried out the design for highly angular dependence of HCG. We are able to control the angular dependence by tuning the duty cycle.

We fabricated a-Si/SiO2 HCG on Si substrate. We carried out nanoimprint lithography for making HCG followed by Cl2-ICP dry etching. Sub-wavelength grating patterns can be transferred with high throughput, low-cost and large area. We carried out far-field measurements of reflections for characterizing the angular dependence of reflectivity. The result shows much larger angular dependence of HCG than that of DBRs. We fabricated 980nm VCSELs with HCG as a top mirror. First, we deposited Si and SiO2 by plasma CVD and then carried out nanoimprint lithography for making patterns followed by ICP etching. The oxide aperture diameter is 5-6?m. The threshold current is 1mA and the maximum output 0.5mW, which could be improved by optimizing the reflectivity of HCG. A SMSR is over 25 dB at bias of 3 times threshold. The data indicate the single transverse-mode operation of HCG VCSELs thanks to the angular dependence of HCG.

8995-18, Session 5

Subwavelength grating reflectors in MEMS tunable Fabry-Perot infrared filters with large aperture

Steffen Kurth, Fraunhofer-Institut für Elektronische Nanosysteme (Germany); Karla Hiller, Technische Univ. Chemnitz (Germany); Marco Meinig, Jan Besser, Fraunhofer-Institut für Elektronische Nanosysteme (Germany); Mario Seifert, Martin Ebermann, Norbert Neumann, InfraTec GmbH (Germany); Thomas Gessner, Fraunhofer-Institut für Elektronische Nanosysteme (Germany); Florian Schlachter, AMO GmbH (Germany)

Since MEMS tunable Fabry-Perot infrared filters using distributed Bragg reflectors (DBR) are mature for commercialization, enhanced performance and reduced fabrication complexity and cost are in the focus now. This paper presents a novel tunable infrared filter applying a subwavelength grating that substitutes the DBRs reducing cost and effort. It consists of uniformly arranged disc resonators which are made of 100 nm thick aluminum at a 200 nm silicon nitride membrane carrier that stands freely after fabrication. This design approach has the advantage that an optimization can be done by varying geometry parameters of lateral structures. Moreover, the materials are highly compatible to standard MEMS processes. The dimensions of the subwavelength structures were optimized based on finite difference time domain (FDTD) analysis. The fabrication sequence consist of silicon MEMS technology steps as like as deposition and patterning of electrodes and of isolation layers, silicon etching, and wafer bonding, and it includes nano imprint lithography for forming the subwavelength structures at wafer level. The samples have an aperture of 2 mm and are mechanically tuned by electrostatic forces with tuning voltages up to 75 V. They show the typical characteristics of Fabry-Perot filters but with high peak transmittance within a remarkably large wavelength range (T>50% @2.5 µm … 8.5 µm) spanning over 5 orders of the optical resonator. The optical performance was measured by Fourier transform infrared spectrometer and compared to the simulation results. It shows a widely good agreement between calculation and measurement.

8995-19, Session 5

130-nm tunable grating-mirror VCSEL *(Invited Paper)*

Il-Sug Chung, Jesper Mørk, Technical Univ. of Denmark (Denmark)

We have reported that a combination of the high-index-contrast grating (HCG) mirror as movable mirror and the extended cavity configuration with an antireflection layer can provide a tuning wavelength range of 100 nm for tunable VCSELs. Here, we report that using the air-coupled cavity configuration instead of the extended cavity configuration can bring 130-nm tuning range around 1300-nm wavelength. The air-coupled cavity is known to reduce the quantum confinement factor in VCSELs, increasing threshold. In our air-coupled cavity HCG VCSEL case, the very short power penetration length in the HCG minimizes this reduction of the quantum confinement factor, not as significant as in the air-coupled cavity DBR VCSEL.

8995-20, Session 5

Transmission filtering capabilities of a suspended silicon grating

Justin M. Foley, Steven M. Young, Jamie D. Phillips, Univ. of Michigan (United States)

Spectral filtering is extensively used in imaging, display and spectroscopy applications; however, achieving these capabilities across the electromagnetic spectrum can be challenging. High index contrast dielectric gratings (HCGs) have demonstrated tailorable spectral response including narrowband reflection filters, with the filtered wavelength exhibiting an intuitive dependence on grating geometry. These systems have potential for realizing spectrum-scalable optical elements. Dielectric grating-based narrowband transmission filters have proven more elusive than their reflectance-based counterparts. We recently reported narrowband transmission filtering using a suspended silicon grating at off-normal incidence. For that system, transmission bands emerge when the transverse magnetic (TM, magnetic field directed along the ridges of the grating) incident light has a small component of propagation in the direction of the grating periodicity. These bands are a consequence of weak coupling to supported TM modes. In this presentation, we will discuss our ability to couple to a different set of modes by changing the plane of incidence to have propagation along the invariant direction of the grating. Using a suspended silicon system designed using finite element analysis, characterized with Fourier transform infrared spectroscopy, and analyzed using finite element modal analysis, spectral filtering is demonstrated at higher frequencies than those previously reported. The filtered wavelength exhibits a simple dependence on the grating period and flexibility that can be leveraged for imaging and spectroscopy applications. Additionally, the operational principle can be geometrically scaled for applications in different frequency ranges.

8995-21, Session 6

Characterization of planar microlenses made of high contrast gratings *(Invited Paper)*

Annett B Klemm, Univ. of York (United Kingdom); Daan Stellinga, The Univ. of York (United Kingdom); Emiliano R Martins, Univ. of St. Andrews (United Kingdom); Liam Lewis, Tyndall National Institute (Ireland); Liam O'Faolain, Univ. of St. Andrews (United Kingdom); Thomas F Krauss, The Univ. of York (United Kingdom) and Univ. of St. Andrews (United Kingdom)

We demonstrate high aperture (up to n.A.~0.64) three-dimensional focusing in free space based on wavefront-engineered high contrast gratings. The grating lens' optical response is tailored by spatially varying the grating ridge and groove width in two dimensions to achieve focal lengths of order 100 µm that are crucial for micro-optical applications. The phase profile of the lens includes multiple 2π phase jumps and was obtained by applying an algorithm for finding the optimal path for both phase and amplitude. Experimental measurements reveal a lateral spot size of 5 µm that is close to the size of a corresponding Airy disk.

8995-22, Session 6

A polychromatic approach to far-field superlensing *(Invited Paper)*

Geoffroy Lerosey, Fabrice Lemoult, Mathias Fink, Institut Langevin (France)

In this talk I will show how the use of time dependent and broadband wavefields, in conjunction with metamaterials, permits to beat the diffraction limit from the far field for imaging or focusing purposes. I will introduce the idea of resonant metalens, first demonstrated in the microwave domain, and explain its principles. In particular, I will show how the concept of time reversal can be utilized to focus in this metamaterial based lens and from the far field, onto focal spots much smaller than the diffraction limit. I will then prove the generality of the approach by demonstrating its transposition to the acoustic domain. Then I will present our latest theoretical and numerical results obtained using a resonant metalens made out of plasmonic nanorods in the visible part of the spectrum. I will show that this lens allows, using polychromatic light, to focus light using far field time reversal onto spots as small as 1/30th of the wavelength in the visible. Finally I will prove that our approach can also be used in order to image from the far field and with a subwavelength resolution and could lead to real time sub-diffraction imaging systems.

8995-23, Session 6

The aberrations of flat lenses and design for aplanatic metasurfaces

Francesco Aieta, Patrice Genevet, Mikhail A. Kats, Federico Capasso, Harvard School of Engineering and Applied Sciences (United States)

Optical metasurfaces are artificial interfaces designed to manipulate light at the subwavelength scale and exhibit functionalities not attainable with conventional optical components. In the case of metasurfaces composed of inhomogeneous arrays of phase discontinuities the wavefront of light can be reshaped and redirected upon excitation and re-emission of subwavelength resonators with suitably designed scattering properties. By using a hyperboloidal distribution of phase discontinuities, one can design a metasurface to focus light without spherical aberrations that are typically present in refractive spherical lenses. The subwavelength control over the phase front provided by the metasurface allows for the design flat lenses with high numerical aperture that focus light under axial illumination without aberrations. However, the practical implementation of the device or a different mode of operation of the lens can lead to the appearance of aberrations. We report a quantitative analysis of the primary monochromatic aberrations associated with flat lenses based on metasurfaces. The effect of the discretization of the phase profile is evaluated and it is shown that four elements are enough to guarantee an imaging quality limited only by diffraction of light. We prove that for a continuous phase profile and normal incidence the lens is aberration-free, while for off-axis illumination the WAF contains coma and other aberrations, though it remains free from spherical aberrations and barrel and pincushion distortion. Following the approach proposed for Fresnel zone plates, we present a design for an aplanatic ultra-thin lens, which can focus light without both spherical aberrations and coma.

8995-24, Session 6

A single GMR grating lens focusing two orthogonally-polarized beams into opposite directions

Seok-Ho Song, Junhyung Lee, Hanyang Univ. (Korea, Republic of)

High contrast, GMR gratings can possess a focusing power by dramatic control of local resonance phases after reflection or transmission of incident beams. The GMR grating lenses developed so far are mostly resonant only for single polarization states and for either one of the reflection or transmission directions.

We propose a novel GMR grating lens focusing two orthogonally polarized beams into opposite directions: TE-polarized focus in transmission while TM-polarized in reflection. The GMR grating lens is comprised of one dimensional silicon grating with a fixed period and fill factor, but for a parabolic lens phase the grating thickness is varied in space. Amplitude and phase responses of the GMR gratings are completely separable for TE and TM polarizations in opposite directions, resulting in a novel GMR device possessing both functions of power focusing and polarization filtering. We show the novel functions of GMR grating lenses with focal length of about 10 wavelengths? in both directions and power efficiency of above 80 % converging to diffraction-limited foci with 20 dB polarization extinction.

We believe that the demonstration of separable but simultaneous modulation of resonance phases at a single GMR gating for two orthogonal polarization states of incident light well reveals one of the typical advantages using flat high-contrast gratings in nanophotonic applications.

8995-14, Session PWed

Giant field enhancement in structured dielectrics film

Vito Mocella, Silvia Romano, Istituto per la Microelettronica e Microsistemi (Italy)

The field enhancement of a structured dielectric surface is a relatively unexplored field, with an increasing interest in last years [1] [2,3]. In this paper we show that a thin layer lattice in a low contrast dielectric medium can exhibit an extremely large field enhancement, as large as 700 times the amplitude of the incident wave.

It is now recognized that a dielectric photonic crystal (PhC) can behave as a Lorentz resonator and this is strongly connected with negative index properties of the PhC [4].

The effect under consideration is related to the so called bound states in the continuum [5] where the mechanism that allows the bounded state is able to stabilize the trapped mode controlling the field amplification, that increases with increasing mode lifetime.

The field enhancement associated with SPPs is the basis of the Surface Enhanced Raman Scattering (SERS) effect [6]. In the present case the SERS enhancement would correspond to the fourth power of the field enhancement, i.e. a factor 11.

In add it should be considered that this corresponds to a very narrow resonant peak which, together with the field enhancement property, can have a wide range of possible applications.

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8995-25, Session 7

Optomechanics with high-contrast gratings *(Invited Paper)*

Utku Kemiktarak, National Institute of Standards and Technology (United States) and Joint Quantum Institute (United States); Corey Stambaugh, National Institute of Standards and Technology (United States); Haitan Xu, Jacob Taylor, John R. Lawall, National Institute of Standards and Technology (United States) and Joint Quantum Institute (United States)

By virtue of offering near-unity reflectivity, extremely high mechanical quality factors, and ultralow mass, high-contrast gratings fabricated from silicon nitride offer a fruitful new platform for optomechanics. We have constructed Fabry-Perot cavities using such gratings fabricated from low-stress silicon nitride, and realized a cavity finesse as high as 2800 and mechanical quality factors as high as Q = 780 000. We will briefly review optically cooling the mechanical modes of the grating reflectors, as well as recent experiments involving “phonon lasing.” Our most recent fabrication efforts involve the use of high stress stoichiometric silicon nitride. While more challenging to fabricate, stoichiometric material offers the promise of still lower optical and mechanical losses. To aid in the optimization of these structures, we have developed a cavity-enhanced technique to measure the index of refraction, absorption, and thickness of silicon nitride membranes after release from a substrate. In addition, we are now creating compound optical cavities by using the gratings as a reflective element within another cavity. In this way, we are better able to elucidate the optical loss mechanisms. Furthermore, this configuration should allow us to achieve an optical linewidth lower than the mechanical resonance frequency (the “resolved sideband limit”), a necessary condition for optical cooling to the quantum ground state. Finally, it allows for the creation of squeezed light and force detection beyond the standard quantum limit. We will report on progress towards these goals.

8995-26, Session 7

High-contrast grating MEMS optical phase-shifters for two-dimensional free-space beam steering *(Invited Paper)*

Mischa Megens, Byung-Wook Yoo, Univ. of California, Berkeley (United States); Trevor K. Chan, Univ. of California, Davis (United States); Weijian Yang, Tianbo Sun, Connie J. Chang-Hasnain, Ming C. Wu, Univ. of California, Berkeley (United States); David A. Horsley, Univ. of California, Davis (United States)

We report an optical phased array (OPA) for two-dimensional free-space beam steering. The array is composed of tunable MEMS all-pass filters (APFs) based on polysilicon high contrast grating (HCG) mirrors. The cavity length of each APF is voltage controlled via an electrostatically-actuated HCG top mirror and a fixed DBR bottom mirror. The HCG mirrors are composed of only a single layer of polysilicon, achieving >99% reflectivity through the use of a subwavelength grating patterned into the polysilicon surface. Conventional metal-coated MEMS mirrors must be thick (1-50 um) to prevent warpage arising from thermal and residual stress. The single material construction used here results in a high degree of flatness even in a thin 300 nm HCG mirror. Relative to beamsteering systems based on a single rotating MEMS mirror, which are typically limited to bandwidths below 50 kHz, the MEMS OPA described here has the advantage of greatly reduced mass and therefore achieves a bandwidth over 500 kHz. The APF structure affords large (~2 [pi]) phase shift at a small displacement (< 50 nm), an order-of-magnitude smaller than the displacement required in a single-mirror phase-shifter design. Beamsteering is demonstrated using both binary and analog phase patterns and is accomplished with the help of a closed-loop phase control system based on a phase-shifting interferometer that provides in-situ measurement of the phase shift of each APF in the array.

8995-27, Session 7

High pixel density optical holographic array based on high-contrast metastrctures

Li Zhu, Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

The optical holographic array is very interest for displaying objects in three dimensions. It reproduces the 3D scenes for the unassisted eyes by modulating both of the amplitude and phase of the optical beam. In order to create sharp and fine resolution 3D images, the high pixel density of the holographic array is necessary. The advanced nanoscale lithographic techniques enables the possibility to define the subwavelength features. In this work, we demonstrate the high contrast metastructure (HCM) with a single layer of lithographical pattern is very promising for composing the holographic array with the pixel size close to the diffraction limit.

The high contrast metastructure is a layer of high index dielectric material fully surrounded by the low index materials with feature size smaller than the optical wavelength. It has shown the very unique properties to replace the distributed Bragg reflectors for broadband, high-reflectivity mirrors or to design the planar optical lenses, by engineering the reflection amplitude or phase, respectively. It has been demonstrated that the optical property of the HCM is determined by the local periodicity. By designing the duty cycle in two in-plane directions within the local period, the HCM can cover the entire amplitude and phase map, giving designs for any amplitude and phase combinations. By filling such design map, a holographic array with 3?m pixel size to record the near-field information of the given object is simulated and reproduces the far field image holographically.

8995-28, Session 7

Output beam profile control of slow-light Bragg reflector waveguide deflector with high-contrast sub-wavelength grating

Xiaodong Gu, Fumio Koyama, Tokyo Institute of Technology (Japan)

We demonstrated a super-high resolution beam scanner based on a Bragg reflector waveguide. In this device, radiation profile is exponentially decaying if without any gain engineering. However, for achieving high-quality output beam, it is important to control the profile, for example to a Gaussian distribution. We propose a solution for this by mounting a

high-contrast sub-wavelength grating (HCG) on the waveguide surface. Numerical simulations using finite-difference time-domain method (FDTD) and rigorous coupled wave analysis (RCWA) were carried out. We found that, by designing the thickness, period and duty cycle of HCG, the output phase and intensity can be changed. As a result, it is possible to shift the output direction and modify the beam profile. We discussed their dependences on HCG parameters. On the other hand, the thicknesses (numbers of pairs) of the top- and bottom- distributed Bragg reflectors (DBRs) mirrors are influential to the results. A discussion on the thickness dependence was carried out. We found that, HCG has stronger influence to thinner mirrors. Because HCG can provide high reflectivity, thin mirrors are not a problem in such slow-light waveguides. We believe this proposal can offer us a method to obtain desirable output beam profile of Bragg reflector waveguides deflectors.

8995-29, Session 8

Transmissive high-contrast grating for efficient optical mode conversion

David Fattal, Sonny Vo, Wayne V. Sorin, Hewlett-Packard Labs. (United States)

We experimentally demonstrate the use of high contrast grating (HCG) lenses to impart an angular momentum conversion up to the 7th order. A single-mode Gaussian input results in donut-shaped beam output intensity patterns in the image plane. We demonstrated transmission efficiency of greater than 70% coupling from a single-mode fiber input to a multi-mode fiber output. An application we investigated was the use of these higher order angular momentum HCGs as an optical modal isolator to isolate reflections back into the single mode fiber input. We measured isolations of greater than 25 dB from a mirror in the image plane.

8995-30, Session 8

Subwavelength metastructures for dispersion engineering in planar waveguide devices *(Invited Paper)*

Robert Halir, Alejandro Ortega-Moñux, Univ. de Málaga (Spain); Pavel Cheben, National Research Council Canada (Canada); Alejandro Maese-Novo, Diego Pérez-Galacho, Carlos Alonso-Ramos, Iñigo Molina-Fernandez, Juan Gonzalo Wangüemert-Pérez, Univ. de Málaga (Spain); Jens Schmid, Dan-Xia Xu, Siegfried Janz, National Research Council Canada (Canada)

High contrast structures with a sub-wavelength pitch, small enough to suppress diffraction, exhibit extraordinary optical properties: depending on the design they may behave as perfect mirrors, homogenous materials with controllable refractive index, or strongly dispersive materials. Here we discuss on the design possibilities such structures offer in planar waveguide devices in silicon-on-insulator. We briefly review the application of sub-wavelength structures in a variety of waveguide devices. We then focus on some of the latest advances in the design ultra-compact and ultra-wideband multimode interference couplers based on dispersion engineered sub-wavelength structures.

8995-31, Session 8

Grating-based guided-mode resonance devices and degradation of their performance in real-life conditions

Aliaksandra Ivinskaya, René Bergmann, Jan R. Kafka, Mogens H. Jakobsen, Technical Univ. of Denmark (Denmark); Fridolin Okkels, DTU (Denmark)

Guided-mode resonances in structures having periodicity along at least one dimension were widely employed in the last decade in various optical devices. Initially it was shown that at frequencies close to the second order band gap periodic structures can feature total reflection of light due to the guided modes propagating along the surface of the grating. As an application, this allows to substitute a thick multilayer Bragg mirror in VCSELs by a thin grating-based mirror. Most devices utilizing guided-mode resonances were theoretically and numerically investigated with the idealized model of an infinite periodic structure illuminated by a plane wave. To see how grating-based components can perform in real life we take into account two critical factors: the finite size of the grating and the Gaussian shape of the light source replacing a plane wave. These factors can significantly change and impair the performance of filters, mirrors, sensors and other devices operating by the guided-mode resonance effect. We also show experimentally that for some kinds of gratings guided-mode resonances can vanish if the grating is illuminated by extended source, i.e. heated plate in our case, focused on the sample.

8995-32, Session 8

High-order grating coupler for high efficiency vertical to in-plane coupling

Arvinder S. Chadha, Yichen Shuai, Weidong Zhou, The Univ. of Texas at Arlington (United States)

Optical interconnects provide an attractive way to meet the increasing bandwidth and computation demands. However, coupling of the light to on-chip waveguides is a big challenge. Compact vertical to in-plane couplers (VICs) are critical components for optical interconnects and integrated photonic chips. Several vertical to in-plane couplers have been demonstrated to couple light out of or into the waveguide. Most couplers use the fiber at near normal incidence to couple the light into the waveguide. However, the angled fiber is not desirable for low cost packing and is mechanically unstable. Slanted grating and chirped grating couplers have been demonstrated to couple light using normal incidence. However, the slated grating structure requires complicated non-standard fabrication processes.

More recently, a novel design of a surface normal first order grating coupler with high coupling efficiency is proposed, based on subwavelength high contrast gratings (HCGs). Conventional second order gratings have poor efficiency typically below 25% in each in-plane directions. In this paper, we present a design of a robust broadband high efficiency vertical to in-plane optical coupler using second-order HCG structure. The coupler is designed for TE mode with coupling efficiency of 82.4% at 1,552 nm with a 3 dB bandwidth of 42 nm. The fabrication tolerance of both the first-order and second-order grating coupler with surface normal coupling is also assessed. The measurement results suggest large fabrication tolerances on the second-order vertical to in-plane optical coupler.

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8995-33, Session 9

Resonant semiconductor nanostructures for optoelectronic devices *(Invited Paper)*

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

Semiconductor nanostructures are at the heart of electronic devices and systems. Due to their high refractive index, they also provide a myriad of opportunities to manipulate light. When properly sized and shaped, they can support strong optical resonances that boost light-matter interaction over bulk materials and enable their use in controlling the flow of light at the nanoscale. As a result, new optoelectronic devices can be realized that simultaneously perform electronic and optical functions. In this

presentation, I will discuss the use of such devices, including deep-subwavelength, resonant semiconductor nanostructures in a range of optoelectronic devices, including detectors, light sources, solar cells, and imaging systems.

8995-34, Session 9

spectrum splitting using multi-layer sub-wavelength high-index-contrast grating (HCG) for improved solar energy harvesting efficiency

Yuhan Yao, He Liu, Shujin Huang, Wei Wu, The Univ. of Southern California (United States)

In order to harvest solar energy with efficiency beyond the state-of-the-art solar cells, spectrum splitting schemes were proposed. However, most of those systems are based on bulky geometrical optical elements and expensive optical filters, and require drastic change from conventional photovoltaic setup.

We invented a spectrum splitting system. The key in this invention is a high-efficiency planar dispersive mirror, which will be used to replace the mirror in a solar concentrator. The dispersive mirror is based on multilayer of chirped sub-wavelength high-contrast dielectric gratings (HCGs). The sunlight will be reflected dispersively to each cell, which are arranged in parallel, according to the wavelength. Lights with short wavelength are reflected by the top HCG layer, and longer wavelengths go through top layers and are reflected by lower layers to different angles. The properly chirped HCG in each layer controls the wavefront of the 0st order diffraction. In our work, the structure and parameter for multi-layer dispersive mirrors (stacked HCGs) are designed and optimized based on numerical (FDTD and RCWA) study. For our structures, the physics behind reflection and phase shift are studied. Our numerical work shows that the dispersive mirror can direct light of different wavelengths into different angles for the entire solar spectrum, maintaining low energy loss. The dispersive mirror will be fabricated using low-cost nanoimprint lithography. Our approach does not only improve the energy harvesting efficiency, but also lower the cost by using low-cost single junction cells. Moreover, this approach has the minimum disruption to the existing infrastructure.

8995-35, Session 9

Transmission matrix analysis for multi-layer high-contrast grating

Weijian Yang, Fanglu Lu, Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

High contrast grating (HCG) is a single layer of periodic subwavelength grating composed of a high-refractive-index material surrounded entirely by low-index materials. Various extraordinary properties have been demonstrated, such as ultra broadband high reflectivity and high quality-factor resonance. While an analytic formulism has been established to explain these phenomena, it is only suitable to solve an isolated single HCG layer.

Here we establish a transmission matrix method to generalize the analytic analysis for HCG with any layer stacking configuration, such as HCG on silicon-on-insulator, double HCG stack, etc. The HCG is treated as a single layer in its thickness direction (z direction). Any other layer can be stacked above or below the HCG. These layers can be either homogeneous dielectric layers or other HCGs with the same period and polarization. Eigen modes with propagation constants in the z direction are solved for each layer. The electric-magnetic field in each layer can be expressed as a sum of its eigen modes, weighted by the corresponding mode coefficients. The mode coefficients for forward (+z) and backward (-z) propagation directions can be expressed in a vector format, labelled as A and B respectively. Transmission matrix is solved for each layer and layer interface to relate A and B at each layer interface. The reflection and transmission coefficients, as well as the electric-magnetic field of the whole system can thus be solved. This provides a flexible and powerful tool to solve and study the HCG with any configuration.

8995-36, Session 9

High-efficiency reflective metasurfaces for anomalous reflection and metahologram

Wei Ting Chen, National Taiwan Univ. (Taiwan); Kuang-Yu Yang, Academia Sinica (Taiwan); Chih-Ming Wang, National Dong Hwa Univ. (Taiwan); Shulin Sun, Fudan Univ. (China); Ta-Ko Juan, National Dong Hwa Univ. (Taiwan); Yao-Wei Huang, Chun Yen Liao, Hao Tsun Lin, National Taiwan Univ. (Taiwan); Qiong He, Shiyi Xiao, Lei Zhou, Fudan Univ. (China); Greg Sun, Univ. of Massachusetts Boston (United States); Ai Qun Liu, Nanyang Technological Univ. (Singapore); Din Ping Tsai, National Taiwan Univ. (Taiwan)

Manipulating light is highly desired in photonics research. Restricted by the variable range of permittivity for natural materials, conventional photonic elements are often optically thick and their light-manipulation abilities are quite limited. Recently, ultra-thin meta-surfaces with abrupt-varying material properties provided by the metallic nanostructures on the interface were found to engineer the refraction index in arbitrary frequencies. Here we demonstrate a new type of gradient meta-surface with 130-nm-thick Au ground plane, which couples with the Au rod optical antennas on the upper layer via a 50-nm-thick MgF_2 spacer. The proposed meta-surface can cancel the transmitted signals and support a single anomalous reflection beam, and thus significantly improve the light-manipulation efficiency. The gradient distributions of reflection phase delay along the interface can be supported by antennas with different geometries, each generating various radiated phases of the induced magnetic-dipole mode inside the sandwiched spacer. By carefully design the structure, we experimentally demonstrate a high-efficiency (~80%) gradient meta-surface working around 850 nm with operation bandwidth larger than 150 nm. In addition, it can redirect an impinging light to a single anomalous reflection beam with the same polarization. Base on the proposed reflective meta-surface, we further demonstrated a polarization-controllable and high-efficiency (~18%) meta-hologram working in visible range at least from 632.8 nm to 850 nm. Applying gold cross nano-antennas coupled with 130-nm-thick gold mirror with a 50-nm-thick MgF_2 as spacer, the polarization-independent phase modulation can be achieved. Different images "RCAS" and "NTU" with high image contract can be reconstructed under x- and y-polarized illumination, respectively. These above-mentioned researches may lead to more compact, efficient and multi-functions electromagnetic components.

8995-37, Session 9

A Fabry-Perot model of subwavelength high-contrast grating

Fanglu Lu, Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

Subwavelength high contrast gratings (HCGs) are endowed with various extraordinary properties, such as high reflection, high-Q resonance and phase engineering capability. To explain the underlying physics of these HCG properties, we present an intuitive Fabry-Perrot etalon analogy for HCG. As a result, a simple close-form equation of HCG's reflection and transmission coefficient is derived for the first time. The equation bears maximum resemblance to Fabry-Perrot etalon, except that the interface reflection and transmission coefficient are in a form of matrix, because there are multiple modes both inside and outside HCG. In other words, HCG is essentially a multi-mode Fabry-Perrot cavity. The model is consistent with our previous more complicated analytical solution, as well as numerical simulation result with rigorous coupled-wave analysis.

The Fabry-Perot model unveils the fundamental physics of HCG properties. Cancelling of two HCG modes, together with evanescent wave outside HCG, lead to perfectly 100% reflection for HCG. HCG high-Q resonance can be attributed to the strong coupling between HCG mode and evanescent wave outside. HCG phase originates from both mode propagation phase and resonance phase. For HCG lens design, where resonance is weak, HCG phase is dominated by propagation constant, and thus primarily controlled by HCG barwidth. With these understanding, this model is posed to simplify the design of HCG-based devices.

8995-38, Session 10

Engineering of refractive index metastructures in silicon photonic circuits *(Invited Paper)*

Pavel Cheben, Jens Schmid, Dan-Xia Xu, Jean Lapointe, Siegfried Janz, Martin Vachon, National Research Council Canada (Canada); Carlos A. Alonso Ramos, Robert Halir, Alejandro Ortega-Moñux, Juan Gonzalo Wangüemert-Pérez, Iñigo Molina-Fernández, Univ. de Málaga (Spain); Aitor V. Velasco, Maria L. Calvo Padilla, Univ. Complutense de Madrid (Spain); Daniel Benedikovic, Milan Dado, Jarmila Müllerová, Univ. of ?ilina (Slovakia)

A new class of planar waveguide structures and devices have emerged exploiting refractive index engineering by subwavelength gratings. By etching an array of gaps of a pitch smaller than the Bragg resonance length into a planar waveguide, a metastructure is formed with an effective index controlled by the grating duty ratio. This way, a wide range of synthetic material refractive indexes can be obtained, thereby circumventing the fundamental constraint of a limited number of materials available in silicon photonics. We discuss the principles, design, fabrication and applications of subwavelength metastructures in silicon photonics. We show that subwavelength engineering is advantageously used to increase the minimum feature size in photonic circuit design to 100 nm or more, compatible with deep-uv 193 nm lithography typically used in silicon photonic foundries. Practical examples will be presented, including recent advances in high efficiency fibre-chip edge couplers and surface grating couplers, polarization splitters and rotators, microspectrometer chips, and wavelength multiplexers for data interconnects.

8995-39, Session 10

Positive and negative roles of surface-plasmons in Fano-type resonance at metallic nanostructures

Seok-Ho Song, Hanyang Univ. (Korea, Republic of); Jae Woong Yoon, Univ. of Texas at Arlington (United States)

Metallic nanostructures are of immense scientific interest for their unexpectedly strong interaction with light in deep subwavelength scales. Propagating and localized surface plasmon-polaritons (SPPs) are considered as the main mechanism of strong light localization into nanoscale objects. Many theoretical and experimental papers still claim that SPPs play only a negative role while a number of controversial analyses show SPP's contribution in certain positive ways. The role of SPPs is seemingly paradoxical and thereby the essential physics is unclear with diverging interpretations.

Here, we propose a single unified theory that explains metamorphic SPP-related effects. Various surface-plasmonic effects and coexisting CM resonances can be consistently described by a single unified model that treats a metallic nanoslit array as an optical cavity with Fano-resonant boundaries. We theoretically prove that most of SPP-related effects such as the anti-resonant extinction, null field at the aperture opening, bandwidth narrowing, and abrupt resonance center shift are all rooted in a single resonance interaction: a surface-plasmonic Fano resonance in the coupling between external light and CM at the entrance and exit interfaces. With SPP excitation, a metal surface acts as a Fano-resonant gate that closes or opens nanoslit cavities. This SPP-induced cavity modification effect successfully describes metamorphic SPP-related features in a physically intuitive manner. Importantly, the theory shows excellent quantitative agreement with rigorous numerical calculations and provides profound physical insight on the resonance properties of nanoplasmonic systems.

Associated Fano-type interference at the interface can describe negative and positive SPP-related effects such as the anti-resonant extinction, null field at the aperture opening, bandwidth narrowing, and abrupt resonance center shift. We believe our interpretation unifies many previous explanations in parts and clarifies the reasons of misunderstanding on the role of SPPs and canonical Rayleigh-Wood anomaly.

8995-40, Session 10

Photon management in thin-film organic devices: OLED and solar cells *(Invited Paper)*

Karl Leo, Technische Univ. Dresden (Germany)

Devices based on rganic thin-film have achieved significant progress in the last years, with OLED displays achieving already widespread commercial use. One of the key steps for further improvement is improved outcoupling and incoupling in OLED and solar cells, respectively. In this talk, I will review our recent work on improving the photon management in such devices. In particular, I will cover periodically structured substrates for OLED and metal nanoparticle approaches for solar cells.

8995-41, Session 10

Epitaxial thin films for hyperbolic metamaterials

Daniel B. Fullager, Michael A. Fiddy, Hossein Alisafaee, Raphael Tsu, The Univ. of North Carolina at Charlotte (United States)

Recent progress in the area of hyperbolic metamaterials (HMMs) has sparked interest in transparent conductive oxides (TCOs) that behave as plasmonic media in the near-IR and optical frequency range for imaging and sensing applications. It has been shown that by depositing alternating layers of negative-epsilon/positive-epsilon materials, a medium can be created whose index can be tailored to be near zero. Modeling structures with sub-unity indices of refraction reveals resonant properties that enable evanescent fields containing sub-wavelength information to be coupled to propagating radiation. We investigate the optical, electronic, and physical properties of radio frequency plasma-assisted molecular beam epitaxial (RF-MBE) growth of alternating layers of ZnO and TCO of uniform thickness for HMM applications. Preliminary work creating HMMs with ZnO and Al-doped ZnO (AZO) has shown a negative real part of the permittivity at near-IR whose modulus is proportional to the number density of Al dopant. However, increasing the Al content of the AZO increases the transmission losses to unacceptable levels for device applications at industry standard wavelengths. A TCO with conductivity and physical structure superior to that of AZO is gallium-doped ZnO (GZO). Properly grown GZO has been demonstrated to possess improved crystal quality over AZO due to the higher diffusivity of Al in the ZnO. AZO and GZO HMM structures grown by RF-MBE

are characterized by scanning electron microscopy (SEM), atomic force microscopy (AFM), X-ray diffraction (XRD), Hall effect, four-point probing, deep-level transient spectroscopy (DLTS), ellipsometry, visible and ultraviolet spectroscopy (UV-VIS) and in-situ reflection high energy electron diffraction (RHEED).

8995-42, Session 10

Unidirectional optical coupling for plasmonic waveguide based on metallic-dielectric high-contrast gratings

Fan Lu, Kun Li, Peking Univ. (China); Zhonghua Wang, Peking University (China); Zhijun He, Dalin Liu, Anshi Xu, Peking Univ. (China)

Due to the capability of extreme field confinement, plasmonic devices are currently booming as promising candidates to bridge nanoscale electronics and dielectric photonics. Unidirectional coupling free-space light into plasmonic waveguides is a vital issue for functional plasmonic applications. The metallic-dielectric high contrast gratings (MDHCG) have aroused increasing research interest and have been utilized to realize many important functionalities, such as the polarization-insensitive reflector, light absorption, near infrared polarizer, electromagnetically induce transparency (EIT) phenomenon. Based on the MDHCG, we proposed several different schemes to achieve the unidirectional coupling of incident light into the popular plasmonic waveguides. Different from the previous SPP couplers with single slit or asymmetrical slit, here the wide angular spectrum, coupling efficiency, wavelength broadband and the type of plasmonic waveguide are our main concern. The operation principle and performance of the structures are analyzed and discussed. Simulation results show that the obliquely incident planewaves could be coupled into the plasmonic waveguide with angular full-width-half-maximum (AFWHM) wider than 25 degree and spectral FWHM larger than 250nm.We believe that the MDHCG could provide satisfactory solutions to realize the unidirectional plasmonic couplers for different application scenario. The proposed structures will find potential applications in novel plasmonic devices, and biological or chemical sensing, and future photonic integrated circuits.

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8996-1, Session 1

Molecular beam epitaxial growth and characterization of intrinsic and p-type InN nanowires *(Invited Paper)*

Zetian Mi, Songrui Zhao, Binh Huy Le, McGill Univ. (Canada); Omid Salehzadeh, Shima Alagha, Karen Kavanagh, Simon Watkins, Simon Fraser Univ. (Canada)

Indium containing narrow bandgap semiconducting nanowires, including InN, InAs, and InSb hold tremendous promise for future ultrahigh-speed electronic and infrared photonic devices. To date, however, their practical device applications have been limited by the near-universal electron accumulation on the grown surfaces. In this context, we have investigated the molecular beam epitaxial (MBE) growth and characterization of InN nanowires. We have achieved, for the first time, intrinsic and p-type InN. We have further demonstrated that the surface charge properties of InN can be precisely tuned through controlled dopant incorporation.

In this experiment, InN nanowires were grown on Si (111) substrates using a self-catalytic growth process by radio-frequency plasma-assisted MBE. The nanowires exhibit non-tapered morphology, with well-defined hexagonal structure. The nanowires are oriented along the c-axis, with their sidewalls being non-polar m-planes. Detailed optical and electrical transport studies confirm that the undoped InN nanowires can exhibit extremely low residual electron density (~ 1E15 cm-3). The electron mobility is derived to be in the range of ~ 10,000 cm2/V?s at room-temperature, approaching the theoretical value for pristine InN. The near-surface Femi-level was measured to be ~ 0.5 eV above the valence band maximum (VBM), suggesting the absence of surface electron accumulation and Fermi-level pinning. The near-surface Fermi-level can be further tuned from ~0.1eV to 1eV above the VBM, i.e. from p-type degenerate to n-type degenerate through controlled Mg and Si dopant incorporation. A detailed study of the hole concentration and mobility of Mg-doped InN is being conducted and will be reported.

8996-2, Session 1

Advances on MBE selective area growth of III-nitride nanostructures: from nanoLEDs to pseudo substrates *(Invited Paper)*

Enrique Calleja, A. Bengoechea-Encabo, Steven Albert, Miguel A. Sanchez-Garcia, F. Barbagini, D. Lopez-Romero, Univ. Politécnica de Madrid (Spain); Achim Trampert, Uwe Jahn, Paul-Drude-Institut für Festkörperelektronik (Germany)

New advances on Selective Area Growth (SAG) of InGaN/GaN nanostructures by plasmaassisted MBE on GaN/sapphire templates and Si (111) substrates are presented. Both, axial and core-shell approaches are followed. Very intense green emission is achieved on axial structures, whereas the first results on core-shell LEDs by MBE are also discussed. Details about the strain relaxation mechanisms are given for axial LED structures using either a fixed or graded In composition InGaN active region. Ordered arrays of GaN nanostructures are grown and subsequently merged into a continuous film to produce high quality semi-polar and non-polar substrates. Results show that in both semi-polar and non-polar orientations, the resulting films exhibit a strong luminescence, orders of magnitude higher that the substrate used.

8996-3, Session 1

Integrated nanopillar devices: 3D engineering of optoelectronics from the bottom up

Adam Scofield, Diana L. Huffaker, California NanoSystems Institute (United States) and Univ. of California, Los Angeles (United States)

The field of III-V nanowires and nanopillars has grown substantially over the past decade due to their potential impact on the next generation of electronic and opto-electronic devices. Much of this potential is derived from the ability to control axial and radial growth directions of the nanowires or nanopillars during their formation. Such capability allows realization of heterostructures that are either impossible or produced with extraordinary difficulty by planar techniques. In opto-electronic device applications, the versatility of nanopillar growth can be further extended by lithographic control of the position and dimensions of the pillars, thereby enabling optical properties such as resonances to be engineered with the nanopillars themselves. Here, we present our developments in catalyst-free selective-area epitaxy of III-V nanopillars which utilizes lithographic control of the pillar dimensions to form devices such as photonic crystal lasers and plasmonically enhanced avalanche photodetectors. We further demonstrate coupling of light to and from nanopillar photonic crystal cavities with passive dielectric waveguides, opening up the possibility of monolithic integration of nanopillar devices on a large scale. Finally, the outlook of integrating nanopillar optoelectronic devices into larger scale systems such as low-power transceivers for datacom and infrared imagers will be discussed.

8996-4, Session 1

Directed emission of spontaneous emission into guided modes of photonic crystal nanostructures

Thorsten Reichert, Stefan Lichtmannecker, Martin Zeitlmair, Günther Reithmaier, Max Bichler, Kai Müller, Michael Kaniber, Jonathan J. Finley, Technische Univ. München (Germany)

Low temperature confocal spectroscopy measurements were performed in two detection geometries, parallel and perpendicular to the waveguide axis. Such measurements facilitate the unambiguous identification of the fundamental guided waveguide mode . We excite the waveguide modes by detecting the emission from self-assembled InGaAs QDs embedded at the midpoint of the GaAs photonic crystal membrane. The emission spectra recorded parallel and perpendicular to the waveguide axis are found to be in very good quantitative agreement with bandstructure simulations performed using structural parameters extracted from materials microscopy. By conducting lifetime measurements as a function of the QD emission energy, traversing the fast and slow guided regions of the waveguide dispersion, a clear reduction of the average spontaneous emission lifetime from 1.31 to 0.44 ns is observed. We continued by determining the QD decay rates into the photonic bandgap and without a tailored photonic environment. By comparing the emission rate of QDs coupled to the slow part of the guided mode to dots emitting into the photonic bandgap, we extract a spontaneous emission coupling efficiency ? > 90 %. Furthermore we directly measure Purcell-factors > 2 by comparing the decay rates of a QD coupled to the slow part of the waveguide mode with the bulk decay rate at the same energy. The exquisite control of the QD decay rate and the directional emission provides an efficient and fast on-chip single photon generation source for future quantum optical circuits in nanoscale dimensions.

8996-5, Session 1

Epitaxial growth of quantum dots on InP for device applications operating at the 1.55 µm wavelength range

Elizaveta S. Semenova, Irina V. Kulkova, Shima Kadkhodazadeh, Kresten Yvind, Technical Univ. of Denmark (Denmark)

The development of epitaxial technology for the fabrication of quantum dot (QD) gain material operating in the 1.55µm wavelength range is a key for the evolvement of telecommunication. High performance QD demonstrated on GaAs only covers the wavelength region 1-1.35µm. In order to extract QD benefits for the longer telecommunication wavelength range the technology of QD fabrication should be developed for InP based materials. In our work, we take advantage of both QD fabrication methods Stranski-Krastanow (SK) and selective area growth (SAG) employing block copolymer lithography. Due to the lower lattice mismatch of InAs/InP compared to InAs/GaAs, InP QDs have a bigger diameter and they are more shallow compared to GaAs based dots. This shape causes low carrier localization and small energy level separation which leads to a high threshold current, high temperature dependence, and low laser quantum efficiency.

Here, we demonstrate that with tailored growth conditions, which suppress surface migration of adatoms during the SK QD formation, an almost twice smaller diameter (18nm versus 30nm) of the base and improved aspect ratio are achieved.

To gain advantage of non-strain dependent QD formation we developed SAG, for which the growth occurs only in the nanoopenings of a mask covering the wafer surface. In this case the QD composition can be chosen in a wide range. In combination with etching in situ inside the mask openings this method yields high purity material and provides significant freedom for reducing the aspect ratio of QDs with the possibility to approach the ideal one.

8996-6, Session 2

Nanowires on demand: in-situ control of nanowire properties *(Invited Paper)*

Silvija Gradecak, Massachusetts Institute of Technology (United States)

Nanowires offer solutions to some of the current challenges in science and engineering, but realization of their full potential will be ultimately dictated by the ability to control their structure, composition, and size with high accuracy. In this talk, I will discuss our recent results on the controlled growth, doping, and applications of III-V nanowires, as well as advanced electron microscopy techniques for direct correlation of structural and physical properties with high spatial resolution. We have developed a simple, yet powerful, approach to modulate both the diameter and composition of individual III-V nitride nanowires by adjusting in-situ the nanowire seed particle composition and volume. By elucidating the underlying mechanisms controlling structural evolution, we demonstrated the synthesis of axial InN/InGaN nanowire heterojunctions, compositionally tunable AlGaAs nanowires, GaAs/AlGaAs core-shell nanowires, and their controlled doping. We have demonstrated that the cathodoluminescence (CL) technique, coupled with scanning transmission electron microscopy (STEM), effectively bypasses the resolution limit of conventional far-field photoluminescence spectroscopy and allows direct structure-property correlation on the nanoscale. Finally, applications of semiconductor nanowires for LED and solar cell applications will be described.

8996-7, Session 2

Nonplanar nanoselective area growth of InGaAs/InP

Nadezda Kuznetsova, Pierre Colman, Elizaveta S. Semenova, Shima Kadkhodazadeh, Technical Univ. of Denmark (Denmark); Nataliya Kryzhanovskaya, Department of Nanotechnology (Russian Federation); Sara Ek, Weiqi Xue, Technical Univ. of Denmark (Denmark); Martin Schubert, Technical Univ. of Denmark (Denmark) and Univ. Konstanz (Germany); Alexey Zhukov, Department of Nanotechnology (Russian Federation); Kresten Yvind, Technical Univ. of Denmark (Denmark)

In this study, we have investigated metal-organic vapor phase epitaxial nano-patterned selective area growth of InGaAs/InP on non-planar (001) InP surfaces. Due to high etching resistance and the small molecular size of negative tone electron beam HSQ resist, the protection mask formed in HSQ has small feature sizes in ten nanometer scale and allow realization of in-situ etching. As was observed in the SAG regime, in-situ etching of InP by carbon tetrabromide leads to formation of self-limited structures. By altering etching time, the groove shape can be changed from a triangular trench to a trapeze. Another appealing aspect of in situ etching is that the shape of InGaAs can be tuned from a crescent to a triangular or a line by varying growth parameters. Quantum wires can be fabricated by growing directly in the bottom of V-shaped groove. In addition, changes of growth parameters lead to anistropic or isotropic character of etching. The investigated technique of nano-patterned selective area growth allows obtaining different profiles of structures and different quantum structures such as quantum well or wires in the same growth run. To investigate the shape and crystalline quality of the active material, the cross-sectional geometry was observed by field emission scanning electron microscopy and scanning transmission electron microscopy. The optical properties were carried out at room temperature using micro-photoluminescence setup. The results showed different deposition rates for openings oriented along [0-11] and [0-1-1] directions with higher rate along [0-1-1]. The fabricated active material was incorporated into photonic crystal waveguides and lasers.

8996-8, Session 2

Optical and electrical properties of individual CdSe quantum nanowires

Aina Reich, Dennis Franz, Sebastian Schäfer, Christian Strelow, Tobias Kipp, Alf B. Mews, Univ. Hamburg (Germany)

We report on the investigation of individual CdSe-based quantum nanowires (QNWs) by means of confocal photoluminescence (PL) spectroscopy, transmission electron microscopy (TEM), atomic force microscopy (AFM), and electrostatic force microscopy (EFM). The QNWs are chemically synthesized exploiting the so-called solution-liquid-solid method in which Bismuth particles act as catalysts [1].

By correlating confocal PL measurements with TEM studies on one and the same individual QNWs we establish a detailed structure-property relationship [2]. We discuss the diameter dependent optical band gap of QNWs. By combining confocal optical methods with simultaneous EFM measurements, we show that the initially homogeneously distributed charge in QNWs is separated upon local illumination, as can be explained within a diffusion-based model [3]. By actively charging isolated CdSe QNWs with a biased AFM tip, the PL is either enhanced or reversibly or irreversibly quenched [4]. We also investigated type-II heterostructure block NWs from CdSe and CdTe that exhibit a charge separation across the interface, as measured by EFM with and without local laser illumination [5]. Finally, we will present results of time-resolved low-temperature confocal PL spectroscopy that bear interesting features of the QNWs that are hidden at room temperature.

Altogether, we can draw a comprehensive picture of the optical and electrical properties of CdSe-based QNWs including effects from different diameters, crystal lattice modifications, the dielectric surrounding, as well as from defect or surface trap states.

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8996-40, Session 2

Atomic scale characterization of semiconductor quantum dots for novel

Holger Eisele, Technische Univ. Berlin (Germany)

No Abstract Available

8996-9, Session 3

Green- to red-emitting InGaN-based nanocolumn LEDs with regularly-arranged triangular lattice nanocolumn arrays *(Invited Paper)*

Katsumi Kishino, Ai Yanagihara, Atsushi Takahashi, Yusuke Igawa, Hiroaki Hayashi, Kouji Yamano, Shunsuke Ishizawa, Sophia Univ. (Japan)

Self-assembled GaN nanocolumns [1] had introduced multiple-color emission of nanocolumn LEDs [2]. Ti-mask selective area growth (SAG) of the GaN nanocolumns was developed fabricating uniform arrays of GaN nanocolumns [3]. In this talk, we describe fabrication and emission characteristics of InGaN-based nanocolumn LEDs with triangular-lattice GaN nanocolumn arrays. The integration of InGaN/GaN multiple-quantum-well into the nanocolumn arrays provided monochromatic uniform emissions of nanocolumn LEDs. Various series of triangular-lattice GaN nanocolum arrays having the lattice constants from 300 to 400 nm were fabricated, in which nanocolumns 25-period InGaN/GaN supper-lattices and 3-5 period InGaN/GaN MQWs were integrated. In the fabrication process of nanocolumn LEDs, deposition of passivation layer on nanocolumn side walls contributed to elimination of unexpected current leakage paths, where atomic-layer-deposition of Al2O3 film was effectively employed to cover the side wall from the top to the bottom. For the red-emitting LED, the peak wavelength and spectral FWHM were 633 nm and 185 meV, respectively, having a small blue shift of 5nm for increased injection current from 65 to 255 A/cm2. Green light (520-540nm) InGaN-based nanocolumn LEDs operated; the spectral FWHM was 35-50 nm and the typical turn-on voltage was 3.5 V. For the 65 ?m diameter emission area of LED, a light output of 315 ?W was observed.

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8996-10, Session 3

Polarization-induced nanowire light-emitting diodes with deep ultraviolet emission

Thomas F. Kent, Santino D. Carnevale, A.T.M. Golam Sarwar, Roberto C. Myers, The Ohio State Univ. (United States)

Polarization-induced nanowire light emitting diodes (PINLEDs) are fabricated by grading the Al composition along the c-direction of AlGaN nanowires grown on Si substrates by plasma-assisted molecular beam epitaxy (PAMBE)*. Polarization-induced charge develops with a sign that depends on the direction of the Al composition gradient with respect to the [0001] direction. By grading in a back and forth fashion (i.e. GaN to AlN to GaN), a polarization-induced pn junction is formed. Here we demonstrate compositional control over UV emission wavelength from 320 nm to 280 nm in PINLED's with AlGaN quantum wells. Multiple samples are prepared where the Al composition of the active region is systematically increased. Electroluminescence (EL) and temperature dependent time resolved photoluminescence (TRPL) measurements are conducted to determine emission wavelength, internal quantum efficiency (IQE) as well as radiative and non radiative lifetimes. Initially, emission wavelength in AlGaN monotonically decreases with increasing %Al and emission intensity remains comparable. At higher %Al, however, emission intensity becomes strongly quenched and is dominated by a constant peak at 4.3 eV. To further investigate the origins of the emission quenching, a series of bulk AlGaN nanowires are prepared by PAMBE with compositions ranging from 50% to 100% Al. Using the techniques of x-ray diffractometry and temperature dependent TRPL, bandgap, IQE as well as radiative and non-radiative lifetimes are mapped as a function of composition.

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* Carnevale, S. D.; Kent, T. F.; Phillips, P. J.; Mills, M. J.; Rajan, S.; Myers, R. C. Nano Letters 2012, 2, 915-920.

8996-38, Session 3

New designs for spectral control in nanowire lasers *(Invited Paper)*

Anthony Fu, Peidong Yang, Univ. of California, Berkeley (United States)

The miniaturization of optoelectronic devices is essential for the continued success of photonic technologies. Nanowires have been identified as potential building blocks that mimic conventional photonic components such as interconnects, waveguides, and optical cavities at the nanoscale. Semiconductor nanowires with high optical gain offer promising solutions for lasers with low power consumption. Although much effort has been directed toward controlling their size, shape, and composition, most nanowire lasers currently suffer from emitting at multiple frequencies simultaneously, arising from the longitudinal modes native to simple Fabry–Pérot cavities. Cleaved-coupled cavities, two Fabry–Pérot cavities that are axially coupled through an air gap, are a promising architecture to produce single-frequency emission. The miniaturization of this concept, however, imposes a restriction on the dimensions of the intercavity gaps because severe optical losses are incurred when the cross-sectional dimensions of cavities become comparable to the lasing wavelength. Here we theoretically investigate and experimentally demonstrate spectral manipulation of lasing modes by creating cleaved-coupled cavities in gallium nitride (GaN) nanowires. Lasing operation at a single UV wavelength at room temperature was achieved using nanoscale gaps to create the smallest cleaved-coupled cavities to date. Besides the reduced number of lasing modes, the cleaved-coupled nanowires also operate with a lower threshold gain than that of the individual component nanowires. Good agreement was found between the measured lasing spectra and the predicted spectral modes obtained by simulating optical coupling properties. This agreement between theory and experiment presents design principles to rationally control the lasing modes in cleaved-coupled nanowire lasers.

8996-11, Session 4

Electrical characterization of semiconductor nanowires by scanning tunneling microscopy *(Invited Paper)*

Corentin DURAND, IEMN-CNRS (France); Pierre CAPIOD, IEMN-CNRS (France) and ISEN Lille (France); Maxime BERTHE, IEMN-CNRS (France); Tao XU, ISEN Lille (France); Jean-Philippe NYS, Renaud LETURCQ, IEMN-CNRS (France); Philippe CAROFF, The Australian National University (Australia) and IEMN-CNRS (France); Bruno Grandidier, IEMN-CNRS (France) and ISEN Lille (France)

Outstanding physical effects and performances have been recently demonstrated with III-V semiconductor nanowires and most of these properties have been obtained due to the large surface to bulk ratio of these objects or due to crystal structures that do not exist in bulk counterpart materials. In order to gain additional insights into these materials, scanning tunneling microscopy is an appealing technique that can supplement transmission electron microscopies and conventional electrical characterization techniques. Indeed it is able to probe the surface of semiconductor materials at the atomic scale and we will show how it can be successfully applied to study the nanofaceting morphology, the atomic structure and the surface composition of oxide-free nanowire sidewalls. Based on the observation of different atomic structures in homomaterial heterostructure nanowires, variations of the position of the Fermi level at the surface of the nanowires will be deduced from the measurement of spatially resolved tunneling spectra and correlated with the sidewall morphologies. Then, we will show how multiple probe scanning tunneling microscopy can provide the transport properties of free-standing semiconductor nanowires. In particular, we will determine the physical reasons for a persistent enhancement of the conductivity in non-intentionally doped InAs nanowires upon electron irradiation in ultra-high vacuum. Although an electron beam of a few keV, typically used for the inspection and the processing of materials, propagates through the entire nanowire cross-section, we will demonstrate that the electrical properties of the nanowire are predominantly affected by radiation-induced defects occurring at the nanowire surface and not in the bulk.

8996-12, Session 4

Semiconductor nanowires: emitting and receiving nanoantennas *(Invited Paper)*

Jaime Gomez Rivas, Grzegorz Grzela, FOM Institute for Atomic and Molecular Physics (Netherlands); Ramon Paniagua-Dominguez, Jose A. Sanchez-Gil, Instituto de Estructura de la Materia (Spain) and Consejo Superior de Investigaciones Científicas (Spain)

The shape and dimensions of semiconductor nanowires are responsible for the strong polarization anisotropy in their emission and absorption. The diameter of nanowires (comparable to the wavelength of visible light) leads to optical resonances, which can be described by Mie scattering theory or by coupling to guided modes in a cylindrical geometry. Based on this behavior, it is also expected a strong angular dependence of the emission and absorption by individual nanowires and by ensembles of these nanostructures. The directional optical response of nanowires is a fundamental property that depends on the material, geometry and dimensions of the nanostructures and that needs to be considered in the design of nanowire LEDs and solar cells.

In this contribution we demonstrate the directional emission of single InP nanowires and of photonic crystals of nanowires by probing this emission with Fourier microscopy. The emission is dominated by leaky modes in thin nanowires and by guided modes as the diameter is increased. We have also developed a time-reversed Fourier microscope that enables us to study the dependence of the absorption of single nanowires with the angle of incidence of the light. Measurements show that a maximum absorption is achieved when light is incident parallel to the nanowire axis due to the efficient coupling to the fundamental guided mode. Mie theory describes the absorption for large angles of incidence. Our results demonstrate that semiconductor nanowires can be described as linear nanoantennas which can efficiently emit and absorb electromagnetic radiation in defined directions.

8996-13, Session 4

Optical and electrical characterization of surface passivation of GaAs nanosheets

Shermin Arab, Chun-Yung Chi, Jesse Theiss, P. Daniel Dapkus, Stephen B. Cronin, The Univ. of Southern California (United States)

GaAs nanostructures are used in optoelectronic applications including solar cells, LEDs and fast electronics. Although GaAs shows outstanding optical properties, it suffers from surface states and consequently high surface recombination velocity. The surface depletion effects lead to semi-insulating behaviors in GaAs devices. Passivation of GaAs nanostructures with large band gap semiconductors (AlGaAs) lead to surface stability and improvement in optoelectronic properties. Due to inherent high twin defects, the side wall facets of GaAs nanowires usually consist of (111)A and (111)B micro-facets which could be difficult to passivate. On the other hand, twin-free GaAs nanosheetsgrown by metal organic chemical vapor deposition (MOCVD) may have different passivation effect since the enclosed facets of nanosheets are all atomic flat (110) facets. Based on opto-electric response improvement in passivated GaAs nanowire, we are interested in the performance of passivated nanosheet.

We provide a systematic study to compare the opto-electrical improvement after AlGaAs passivation of GaAs nanosheets. Secondary electron scanning electron microscopy (SE-SEM) contrast imaging is used to characterize the composition and doping. Spacial mapping of Raman shows Raman peaks corresponding to GaAs and AlAs. Both room temperature and low temperature photoluminescent (PL) indicates increase in optical responses of nanosheet after passivation (100X). Electron beam induced current (EBIC) measurements reveal the diffusion length of carries in passivated vs. non-passivated nanosheets. EBIC mapping also reveals a pn junction formed along the boundary between the base and overgrowth regions of nanosheet. Finally, time-resolved PL shows a carrier lifetime increase after passivation in nanosheets.

8996-14, Session 4

Semiconductor single-photon emitters with geometry-controlled polarization

Chu-Hsiang Teng, Lei Zhang, Tyler Hill, Brandon J. Demory, Hui Deng, Pei-Cheng Ku, Univ. of Michigan (United States)

Semiconductor quantum dot based single photon emitters (QD-SPEs) are critical components for quantum cryptography. The control of output polarization is hence important for the data encoding purpose. QD-SPEs using self-assembled, colloidal, or dot-in-wire quantum dots can generate polarized single photon outputs with the help of optical cavities. However, these quantum dot materials are difficult to scale for manufacturing. In this work, we show a scalable single-photon emitter structure using site-controlled elliptical quantum dots with a controllable and completely tunable output polarization. The quantum dot was fabricated using electron beam lithography and a combination of dry and wet etching processes. The active region is a disk-shaped InGaN region sandwiched by GaN barriers. The InGaN disk plane sits on the (0001) plane of the wurtzite lattice and hence exhibits a strong piezoelectric field perpendicular to the disk. The piezoelectric field is reduced due to

strain relaxation by the etching process. By creating an asymmetry for the strain distribution in the InGaN disk, the output polarization of the exciton emission from the quantum dot can be controlled purely by the geometry of the quantum dot. We measured the output of the quantum dot using a micro-photoluminescence setup. Second-order photon correlation and polarization are both measured. We also modeled the elliptical quantum dots using a 6x6 k•p model. Using X-like, Y-like, and Z-like states as basis, we derived the matrix elements corresponding to different polarization directions.

8996-15, Session 5

How small can one shrink a semiconductor laser and is it worth it? *(Invited Paper)*

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

There is a growing interest in increasing density of integration of optical components, passive and active, but there is a natural barrier looming ahead – the diffraction limit, but it can be overcome by introducing metallic strictures, albeit at the cost of increasing loss. This loss may in principle be compensated by gain in semiconductor medium, opening ways for development of sub-wavelength nanolaser (spaser). In this talk we consider how the characteristics of laser change when it size is shrunk below the diffraction limit, and show that, rather counter-intuitively, the threshold current does not decrease with the size, as the slope efficiency decreases, while the linewidth broadens, and the operational speed does not improve by much relative to the same size LED. Therefore the distinction between sub-wavelength LED and laser is quite insignificant from the practical point of view.

8996-16, Session 5

Plasmonic enhancement of the radiative emission rate in size and site controlled InGaN quantum dots

Tyler Hill, Brandon J. Demory, Lei Zhang, Chu-Hsiang Teng, Pei-Cheng Ku, Hui Deng, Univ. of Michigan (United States)

Semiconductor quantum dots (QDs) have the potential as chip-scale high speed single photon sources (SPS) [1] and ultrafast optical switches [2]. InGaN QDs show promise as SPS with high operation temperatures [3]. However, due to the intrinsic piezoelectric field present even in partially strain-relaxed dots, these QD typically exhibit long radiative lifetimes evincing the need for engineering an increased emission rate. We report here enhancement of single photon emission from site-controlled InGaN/GaN QDs via the plasmonic effect.

The InGaN QDs were fabricated via plasma etching of lithographically patterned single quantum wells [4]. Afterwards, a thin Al2O3 spacer layer is deposited via atomic layer deposition to reduce metal absorption, and then a conformal coating of silver is deposited using electron-beam evaporation, where the thickness is chosen to match the plasmon resonance.

Optical properties of individual QDs were characterized via photoluminescence (PL) and time-resolved photoluminescence (TRPL) measurements, using a confocal micro-PL setup. The measured PL intensity and total decay rates were compared with the radiative decay rates and metal absorption simulated via the finite-difference time domain method, from which the enhancement of the radiative emission rate was obtained in a self-consistent manner. Statistical analysis of ~25 individual dots shows an average PL intensity increase of 40% and a five-fold enhancement of radiative emission rate. Second order correlation results are used to study the effect of a metallic coating on the SPS nature of the QDs.

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8996-17, Session 5

Fast single-photon emission from InGaN quantum dots

Brandon J. Demory, Tyler Hill, Chu-Hsiang Teng, Lei Zhang, Hui Deng, Pei-Cheng Ku, Univ. of Michigan (United States)

We demonstrate enhanced single photon emission from InGaN quantum dots (QDs) coupled to a plasmonic cavity. Such a device can be used for on-demand single photon generation. Single photon emission from epitaxial QDs can offer a much higher repetition rate compared to that from molecules and impurities such as NV centers in diamonds. Previously, we have shown that site-controlled InGaN QDs can be a viable and manufacturable single photon emitter. But the radiative lifetime of excitons in InGaN QDs is still limited to tens of nanoseconds which is too long for high-speed quantum cryptography applications. Placing an emitter inside of a cavity alters its decay rate by the Purcell Factor of the cavity. Because InGaN emission is in the ultraviolet/visible wavelength range, the excitons in InGaN QDs can be coupled to plasmons in noble metals. Using a top-down approach, InGaN QDs are embedded inside of GaN pillars, allowing us to use the QD as a part of the cavity itself, by encasing the QD with a dielectric spacer and a conformal coating of metal. Tuning the thicknesses of the dielectric and metal layers allows us to control the wavelength of plasmon resonance peak of the cavity, which allows us to align the emission wavelength to the Localized Surface Plasmon Resonance (LSPR). The result is an enhanced radiative emission rate without sacrificing the emitter's quantum efficiency.

8996-18, Session 5

Efficient Auger-assisted upconversion in PbSe/CdSe core/shell colloidal quantum dots

Nikolay S. Makarov, Qianglu Lin, Kirill A. Velizhanin, Victor I. Klimov, Los Alamos National Lab. (United States)

Efficient upconversion is of immediate interest for various applications, especially, three-dimensional microscopy and solar-energy conversion. Solution-processible core/shell colloidal quantum dots (QDs) allow for a fairly straightforward manipulation of optical resonances by varying the dimensions of the core and the shell independently. This makes them promising systems for exploring various novel concepts in both linear and nonlinear optics including upconversion at low pump fluences.

Here, we demonstrate that appropriately engineered PbSe/CdSe core/shell QDs allow for highly efficient upconversion of infrared (IR) radiation via a novel mechanism of Auger re-excitation. This process becomes active when the energy released during Auger recombination of a core-localized exciton is sufficient to promote a hole from the core to the shell. Due to a relatively long lifetime of the shell-localized excitons, they can than recombine radiatively, which produces upconverted photoluminescence (PL). This provides a convenient tool for detecting the effect and characterizing its efficiency. These newly developed core/

shell nanostructures also exhibit other beneficial properties compared to monocomponent counterparts such as enhanced absorption cross-sections and longer single exciton lifetimes.

We observe that the efficiency of the Auger-assisted upconversion depends quadratically on both the QD absorption cross-section and the excitation fluence and, importantly, is independent on pump pulse duration, indicating that it is not due to traditional two-photon absorption. Further, our measurements indicate that up to ~75% of absorbed IR photons can be upconverted via this process even at moderate pump fluences that correspond to absorption of 2 photons per QD per pulse on average. Interestingly, such fluences are achievable at sun light intensities using a common 1000-fold concentration. Our findings suggest that these novel core/shell nanostructures may be utilized for enhancing photoconversion efficiency of practical photovoltaic devices by allowing for more efficient harvesting of low-energy solar photons.

8996-41, Session 5

Plasmon-enhanced ultrathin bulk heterojunction: interplay between optical and thermal responses of AuNPs

Shiva Shahin, Palash Gangopadhyay, Robert A. Norwood, College of Optical Sciences, The Univ. of Arizona (United States)

The gold nanoparticles' (AuNPs) plasmonic effect enhances light absorption, and thus, the efficiency of organic BHJ solar cells. We have previously reported 30% increase in the efficiency of our solar cells by incorporation of 50nm AuNPs1 on the hole collecting electrode. However, beside the plasmonic E-field enhancement in close proximity to AuNPs, their thermal response would play a significant role in determining efficiency of PVs, especially in the regime of plasmon resonance. Under optical excitation, the electric field interacts with mobile carriers inside AuNPs and some part of its energy turns into heat. Then the generated heat diffuses away from the AuNPs' surface and increases the temperature of their surrounding medium. This temperature change may alter exciton generation, dissociation, and collection rate and thus the efficiency of the structure.

In this work we investigate the interplay between the optical and thermal responses of AuNPs and their effect on the OPVs' efficiency using both experiment and simulation. To analyze the optical contribution of AuNPs, we have used photo-excitation electrostatic force microscopy (EFM) to investigate the changes in the surface potential map of the structure when the AuNPs are excited with a laser frequency close to their resonance frequency. To analyze the thermal response of AuNPs, we have used photo-excited scanning thermal microscopy (SThM) to study the change in the temperature of the AuNPs' surface after their optical excitation. Experimental results are in good agreement with FEM simulations using COMSOL Multiphysics.

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8996-19, Session 6

Quantum dots in optical nanocavities: from quantum optics to applications *(Invited Paper)*

Jelena Vuckovic, Stanford Univ. (United States)

Optical nanocavities enable enhanced interaction between quantum dots and the cavity field, as a result of the strong field localization inside of their sub-cubic wavelength volumes. Our research focuses on the interaction of one or more self-assembled InAs quantum dots with modes of GaAs optical nanocavities or photonic molecules. In addition to the study of light-matter interaction, this platform is also interesting for implementing devices for applications ranging from quantum information processing to biophotonics. The examples include ultrafast quantum gates, nonclassical light sources, and spin-photon interfaces for quantum information processing; ultrafast, low energy optical modulators and nanolasers for classical information processing; and single cell nanophotonic probes.

8996-20, Session 6

Advanced colloidal heterostructures with tailored optical properties *(Invited Paper)*

Gabriele Rainò, Thilo Stöferle, IBM Zürich Research Lab. (Switzerland); Iwan Moreels, Istituto Italiano di Tecnologia (Italy); Zeger Hens, Univ. Gent (Belgium); Rainer F. Mahrt, IBM Zürich Research Lab. (Switzerland)

Colloidal semiconductor quantum nanostructures allow controlling the confinement of charge carriers through material composition and geometry (size and shape of the particle itself). This enables the design of nanoscale quantum light sources with tailored optical properties. As an example of such extraordinary control, here we report on our recent results on precisely engineered core/shell nano-heterostuctures allowing to control and tune the quantized energy levels and their radiative rates [1]. Moreover, by wavefunction engineering, the band-edge fine structure splitting energy and therefore the exciton intraband relaxation rate can be accurately adjusted [2]. Time-resolved photoluminescence measurements unveiled an acoustic phonon bottleneck determining the exciton dynamics within the band-edge manifold states [3]. In addition, the role of the shape (i.e. the shape anisotropy) is also highlighted at ensemble and single particle level, being crucial for such small nanoparticles [4]. Recent results on alloyed CdSexS1-x quantum dots are also shown as an alternative way to tune the optical properties via material composition. This level of control of nanoscopic material could pave the way toward more versatile light sources that can find applications as active material in laser devices or as single photon sources.

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8996-21, Session 6

Investigation of Quantum Efficiency in Mid-Wave Infrared (MWIR) InAs/GaSb Type-II Strained Layer Superlattice (T2SL) Detectors

Lilian K. Acosta, Brianna Klein, Elena Plis, The Univ. of New Mexico (United States); Stephen A Myers, SKINfrared LLC (United States); Nutan Gautam, Univ. of California, Santa Barbara (United States); Theodore Schuler-Sandy, Zhaobing Tian, Sanjay Krishna, The Univ. of New Mexico (United States); Eric Frantz, University of Cincinnati (United States)

MWIR detectors are very important in variety of civil and military applications including bio-molecular identification, surveillance, medical diagnostics and defense. The objective of this study is to optimize the absorption in active region of InAs/GaSb T2SL photodetectors for the realization of high-performance MWIR devices.

Two sets of MWIR ([lambda]100% cut-off ~ 5.5µm at 77K) T2SL detectors were realized, with varied thickness of detector absorber region and T2SL period.T2SL material quality was evaluated on the basis of room temperature photoluminescence (RTPL) and the high-resolution X-ray diffraction (HRXRD) data. Then the device performancewas compared usingspectral response, dark current and responsivity measurements. Finally, quantum efficiency was calculated and employed as a metric for the definition of the optimal T2SL period and active region thickness.

For the first part of the study, homojunction pin arcitechture based on 8 monolayers (MLs) InAs/8MLs GaSb T2SL was utilized. Thickness of non-intentionally doped absorber layer was 1.5um, 2.5um, and 3.5um. For the second part of the study, unipolar barrier (pBiBn) devices were grown. The thickness of absorber region and the T2SL constituent InAs layer thickness were kept the same (1.5 um and 8 MLs, respectively) whereas the T2SL constituent GaSb thickness was varied as 6 MLs, 8 MLs, and 10 MLs. A detailed comparison of device performance will be discussed during the presentation.

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8996-22, Session 6

A hybrid nanostructure with GaSb quantum dots coupled to an InGaAs quantum well for solar cell applications

Baolai L. Liang, Ramesh Babu Laghumavarapu, Meng Sun, Paul J. Simmonds, Diana L. Huffaker, California NanoSystems Institute (United States) and Univ. of California, Los Angeles (United States)

This work investigates the use of a quantum dot-well (QDW) hybrid stucture as actve region to increase infrared (IR) absorption for realizing high efficiency solar cells. Device performance is investigated for solar cells with QDs, QW, or QDW incorporated into i-region of a GaAs p-i-n cell. The QDW heterostucture consists of an InGaAs QW coupled to GaSb QDs through a thin GaAs spacer layer. The hybrid QDW structure exhibits a new type-II transition from the electrons confined in the InGaAs QW to the holes confined in the GaSb QDs at longer wavelength compared with the reference GaSb QD structure, thus offering an alternative approach for extending the IR absorption. The type II nature of the QW-QD transition is verified by the blue-shift of the PL peak with increasing excitation intensity, a long emission decay time constant, and a theoretical simulation of the band structure. Our experimental results show that the QDW solar cells outperform the QW and QD solar cells beyond the GaAs band edge. We note that the device VOC degrades with the insertion of nanostructures due to strain induced effects and non-radiative recombination. However, no further degradation in VOC is observed in QDW solar cells in comparison with cells containing only QDs. Importantly, the IR photocurrent from the QDW solar cell surpasses those from the QD and QW solar cells, indicating that the combination of QDs and QW improves IR photon absorption. This QDW hybrid structure provides a new path to solar cells with improved IR photo response.

8996-23, Session 7

Optically-active hybrid nanostructures: Exciton-plasmon interaction and injection of hot plasmonic electrons *(Invited Paper)*

Alexander Govorov, Ohio Univ. (United States)

Excitons and plasmons in nanocrystals strongly interact via Coulomb and electromagnetic fields and this interaction leads to characteristic interference effects which can be observed in optical spectra. Along with the effects of Coulomb interaction, Fermi-sea electrons of metal nanocrystals can be optically injected to a neighboring semiconductor electrode. A size of metal nanocrystal, type of metal, and orientation of the external electric field are important to obtain high quantum efficiencies of generation and injection of plasmonic electrons. The results obtained in this study can be used to design nano-devices based on the Coulomb and tunnel interactions for various opto-electronic applications.

8996-24, Session 7

Optical constants of solution-deposited RuO2 transparent conducting nanoskins *(Invited Paper)*

Jeffrey C. Owrutsky, James P. Long, Christopher N. Chervin, Konrad M. Bussmann, Debra R. Rolison, U.S. Naval Research Lab. (United States)

Optical and electrical properties of thin RuO2 nanoskins produced by cryogenic solution deposition on flat dielectric substrates have been characterized by multiple methods. AFM studies indicate that the films that are 10 nm thick per deposition cycle. Nanoskins produced with 2 and 3 cycles, which are 20-30 nm thick, are characterized using ellipsometry and transmission in the near uv to near infrared to determine the optical constants. Four point probe conductivity is used to measure sheet resistances, which are 500-15000 ohm, and electrical conductivities. The results are compared with those for conventional RuO2 films produced by sputtering at room temperature, which are in good agreement with previous studies of sputtered and MOCVD RuO2 films. The nanoskins exhibit lower absorption, which accounts for the real component of the complex dielectric being positive in the entire spectral region studied, in contrast to the sputtered films for which it is negative at energies below 1.5 eV. These results demonstrate that the nanoskins are less metallic and exhibit higher transmission albeit with less electrical conductivity. This process yields self-limiting thin, conformal coatings with high transmission (50-80%) suitable for transparent conductor and spectroelectrochemical applications over a wide spectral range.

8996-25, Session 7

Investigation of luminescent origin of pristine graphene quantum dots and graphene oxide quantum dots

Min Ho Jang, Fei Liu, Hyun Dong Ha, Je-Hyung Kim, Tae Seok Seo, Yong-Hoon Cho, KAIST (Korea, Republic of)

Recently, graphene quantum dots (GQDs) have gained tremendous research interest due to novel properties. However, the luminescence origin of GQDs due to various oxygenous defect site formed by fabrication process is not clear.Therefore, pristine GQDs that do not contain any oxygenous defect should be prepared to clarify the luminescence mechanism of pristine GQDs in comparison with graphene oxide quantum dots (GOQDs) with oxygenous defect groups. In this work, we fabricated monolayer pristine GQDs and GOQDs with highly homogeneous size with less than 4 nm diameters by chemical exfoliation of graphite nanoparticles (GNPs) with 4 nm diameters and carried out systematic study of optical properties. The photoluminescence (PL) of GQDs and GOQDs clearly shows blue and green color, respectively. To clarify luminescent origin, we compared absorption information by means of PL excitation and UV-vis absorbance. The GQDs have strong absorption peak at ultraviolet region whereas the absorption of GOQDs show broad spectrum from visible to ultraviolet region. In addition, we performed time-resolved PL by exciting the samples at various excitation wavelengths. We observed that PL decay curves of GQDs depended on excitation wavelengths whereas that of GOQDs didn't change significantly. The GQDs show faster recombination time than GOQDs by exciting at around absorption peak of GQDs. By characterizing optical properties, we have revealed that that luminescent origin of GQDs and GOQDs originates from intrinsic states in high-crystalline and defect states with oxygenous functional groups, respectively.

8996-26, Session 7

One- versus two-photon photoluminescence excitation spectra of colloidal CdTe quantum dots

Diogo B. Almeida, André A. de Thomaz, Vitor B. Pelegati, Hernandes F. Carvalho, Carlos Lenz Cesar, Univ. Estadual de Campinas (Brazil)

Semiconductor quantum dots [QDs] potential use as components in solar cells and displays motivated an intense effort in modeling and measuring their carriers transport properties. The QDs confinement energies are still controversial because parameters fitting within reasonable numbers can explain the observed spectra. We can increase the information on that matter using experiments with different selection rules, especially comparing the same sample. One and two photon absorption selection rules are very different regarding the parity of the transition levels.

Therefore we decided to perform a set of measurements of 1 and 2 photon PLE of the same QD sample at cryogenic temperatures. The 1-photon PLE was performed in a commercial lamp system [ISS PC1] in which we adapted a cryostat. The 2-photon PLE spectra were acquired with a multimodal microscopy platform in which we coupled a cryostat and an external spectrometer in a confocal microscope. The excitation source was a MaiTai [Spectra-Physics] tuning the wavelength from 780 to 1000 nm. Especial care was necessary to calibrate the PLE signal because it depends on pulse power and duration, both changing during the scan. Second harmonic generation of urea was used to normalize PLE spectrum, and signal collecting optics was calibrated by a black body radiator. Both 1 and 2 photon PLE were performed in the same temperature and the same wavelength collecting window. Our results show clearly the difference in the selection rules between 1 and 2 photon PLE and they agree well with calculated oscillator strengths.

8996-27, Session 7

Properties of ErAs nanoparticle-InAs quantum dot complexes as a function of spacing

Kurt G. Eyink, Krishnamurthy Mahalingam, Air Force Research Lab. (United States); Lawrence Grazulis, Univ. of Dayton Research Institute (United States); Elizabeth H. Steenbergen, David Esposito, Andrew Aronow, Jeremy A. Massengale, Murray Hill, Air Force Research Lab. (United States); Frank Szmulowicz, Univ. of Dayton Research Institute (United States); Luke J. Bissell, Vitaliy N. Pustovit, Air Force Research Lab. (United States)

Enhanced optical absorption and emission properties compared to normal quantum dots are expected from metal nanoparticle-quantum dot complexes. Typically these complexes are formed from colloidal particles tethered together using ligands. Here we have formed these complexes using molecular beam epitaxy. In particular, we have coupled ErAs semimetal nanoparticles to InAs quantum dots in a GaAs host. Preliminary calculations show the potential for an optical field enhancement factor as large a 100. We have made stacks of these ErAs-InAs complexes with a GaAs spacer layer thickness that was varied from 8 nm to 40 nm. TEM and XRD show these structures to be high quality. Photoluminescence and spectroscopic ellipsometry were used to study the optical properties as a function of the GaAs spacing layer thickness. We found that PL intensity decreases as the spacer layer thickness decreases. The spectroscopic ellipsometry data shows that the complexes have metal-dielectric stack characteristics.

8996-28, Session PWed

Near -field fluorescence characteristics for nano-patterned glass fabricated by direct laser writing

Jin-Myoung Mok, Yonsei Univ. (Korea, Republic of) and Univ. Bordeaux I (France); Yannick G. Petit, Univ. Bordeaux I (France); Eung Jang Lee, Hong-Gyu Ahn, Yonsei Univ (Korea, Republic of); Thierry Cardinal, University of Bordeaux I (France) and ICMCB (France); Seung-Han Park, Yonsei Univ. (Korea, Republic of)

A ring-shape nano-pattern is induced by femtosecond laser in a silver-containing glass. And the patterned is appeared on the surface by polishing out the glass. The ring shape fluorescence is measured by near-field scanning optical microscope and we can get the highly-resolved image of the pattern.

8996-29, Session PWed

Material parameter dependence of quantum-dot G factors

Craig E. Pryor, The Univ. of Iowa (United States)

Accurate modeling of the electronic states of a nanostructure depends on an extrapolation of macroscopic bulk properties to the nanoscale. It has been known for a long time that calculated energy levels have varying sensitivities to the different input material parameters. Here we examine the variation with material parameters for energy levels in a magnetic field (i.e. g factors). Using 3D strain-dependent numerical calculations we determine the material parameter sensitivity of calculated g factors. For typical self-assembled quantum dot structures, reasonable parameter variations give a shift from g=2 on the order of 0.1. This could be significant for applications requiring structures in which dots are designed to have g=0.

8996-30, Session PWed

Structural and optical characterization of fresh water diatoms (Cyclotella sp.): nature's nanoporous silica manufacturing plant

Nirmal Mazumder, National Yang-Ming Univ. (Taiwan); Ankur Gogoi, Kaziranga Univ. (India); Alak K. Buragohain, Gaz A. Ahmed, Amarjyoti Choudhury, Tezpur Univ. (India)

Diatoms are microscopic, eukaryotic, photosynthetic algae that are found in both fresh water and marine environment and also in moist habitats. There are over 200000 species of these photosynthetic algae with world wide distribution. Diatoms fabricate nanoscale structures of silica which are different for different species. The diversity of such nanostructures appears to be quite significant and extends possibilities for their use in nanofabrications of a multitude of devices having wide ranging applications in engineering, medical and various other fields. In the present study we report the findings of structural and optical characterization of diatoms (Achnanthes sp.) from the lentic ecosystem.

8996-31, Session PWed

Ferroelectric device using lead zirconate titanate (PZT) nanoparticles

Younghun Paik, Hossein Shokri Kojori, Sung Jin Kim, Univ. of Miami (United States)

We successfully demonstrate lead zirconate titanate (PZT) nanoparticles in aqueous solution and fabricated a photosensitive device. All solution based low temperature process was used to fabricate a PZT nanoparticle based device and it exhibits a ferroelectric photovoltaic property. Lead acetate trihydrate (Pb(CH3COO)2-3H2O), titanium isopropoxide and zirconium propoxide were dissolved into 2-Methoxyethanol solution to prepare a PZT sol-gel precursor solution. Then the synthesized gel-like nanoparticles were crystalized by consecutive annealing under argon atmosphere and sintering process in air. The crystalline structure and the size of the nanocrystals were studied using X-ray diffraction and TEM (Transmission electron microscopy) respectively. We observed 30 - 60 nm of PZT nanoparticles and this result is also well matched with DLS (Dynamic light scattering) measurement. We fabricated ferroelectric devices using the PZT nanoaprticles and various optical and electrical characterizations verify ferroelectric properties. To the best of our knowledge, this low temperature solution processed ferroelectric device using PZT nanoparticle is the first successful demonstration. We also observed a typical ferroelectric photovoltaic effect from a PZT nanoparticle based device which is fabricated on an ITO substrate. The open circuit voltage (Voc) varies depending on the film thickness and the best Voc was 2.1V.

8996-32, Session PWed

The role of stress in the confinement levels of CdTe quantum-dot-doped glasses

André A. de Thomaz, Diogo B. Almeida, Vitor B. Pelegati, Hernandes F. Carvalho, Luiz C. Barbosa, Carlos Lenz Cesar, Univ. Estadual de Campinas (Brazil)

The confinement energy levels is the most fundamental property for the development of all Quantum Dots (QDs) optical based devices, such as displays, lasers, photodetectors or efficient solar cells. Although, several evidences of the role of the stress in QD doped glasses existed, including a paper of our group showing thermal expansion coefficient mismatch stress induced phase transitions, the evidences were weakened by the lack of a direct comparison between stressed versus non-stressed QDs. In this paper we unequivocally show the large impact of the stress in the QD confinement energies. For that we used the same CdTe QD doped glass for which we observed the phase transitions and compared it to a colloidal CdTe with the same room temperature absorption peak. Colloidal QDs are free of embedded matrix stresses and are, therefore, the perfect contraposition for comparison with QD doped glass. The fact that glass matrix did not allow the QD to expand/contract freely, caused the phase transitions by induced stress. The colloidal QDs were dried in a film on top of a cover glass to allow vacuum and measurements at cryogenic temperatures. We observed the fluorescence spectra and fluorescence lifetime for both QDs as a function of temperature. Our QD doped glass results confirmed the phase transitions in the same temperatures observed before. Colloidal and QD doped glass different thermal behavior proved, beyond any doubt, the role of the stress in the QD confinement and shows that caution is required to analyze previous results on QD doped glasses.

8996-33, Session PWed

Two- and three-photon upconversion luminescence switching in Tm3+/Yb3+ co-doped NaNbO3 nanophosphor

Kagola Upendra Kumar, Wagner Ferreira da Silva, Univ. Federal de Alagoas (Brazil); Venkata Krishnaiah Kummara, Jayasankar C. K., Sri Venkateswara Univ. (India); Carlos Jacinto da silva, Univ. Federal de Alagoas (Brazil)

Upconversion (UC) emissions were observed in the NaNbO3: 1%Tm3+-x% Yb3+ (x = 1, 3 and 5) nanocrystals upon 976 nm laser diode excitation. The blue emission observed at 476 nm was assigned to the 1G4 ? 3H6 transition. A week red emission around 650 nm and an intense NIR emission between at 805 nm were assigned to the 1G4 ? 3F4 and 3H4 ? 3H6 transitions, respectively. The intensity of 1G4?3H6 transition at 480 nm is dominant with increase in Yb3+ ion concentration. On the other hand, the 5% Yb3+ is an optimum concentration for large absorption cross section at 976 nm and efficient Yb3+ ? Tm3+ energy transfer may be expected. In addition to that, a color switching was also observed with increase in the Yb3+ ion concentration as well with pump intensity of CW diode laser and femtosecond (fs) laser. This phenomenon is attributed to pump induced saturation and depletion effect of Tm3+ ion 1G4 energy state and intermediate levels. The UC emission switching threshold was estimated to be 250 mW (11.6 kW/cm2) at 976 nm of fs laser. To evaluate the chromatic switching contrast of NaNbO3 nanocrystal, the luminescence ratios of the blue band to the NIR (RbN=I480/I805) for the pump power of 50 (2.3 kW/cm2) and 375 mW (17.5 kW/cm2) were calculated to be 0.4 and 1.26, respectively, with three-fold increase. With the obtained results we can conclude that Yb3+-Tm3+ codoped NaNbO3 nanocrystals enable pump-controlled luminescent switcher and emission wavelength switching with large spectral separation by changing the pump power of CW or fs laser at 976 nm, easily.

8996-34, Session PWed

Substrate-induced effects on the plasmonic properties of strongly coupled silver nanocubes

Daniel Prezgot, Anatoli I. Ianoul, Carleton Univ. (Canada)

The optical properties of the plasmonic modes of supported strongly coupled silver nanocubes are studied. Silver nanocube monolayers with controlled interparticle distances Langmuir-Blodgett technique. By varying the surface pressure and/or surfactants of the nanocubes, control over interparticle distances is achieved. Silver nanocube monolayers are deposited on substrates with varying refractive indices. Substrates include glass, quartz, and thin films of silicon, titanium oxide and metals on glass. The coupling mode is blue shifted with increasing refractive index and displays unique polarisation and angle dependant properties. These optical properties are characterized by UV-visible extinction, transmission, and reflection. Surface-enhanced Raman spectroscopy (SERS) is used as a tool to probe the electric field enhancements of the silver nanocube monolayers. SERS enhancement of silver nanocube monolayers is found to be highly substrate dependant, with enhancements up to an order of magnitude above or below glass. This work demonstrates the importance of substrate choice in coupled plasmonics and can be used in applications which rely on these phenomena, such as SERS based sensors.

8996-35, Session PWed

Plasmonic properties of silver nanocube monolayers deposited on thin metal films

Adam Bottomley, Anatoli I. Ianoul, Carleton Univ. (Canada)

The present work investigates the plasmonic properties and behaviour of silver nanocube monolayers deposited on thin metal films. Monolayers were deposited via the Langmuir-Blodgett method using a phospholipid as a passive spacer. Interparticle coupling was controlled by varying the surface pressure at which deposition occurred. The interaction of the nanocube monolayers with metal films was mediated by utilizing polyelectrolyte layering to generate a passive spacer between the cubes and substrate with a controllable distance. Refractive index sensing (RIS) was used to elucidate the behaviour of the plasmonic modes at various refractive indices. Silver nanocubes were characterized by UV-Vis spectroscopy and transmission electron microscopy, and the monolayers were characterized by UV-Vis reflection and transmission spectroscopy, and atomic force microscopy.

8996-37, Session PWed

Determination of the orientation of a single nano-emitter by polarisation analysis

Clotilde Lethiec, Institut des NanoSciences de Paris (France); Julien Laverdant, Lab. de Physique de la Matiére Condensée et Nanostructures (France); Clémentine Javaux, Benoit Dubertret, Ecole Supérieure de Physique et de Chimie Industrielles (France); Catherine Schwob, Laurent Coolen, Agnès Maître, Institut des NanoSciences de Paris (France)

Efficient coupling of nanoemitters to photonic or plasmonic structures requires the control of the orientation of the emitting dipoles. We propose in this paper to determine the nature and the polarization of nanoemitters by polarization analysis of their emission.

A nanoemittor can be considered either as a single radiating dipole, or as the sum of two orthogonal incoherent dipoles (2D dipole). The emission of a single nanoemitter coupled to a photonic structure in terms of dynamics, polarization and radiation pattern, depend on the dipole dimensionality of the emitter, and of its orientation with respect to the structure.

This dimensionality of a given type of nanoemitter is determined by polarimetric emission analysis of a statistical collection of individual emitters. The polarization anisotropy distribution, defined as (Ix-Iy)/(Ix+Iy) where x and y are two orthogonal polarization directions, is limited by extreme values which depends on the dimensionality of the dipole. For CdSe/CdS nanocrystals, the polarization anisotropy reveals a clear signature of a 2D dipole.

Once the dimensionality of the emitter is known, the analysis of the emission of a single emitter by turning the polarizer/analyzer gives information on its orientation.

The phase and the contrast of the sinusoidal curve provide information about polar and azimuthal angles. This determination of dipole orientation by polarization analysis is complementary to defocused microscopy, and can give information even when defocused microscopy is not suitable (2D dipole at a metallic interface…). We illustrate an analytical model by several measurements on high quality semiconductor core/shell nanocrystals and nanorods.

8996-39, Session PWed

Optimisation study of the synthesis of vanadium oxide nanostructures using pulsed laser deposition

Bathusile N Masina, Council for Scientific and Industrial Research (South Africa) and School of Physics, University of KwaZulu-Natal, Private Bag X54001, Dubarn, 4000 (South Africa); Slimane Lafane, Ctr. de Développement des Téchnologies Avancées (Algeria); Lorinda Wu, CSIR National Laser Ctr. (South Africa); Tahar Kerdja, Samira Abdelli-Messaci, Ctr. de Développement des Téchnologies Avancées (Algeria); Andrew Forbes, CSIR National Laser Ctr. (South Africa) and Univ. of KwaZulu-Natal (South Africa)

Vanadium dioxide (VO2) is electrically conducting at temperature higher than 68oC and insulating at temperature lower than 68oC. Due to this behaviour, VO2 has been presented as an attractive thin film material for electrical or optical storage, laser protection and solar energy control for windows in space satellites [1]. It is important to understand the laser plasma interaction and plasma plume expansion during a pulsed laser deposition process of synthesising the VO2 nano-structures, since it is difficult to synthesise a monoclinics VO2 nano-structure with a well-defined size and morphology [2]. We will investigate this by studying the mechanism of the plasma formation and expansion during pulsed laser deposition process of vanadium oxide, since the source of the films is a laser generated plasma composed of neutrals and ionised atoms, molecules and other species [3]. In this paper presentation, a spatio-temporal evolution study of different species such as VI (437.85 nm), VII (237.1 nm) and VO (608.56 nm) are presented and compared. The plume expansion dynamics of an ablated target of VO2 was also investigated using fast imaging technique. Free expansion, splitting and stopping of the plume were observed at different pressure and time delays. Linear expansion was observed at early time delays. However, as time evolves, the plume is decelerated and comes to rest. The plasma plume dynamics was analysed in the framework of drag model.

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8997-1, Session 2

Fabrication of GaP disk resonator arrays coupled to nitrogen-vacancy centers in diamond

Nicole Thomas, Russell Barbour, Univ. of Washington (United States); Yuncheng Song, Minjoo L. Lee, Yale Univ. (United States); Kai-Mei C. Fu, Univ. of Washington (United States)

Nitrogen-vacancy (NV) centers coupled to scalable optical networks have the potential to realize solid-state quantum information processing platforms. Toward this goal, we demonstrate coupling of near-surface NV- centers to an array of GaP optical resonators. Thus far, the NV-center optical emission has been coupled to pre-fabricated gallium phosphide (GaP) cavities randomly released on the diamond substrate. This approach - though appealing for the possible integration of photonic switches based on the linear electro-optic effect in GaP - does not allow for the integration of photonic devices into large-scale quantum networks.

We demonstrate the transfer of submicrometer thick, mm-sized GaP sheets from a GaP/AlGaP/GaP substrate to a diamond sample prepared with near-surface NV- centers. We fabricate large arrays of GaP disk resonators with varying diameters (1 to 20 ?m) on the diamond substrate via electron beam lithography and dry etching, and show coupling of the NV- center emission to the cavity structures. Quality factors above 10,000 were observed in 5 ?m diameter disks on the non-etched diamond substrate. Similar quality factors in smaller sized devices are expected with diamond substrate etching to further confine the optical mode.

This approach opens a path towards the integration of coupled optical components in the hybrid GaP/diamond system, an essential step towards large-scale photonic networks utilizing NV- centers in diamond.

8997-2, Session 3

Targeted decoration of axonal membranes with ND particles for luminescent and ODMR neural synapse imaging *(Invited Paper)*

Miloš Nesladek, IMEC (Belgium); Elena Gjorgievska, Univ. Hasselt (Belgium); Silvya M. Ojovan, The Hebrew Univ. of Jerusalem (Israel); Julia Micova, Jan Stursa, Mirek Ledvina, Academy of Sciences of the Czech Republic (Czech Republic); Micha Spira, The Hebrew Univ. of Jerusalem (Israel)

Fluorescent nanodiamond (fND) particles with engineered NV centres has excessive potential for bimolecular imaging as a replacement of biomolecular markers. It has been suggested that NV centers containing single crystal diamond plates can be used for imaging and spatial mapping of firing neurons, grown on N-implanted single crystal diamond [1]. In our work we came with a new approach for monitoring of neural synapses in vitro using fNDs. The advantage of fND particles is biocompatibility, long term chemical stability in-vitro and in-vivo, possible surface functionalization and sensitivity of NV centres to minute electric and magnetic fields. By targeting the neural receptors with highly luminescent fNDs of ~ 35 nm size [2] grafted with peptides of several sequences [3], we were able to adhere fND directly to the plasma membrane in the axonal regions. In these regions of synapses we expect highest magnetic field end electric charge gradients. Primary cultures of embryonic hippocampal rat neurons as well as aplysia neurons were incubated with fND particles. fND were grafted with various peptides using covalent click-chemistry. The luminescence mapping, transmission electron microscopy and confocal ODMR spectroscopy were used to localize the position of the particles in the cells. These experiments open the gate towards the neural imaging with a numerous application potential including the brain imaging in vivo. Applications are further discussed.

[1] L.T. Hall et al, Sci Rep. (2012);

[2] J. Havlik at al, Nanoscale, ,5, 3208-3211, (2013)

[3] M. Spira and A. Hai, Nature Nanotechnology 8, (2013)

[4] V. Petrakova at al, Advanced Functional Materials 22, (2012)

8997-3, Session 3

Nanoscale nuclear magnetic resonance with a nitrogen-vacancy spin sensor *(Invited Paper)*

H. Jonathon Mamin, Moonhee Kim, Mark H. Sherwood, Charles T. Rettner, IBM Almaden Research Ctr. (United States); Kenichi Ohno, David D. Awschalom, Univ. of California, Santa Barbara (United States); Daniel Rugar, IBM Almaden Research Ctr. (United States)

The ability to perform magnetic resonance imaging (MRI) on the nanoscale would open up the possibility of three-dimensional, element-specific imaging of biologically relevant objects at high resolution. The key to any approach to nano-MRI is the ability to detect the faint magnetic fields produced by small numbers of magnetic nuclear spins. In the past, we have used nanomechanical resonators with magnetic tips and optical readout to couple to the spins and sense the force exerted by them. More recently, we have explored the use of nitrogen-vacancy (NV) centers in diamond, where the concept is to take advantage of the optical and spin properties of these atom-like defects to create ultrasensitive magnetic field transducers. With this technique, we have demonstrated the ability to perform magnetic resonance on nuclear spins contained in a roughly (24 nm)3 volume of the polymer poly(methyl methacrylate). Future progress will require engineering the diamond to achieve better placement and coherence properties of the individual NV centers, and improving the collection efficiency from these single photon emitters.

8997-4, Session 3

Use of upconversion fluorescent nanoparticles for imaging and detection *(Invited Paper)*

Yong Zhang, Muthu Kumara G. Jayakumar, Kai Huang, National Univ. of Singapore (Singapore)

Lanthanide based nanoparticles with upconversion fluorescence are synthesized and their surfaces are modified to render them water dispersible and biocompatible. Use of these nanoparticles for bioimaging and biodetection introduces many advantages, for example, minimum photo-damage to biological samples, weak auto-fluorescence, high sensitivity and high light penetration depth, etc. The nanoparticles with core-shell structure have been prepared to improve the upconversion efficiency. Different lanthanide ions are doped into the core or the shell to tune the emission color. The nanoparticles have been used for multiplexed imaging of different receptors on the cell membrane and dynamic tracking of cells. They have also been used for imaging in deep tissues. Due to their unique optical property, they are also used for ultrasensitive detection of biomarkers in pathogenic samples. Although these upconverting nanoparticles are very promising fluorescent

materials, their applications are limited due to the low upconversion efficiency. There is an urgent need to develop new strategies for improving the upconversion efficiency.

8997-5, Session 3

Cell apoptosis induced by upconversion UV emission from rare-earth doped nanoparticles *(Invited Paper)*

Gengxu Chen, East China Normal Univ. (China) and State Key Lab. of Precision Spectroscopy (China) and Univ. Stuttgart (Germany); Roman L. Kolesov, Kangwei Xia, Andrea Zappe, Rolf Reuter, Univ. Stuttgart (Germany); E. Wu, Heping Zeng, East China Normal Univ. (China) and State Key Lab. of Precision Spectroscopy (China); Jörg Wrachtrup, Univ. Stuttgart (Germany)

Ultraviolet (UV) induced cell apoptosis, one of the best-known case in biological sequences of DNA damage, is often used in the research of cancer therapy. The formation of DNA photoproducts induced by UV radiation distorts DNA structure and blocks DNA transcription and replication, resulting in cell apoptosis. Optical upconversion process in rare-earth doped materials can produce ultraviolet (UV) emission with visible or even infrared excitation at much lower laser intensities than for two-photon transitions in molecules. If such nanoparticles are located inside living cells, apoptosis of the cells will be induced by the UV emission with an appropriate excitation on the nanoparticles. Here, we demonstrate apoptosis of the HeLa cells incubated in a buffer containing praseodymium doped yttrium aluminum garnet (Pr:YAG) nanoparticles, when the intracellular Pr:YAG nanoparticles are made to produce upconversion UV emission. Based on the life status statistics of exposed cells vs.UV emission intensity, the dosage of intracellular UV emission required to initiate apoptosis is also determined. Our investigation might pave a way to novel methods of laser-assisted cancer treatment.

8997-6, Session 4

Evaluation of the phase correlation between the optical pulses for transmission in quantum key distribution

Toshiya Kobayashi, Akihisa Tomita, Atsushi Okamoto, Hokkaido Univ. (Japan)

Quantum key distribution (QKD) has attracted attention as a means to achieve unconditionally secure communication. BB84 QKD protocol has been proven unconditionally secure. Moreover, BB84 protocol using a weak coherent state light source, as well as a single photon source, is shown secure over long distances with decoy method. A key assumption in the security proof is that the phase of each pulse emitted from the source is random. If the pulse phase correlates, an efficient eavesdropping method exists by exploiting the phase correlation. The laser pulse phase may correlate at a high clock frequency because, as the pulse interval becomes short, the previous pulse component may act as the seed.

In this work, we have evaluated the phase correlation between the optical pulses experimentally by observing interference between adjacent pulses with an asymmetric Mach-Zehnder interferometer. If interference is observed between the adjacent pulses, we can conclude that the phase correlation exists. We estimated the phase correlation quantitatively using visibility of the interference fringe.

A DFB laser for 10 Gbps direction modulation was used. The duration of the gain-switched laser pulse was shorter than the pulse interval. The phase correlation did not appear between the pulses even at 10GHz clock frequency. We observed the phase correlation if the DC bias current exceeds the threshold. The phase correlation became stronger as the DC bias current increased.

We conclude that the secure QKD equipment can be implemented with lasers at 10GHz clock frequency as long as driven by gain switch.

8997-7, Session 4

Quantum nonlinear optics: Implications for quantum information *(Invited Paper)*

Robert W. Boyd, Univ. of Ottawa (Canada)

Nonlinear optical processes such as parametric down conversion and squeezed light generation are key elements of most quantum protocols, leading to crucial applications such as quantum imaging, sub-shot-noise metrology, and secure communication.

Quantum imaging entails imaging modalities that make use of quantum states of light allows for dramatic new possibilities in the field of image science. We review some of the conceptual possibilities afforded by quantum imaging and describe some recent work that displays some of these features. We also address the complementary issue of how advanced imaging protocols can allow one to utilize and manipulate the enormous information content residing in the transvers structure of an optical field.

By its conventional definition, a photon is one unit of excitation of a mode of the electromagnetic field. The modes of the electromagnetic field constitute a countably infinite set of basis functions, and in this sense the amount of information that can be impressed onto an individual photon is unlimited. We describe how this large information content can be exploited for applications in quantum information science. As one example, we are currently developing a system to perform quantum key distribution at a high transmission rate by exploiting the transverse degree of freedom of the photon. Specifically, we aim to transmit more than one classical bit of information per photon by making use of this large information capacity. We also describe how image formation making use of quantum states of light allows dramatic new possibilities in the field of image science. One such example that we are studying is the possibility of performing imaging by impressing an entire image onto a single photon. We have also studied the properties of light fields with transverse distributions that impart orbital angular momentum (OAM) onto the photon. These OAM states constitute a complete basis, and thus any quantum image can be described in terms of these states. Our work has quantified the thought that these states can be used as effective carriers of quantum information.

8997-8, Session 4

High-speed bridge circuit for InGaAs avalanche photodiode single-photon detector

Hirofumi Hashimoto, Akihisa Tomita, Atsushi Okamoto, Hokkaido Univ. (Japan)

We report a bridge circuit based photon detector which can achieve low noise, high efficiency in optical communication wavelength bands.

Because of low power consumption and small footprint, avalanche photo diodes (APD) have been commonly applied to photon detection. In the photon detection at the 1.55 μm optical communication wavelength bands, InGaAs-APDs are used. Recently, high speed quantum communication has been demonstrated for high bit-rate quantum key distribution. For the high speed quantum communication, photon detectors should operate at GHz-clock frequencies. The GHz-clock operation of an InGaAs-APD photon detector has been demonstrated with sinusoidal wave gating. The sinusoidal wave appearing in the output is removed by sharp band-rejection filters. However, the use of filters limits the operating frequency. Moreover, filter design is difficult to realize sharp rejection with a small volume filter.

We propose a bridge circuit for photon detectors to reject the sinusoidal gating wave. This circuit removes the filter which limits the operating frequency. The balanced-APD photon detectors have been demonstrated

with less than 100-MHz gating. We design a RF bridge circuit for GHz sinusoidal gating operation. The sinusoidal gate is transformed to differential wave by a RF transformer and applied to APDs with DC bias voltage through a bias-T. The RF transformers and bias-Ts are compatible to surface mount, so that the whole circuit was constructed on a 32 x 38 mm square board. We achieved the balanced operation at 2 GHz. This simple and compact photon detector has an advantage of wide operation frequency range.

8997-9, Session 4

QEYSSAT: a mission proposal for a quantum receiver in space *(Invited Paper)*

Thomas D. Jennewein, Univ. of Waterloo (Canada)

Quantum information, and its use in quantum communication and other novel protocols, has its origins in the very fundamental and philosophical questions on quantum superposition and quantum entanglement. Today, we know that these new protocols will enable communication tasks not possible with classical systems. One very important example is the key exchange between different communication partners secured by quantum communication. The long-term vision is to establish a global quantum entanglement network between multiple sites, and satellite based quantum communication could play an important role in achieving this goal. At the same time, a satellite based quantum entanglement network could enable interesting tests of quantum mechanics at distances and velocities not possible on the ground.

As the Principal Investigator of our mission proposal named QEYSSat I will present the main goals and objectives of our system, which aims to place a quantum receiver on a micro satellite and would be useful to test entanglement over large distances as well as demonstrate global quantum communication. I will outline recent advances we have made towards implementing the proposed payload, including laboratory tests of the hard and software that demonstrate the proof-of-concept, a series of feasibility studies and our detailed quantum link performance analysis.

8997-34, Session 4

A photon-pair-emitting laser diode

Fabien Boitier, Adeline Orieux, Claire Autebert, Univ. Paris 7-Denis Diderot (France); Aristide Lemaître, Elisabeth Galopin, Lab. de Photonique et de Nanostructures (France); Christophe Manquest, Carlo Sirtori, Ivan Favero, Giuseppe Leo, Sara Ducci, Univ. Paris 7-Denis Diderot (France)

Photonics is playing a central role in the development of quantum information technologies. In this context, electrically driven sources of non-classical states of light have a clear advantage over optically driven ones in terms of portability, energy consumption and integration. Semiconductor materials are an ideal choice to achieve extremely compact devices where the generation, manipulation and detection of non-classical states of light could be performed within a same photonic circuit, setting the stage for the realization of complex logical operations

Here we present the first electrically injected source emitting photons pairs at telecom wavelength and operating at room temperature. The device is based on type-II intracavity SPDC in an AlGaAs laser diode and generates pairs at 1.57 µm. The active medium is a quantum well inserted in the core of the structure. Two Bragg mirrors provide both a photonic band gap vertical confinement for the laser mode — a Transverse Electric Bragg mode — and total internal reflection claddings for the photon-pairs modes — one TE00 and one TM00. The laser characteristics and the nonlinear optical behavior are investigated within the same device; the tunability curves of the laser emission and of second harmonic signal intersect at room temperature. The demonstration of photon pair emission is done via time-correlation measurements, giving an internal conversion efficiency higher than ~ 10?9 pairs/pump photon. Our device, based on conventional diode laser fabrication processing, let envision the use of III-V semiconductors for a widespread diffusion of quantum communication technologies.

8997-10, Session 5

Long-Distance Continuous-Variable Quantum Key Distribution with Advanced Reconciliation of a Gaussian Modulation

Laszlo Gyongyosi, Budapest Univ. of Technology and Economics (Hungary) and Hungarian Academy of Sciences (Hungary); Sandor Imre, Budapest Univ. of Technology and Economics (Hungary)

We show a two-way Continuous Variable Quantum Key Distribution (CVQKD) protocol with a range of 160 km of optical fiber. The protocol uses advanced post-processing and does not require tomography or entanglement, allowing easy implementation. The two-way CVQKD systems allow higher key rates and improved transmission distances over standard telecommunication networks in comparison to the one-way CVQKD protocols. To exploit the real potential of two-way CVQKD systems a robust reconciliation technique is needed. It is currently unavailable, which makes it impossible to reach the real performance of a two-way CVQKD system. The reconciliation process of correlated Gaussian variables is a complex problem that requires either tomography in the physical layer that is intractable in a practical scenario, or high-cost calculations in the multidimensional spherical space with strict dimensional limitations. To avoid these issues, we propose an efficient logical layer-based reconciliation method for two-way CVQKD. We prove that the error probability of scalar reconciliation is zero in any practical CVQKD scenario, and provides unconditional security. The results allow to significantly improve the currently available key rates and transmission distances of two-way CVQKD. The proposed scalar reconciliation can also be applied in one-way systems as well, to replace the existing reconciliation schemes.

8997-11, Session 5

Photonic entanglement sharing: fundamental questions and practical application *(Invited Paper)*

Geoff J. Pryde, Griffith Univ. (Australia)

Photons provide an excellent means of sharing entanglement between remote parties. Here we experimentally address fundamental and practical questions in remote entanglement sharing.

The process of entanglement swapping is even more remarkable than the counter-intuitive properties of nonlocal quantum states, because the swapping protocol entangles subsystems that have no prior direct common history. The result is an entangled quantum state in every aspect (leading to Bell inequality violations), even though the individual particle subsystems never locally interacted.

One might imagine that the nonlocal effects observed in entanglement swapping experiments are somehow stronger than those generated in usual Bell tests, because of the initial independent and uncorrelated nature of the of the particles that ultimately become entangled. This experimental work tests this “bilocal” proposition by comparing nonlocal effects generated in entanglement swapping experiments with those generated in tests of Bell’s inequality.

We also investigated how to combat loss in remote entanglement sharing, which has application to a range of quantum communication protocols. We experimentally demonstrated how noiseless amplification can be used to improve the transmission of a quantum channel. Together with mode teleportation or entanglement swapping that can be used to transmit information or share correlations. We show how this leads to

improved entanglement sharing in quantum repeaters for CV quantum communication.

8997-12, Session 5

The merits of photon-number resolution in nonorthogonal state discrimination *(Invited Paper)*

Alan L. Migdall, National Institute of Standards and Technology (United States) and Univ. of Maryland (United States) and Joint Quantum Institute (United States); Francisco E. Becerra-Chavez, Univ. of New Mexico (United States); Jingyun Fan, National Institute of Standards and Technology (United States) and Joint Quantum Insititute (United States) and Univ. of Maryland (United States)

Measurements of nonorthogonal states and how to best distinguish between them is a problem of both fundamental and practical importance. The fundamental importance lies in the fact that measurement, noise, measurement error are issues at the very heart of quantum mechanics, while the practical importance can be seen in the field of communication, arguably one of the key applications that underpins much of our society. And certainly sensing is another example of an application critical to many aspects of our world. Nonorthogonal state discrimination measurements are typically realized on coherent states produced as a part of an optical communication system where information is encoded in the phase and amplitude of the states. Receivers used to decode this information typically rely on interfering a local oscillator with a portion of the signal and using a null result to indicate a particular incoming state. Conventional receivers employ a static scheme whereby an incoming light pulse is split into several paths with each measured separately. This results in a minimum error probability due to the inherent overlap resulting from the use of nonorthogonal states as the information carrier. It is known that adaptive receivers that alter their analysis process, as previous partial measurements results are determined, can achieve lower error probabilities than is possible with a static receiver. Some adaptive receivers have demonstrated this advantage using photon counting, but without photon number resolving capability. We explore the potential merits of going beyond simple non-photon-number-resolved detection in an adaptive coherent receiver.

8997-13, Session 6

Two-photon Bessel interference patterns shape control in frequency domain by nonlocal dispersion management

Batiste Galmes, Jean-Pierre Decurey, Luca Furfaro, FEMTO-ST (France); Kien Phan Huy, Laurent Larger, John M. Dudley, Univ. de Franche-Comté (France); Jean-Marc L. Merolla, FEMTO-ST (France)

Entangled photons have appeared to be a promising way both for fundamental tests of physical principles and for quantum information applications. Using entangled photons could potentially allow the realization of key distribution protocols over distances greater than a few hundreds of kilometers and security certification. In biological imaging applications, entangled-photon light source also allows yielding original dispersion-free measurements. Hence the manipulation of the non classical properties of such source has great potential for the deployment of novel applications. If many different kinds of photonic entanglement have been used, including entanglement in polarization momentum, angular momentum or time-energy, direct manipulation in frequency domain of time-energy entanglement photons is a relatively unexplored area. Recently we reported experiments in which entanglement is manipulated in the frequency domain using electro-optic phase modulators driven by radio-frequency signals. We experimentally observed a high-visibility two-photon Bessel interference patterns relative to the RF phase signals, demonstrating a violation of the CH74 inequality by more than 18 standard deviations. This experiment represents a first step to study correlation control in frequency domain using standard electro optic components. In what it follows we report a simple non local dispersion control method implemented in an automated platform built entirely from off-the-shelf components. A shape modification of the Bessel-type interference between photons separately detected has been observed and controlled by local dispersion management. Such results show that frequency-bin photon entanglement is a promising platform for the realization of various quantum information experiments.

8997-14, Session 6

Sampling interferometric photon coincidence to measure immanants *(Invited Paper)*

Si-Hui Tan, Singapore Univ. of Technology & Design (Singapore); Hubert de Guise, Isaac P. Poulin, Lakehead Univ. (Canada); Yvonne Y. Gao, Yale Univ. (United States); Barry C. Sanders, Univ. of Calgary (Canada)

BosonSampling proposes using linear-optical interferometers to sample from a probability distribution whose amplitudes are immanants, and then use the known properties of the immanants to argue about the classical complexity of doing the same thing. Recent advances in integrated optical circuits make this possible through coincidence experiments.

We have developed an algorithm for computing immanants of a scattering matrix from output photon coincidences for multiple single-photons entering some of the input ports of a multi-channel interferometer. Our algorithm can be applied to any interferometer and input single-photon configurations, and it works even in cases when the number of input single-photon is smaller than the size of the interferometer or when multiple single-photon enters one input channel of the interferometer. Furthermore, the theory explains all features of the photon coincidence probabilities as functions of time delays between input photons by observing that these coincidence functions depend on weighted sums of moduli of Wigner D-functions. The Wigner D-functions in turn are linear combinations of the immanants of the interferometer matrix.

Our result is useful for the BosonSampling problem in which photon coincidences are the main resource for testing new conjectures. Our immanant coincidence landscapes can also be used to determine unknown parameters of the interferometer transformation, thus making them a useful characterization and verification tool for interferometry. Equivalently, if we have a well-characterized interferometer, its coincidence landscapes are immanant-calculators. This is an important extension of the original BosonSampling result on permanent because some immanants are almost as hard to compute as the permanent of a matrix of the same size.

8997-15, Session 6

Weaving hypercubic cluster-entangled states in the quantum optical frequency comb *(Invited Paper)*

Olivier Pfister, Univ of Virginia (United States); Moran Chen, Pei Wang, Univ. of Virginia (United States); Nicolas C. Menicucci, The Univ. of Sydney (Australia)

The quantum optical frequency comb defined by a single optical parametric oscillator (OPO) offers a vast landscape of quantum modes (Qmodes) which can be entangled, by the broadband nonlinear medium

of the OPO, into a variety of multipartite entangled states. Such states are generated in a "top down" manner and can comprise thousands of Qmodes, as determined by the ratio of the phasematching bandwidth of the OPO's nonlinear medium to its free spectral range. Of particular interest are cluster states which enable one-way quantum computing. In 2011, our group demonstrated the parallel generation of 15 quadripartite "square" cluster states in a single OPO. Here, we present the generation of a 60-Qmode cluster chain, still in a single OPO. (In both cases, the number of verified entangled Qmodes was limited by measurement technology, not by the generation process which, we estimate, should yield at least 10 times as many Qmodes as we could verify.) We also present a new theoretical result which shows that such cluster chains as we generate with single OPOs can be weaved together in order to generate, square-grid and, further, hypercubic cluster-state lattices, the number of OPOs needed being equal to the hypercube's dimension. We also hope to stimulate theoretical research on hypercubic-lattice cluster states.

8997-16, Session 6

Nonmonotonic quantum-to-classical transition in multiparticle interference *(Invited Paper)*

Young-Sik Ra, Pohang Univ. of Science and Technology (Korea, Republic of); Malte Tichy, Albert-Ludwigs-Univ. Freiburg (Germany); Hyang-Tag Lim, Osung Kwon, Pohang Univ. of Science and Technology (Korea, Republic of); Florian Mintert, Albert-Ludwigs-Univ. Frieburg (Germany) and Max-Planck-Gesellschaft (Germany); Andreas Buchleitner, Albert-Ludwigs-Univ. Freiburg (Germany); Yoon-Ho Kim, Pohang Univ. of Science and Technology (Korea, Republic of)

In quantum physics, the wave–particle duality implies that probability distributions for granular detection events exhibit wave-like interference. On the single-particle level, this leads to quantum interference as long as no which-path information is available to any observer, even in principle. For many particle systems, their specific quantum features are manifested in correlation functions. It is often believed that interference fades away monotonically with increasing distinguishability as observed in some of the single-particle and many particle quantum interference experiments. In this work, we demonstrate experimentally and theoretically that such monotonicity of the quantum-to-classical transition is the exception rather than the rule whenever more than two particles interfere. As the distinguishability of the particles is continuously increased, interference signals are in general non-monotonic functions of the distinguishability of the particles [1]. This observation opens perspectives for the experimental characterization of many-particle coherence and sheds light on decoherence processes in many-particle systems.

[1] Ra, Y. S. et al., Nonmonotonic quantum-to-classical transition in multiparticle interference. Proc Natl Acad Sci USA 110, 1227–1231 (2013).

8997-17, Session 7

An entanglement-enhanced microscope *(Invited Paper)*

Shigeki Takeuchi, Hokkaido Univ. (Japan) and Osaka Univ. (Japan)

Optical phase measurement is a key technology in many kinds of metrology. The accuracy of the measurement for a given light intensity, or the number of photons, is limited by the standard quantum limit. However, recently it has been demonstrated that the standard quantum limit can be beaten by using entangled photons.

In this presentation, we report the first demonstration of an entanglement microscope, which is the differential confocal microscope where an entangled photon pair source is used for illumination. We show that the S/N ratio of the image obtained by the entanglement microscope is 1.35 times better than that limited by the standard quantum limit. This experimental demonstration will open the door for the broad application of entanglement-enhanced metrology from biology to material science[1].

We will also report other topics on quantum measurements and sensing, including the experimental demonstration of the dispersion-tolerance of the quantum optical coherence tomography in the high resolution regime[2], and adaptive quantum state estimation of single photon quantum bit[3], and discuss the advantages of AQSE to currently used quantum state tomography.

[1] T. Ono, R. Okamoto, and S. Takeuchi, submitted (2013).

[2] M. Okano, S. Takeuchi, et. al., submitted (2013).

[3] R. Okamoto, S. Takeuchi, et. al., PRL 109, 130404 (2012)

8997-18, Session 7

New results in remote quantum sensing *(Invited Paper)*

Gerald N. Gilbert, The MITRE Corp. (United States)

It was shown several years ago that the use of photonic N00N states as probe signals for remote quantum sensing intended to achieve increased phase sensitivity encounters problems when realistic atmospheric loss is taken into account. It was shown that in the presence of non-vanishing photon attenuation the Heisenberg limit is never achieved, and that attenuated N00N states actually produce worse phase estimates than equally attenuated N-photon separable states unless the transmittance of the medium is sufficiently high. In this talk we examine a new approach to circumventing these problems, reviving the possibility of remote quantum sensing in realistic environments.

8997-19, Session 7

High-dimensional entanglement characterization via compressive sensing *(Invited Paper)*

John C. Howell, Daniel Lum, Greg A. Howland, Univ. of Rochester (United States)

Using compressive sensing, we report on recent demonstrations of ultra-high dimensional entanglement characterization. Using double-pixel intensity correlation measurements, we probe high dimensional momentum-position entangled photons, the joint spectral intensity and 3D ghost object tracking.

8997-33, Session PWed

Time-bin entangled photon pairs on demand

Marijn A. M. Versteegh, Michael E. Reimer, Aafke A. van den Berg, Kavli Institute of Nanoscience Delft (Netherlands); Gediminas Juska, Emanuele Pelucchi, Tyndall National Institute (Ireland); Valery Zwiller, Kavli Institute of Nanoscience Delft (Netherlands)

Time-bin entanglement is more suitable for long-distance quantum communication than polarization entanglement, since time-bin entangled photons are insensitive to birefringence fluctuations in optical fibers. Up to now, time-bin entangled photons have only been produced in stochastic processes, such as parametric downconversion. Here

we present the first method to create time-bin entangled photons on demand.

We use InGaAs1-δNδ quantum dots grown within GaAs barriers and located inside pyramids [1]. These quantum dots have symmetric confining potentials for electrons and holes and thereby allow for the creation of polarization-entangled photon pairs, employing the biexciton-exciton radiative cascade. These polarization entangled photons are created on demand, meaning that per excitation pulse no more than one photon pair is emitted. By sending the emitted photons through an interferometer we convert the polarization entanglement into time-bin entanglement.

[1] G. Juska, V. Dimastrodonato, L. O. Mereni, A. Gocalinska, and E. Pelucchi, Nature Photon. 7, 527 (2013).

8997-20, Session 8

Quantum nanophotonic circuits for ultralow-power classical information processing *(Invited Paper)*

Jason S. Pelc, Ranojoy Bose, Kelley Rivoire, Charles Santori, Raymond G. Beausoleil, Hewlett-Packard Labs. (United States)

While optical nonlinearities are famously weak, the confinement of light to sub-cubic-wavelength volumes using high-quality-factor photonic nanocavities makes low-power nonlinear optical processes possible. The small footprint of nanocavities combined with the high natural bandwidth of photonic systems holds great promise for future information processing applications. But photonic integration trails electronic integration by several decades, and we are only now beginning to envision what a complex nanophotonic circuit might do. We will discuss technology platforms for ultralow-power nonlinear optics using both III-V and group IV semiconductors. We will also describe quantum optical simulations of large-scale photonic sequential logic circuits using phase-space methods, indicating that reliable performance is possible with a few tens of photons per device.

8997-21, Session 8

Integrated cavity electro- and opto-mechanics *(Invited Paper)*

Oskar J. Painter, California Institute of Technology (United States)

By coupling mechanical resonators to the light of optical cavities, the field of cavity-optomechanics aims at observing quantum mechanical behavior of mesoscopic mechanical systems. In the last several years, rapid advances have been made in the field of cavity optomechanics. These advances have moved the field from the multi-km interferometer of a gravitational wave observatory, to the optical table top, and now all the way down to a silicon microchip. In this talk I will discuss our recent efforts to integrate microwave electro-mechanical circuits with photonic crystal opto-mechanical devices, with an aim of creating a quantum optomechanical interface between photons of light and microwave photons.

8997-22, Session 8

Highly mode-selective quantum frequency conversion in a slab waveguide

Michael Vasilyev, Young B. Kwon, The Univ. of Texas at Arlington (United States); Yu-Ping Huang, Northwestern Univ. (United States)

Parametric amplification and frequency conversion of spatially-multimode light have been recently gaining attention in both classical and quantum communication contexts, owing mostly to the emergence of the space-division multiplexing and mode-division multiplexing communication systems. In particular, the use of spatial-mode-selective “1550-nm-to-visible” frequency converters can simultaneously improve the single-photon-detection efficiency and provide spatial-mode demultiplexing. The key to the quantum use of this device is its ability to up-convert the desired mode with 100% efficiency without affecting any other spatially overlapping modes.

In this paper, we propose such a converter based on sum-frequency generation (SFG) in a chi(2) slab waveguide. We build a model based on Green’s function formalism for the SFG equations and perform singular-value decomposition (SVD) of the Green’s function to find the eigenmodes for the signal and the sum-frequency waves. By adjusting the spatial profile of the pump, we manipulate the SVD spectrum to maximize the up-conversion of the first signal mode while minimizing the up-conversion of the rest of the modes. Our initial results show that with a simple Gaussian pump, a 100% conversion efficiency for the first signal mode can be realized while keeping the conversion efficiency of the second mode at 36% (and much lower for the other modes). The use of more complicated spatial profiles of the pump can further increase the contrast between the first and the second signal modes, making a mode-selective quantum frequency converter possible.

8997-35, Session 8

Hybrid integration for spatially-multiplexed single-photon generation

Thomas D. Meany, Macquarie Univ. (Australia); Lutfi A. Ngah, Lab. de Physique de la Matière Condensée (France); Matthew J. Collins, Alex S. Clark, The Univ. of Sydney (Australia); Robert J. Williams, Macquarie Univ. (Australia); Benjamin J. Eggleton, The Univ. of Sydney (Australia); Michael Steel, Michael Withford, Macquarie Univ. (Australia); Olivier Alibart, Sébastien Tanzilli, Lab. de Physique de la Matière Condensée (France)

Currently many quantum communication protocols rely on the use of attenuated lasers as a approximated source of single photons. However, this results in Poissonian photon statistics limiting certain applications [1]. Furthermore, in many quantum information applications multiple, identical, single photon sources are required for the preparation of qubits. Spontaneous parametric downconversion (SPDC) sources have been used to prepare up to 8-photon states [2]. However, non-zero multi-photon contributions result in noise. A spatial multiplexing scheme can be used to increase source brightness, while maintaining a fixed noise contribution [3]. The method uses multiple heralded single photon sources actively routed to a single output [4].

Integrated waveguides in periodically poled lithium niobate (PPLN) are highly efficient sources of heralded single photons [5]. However, PPLN is not the optimum substrate for the production of complex linear components. The femtosecond laser direct-write (FLDW) technique permits the rapid prototyping of 3D waveguide circuits. By focusing a short pulse duration laser inside a transparent material, permanent refractive index modifications can be formed. With appropriate translation of a sample with respect to the laser focus multiple optical components can be been formed in glass fibres and substrates including fibre Bragg gratings (FBG) and waveguides circuits.

Here we use linear FLDW laser written components to interface with PPLN waveguide circuits. We use an active routing scheme to route photons from separate waveguides to an individual output [6]. Using this technique we achieve an enhanced source brightness while maintaining a fixed noise level. By using on-chip components for source preparation we demonstrate the scalability of our technique

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8997-23, Session 9

Single-photon sources without quantum emitters *(Invited Paper)*

Dario Gerace, Univ. degli Studi di Pavia (Italy)

Integrated single-photon sources working in the typical telecommunication band would represent a useful building block in quantum photonics devices. Ideally, pure single-photon states require a two-level emitter as a source. Although the recent progress in fully integrated and telecom-compatible quantum photonics technologies, the ability of generating single-photon states on demand is still lacking, owing to the lack of efficient quantum emitters at such wavelengths. As an alternative, single-photons can be generated through the photon blockade effect: enhanced optical nonlinearities in photonic resonators inhibit the transmission of a coherent light field when a single-photon is present within the system. This process can lead to single-photon generation at the output of a device coherently driven by a resonant laser beam, with large flexibility on the single-photon emission wavelength. Ordinary nonlinear materials require a large number of photons to produce appreciable effects, owing to the intrinsically small nonlinear susceptibilities in in bulk. In this talk, I will review our recent work on nanostructured semiconductor nanocavities based on materials with intrinsic second- or third-order nonlinear response. A theoretical characterization of their efficiency as single-photon nonlinear systems is given by means of the second-order correlation function as the main figure of merit. These results allow to envision the realization of novel quantum photonics devices based on non-resonant material media, fully integrated with current semiconductor technology, as an alternative to single-photon devices based on cavity quantum electrodynamics with artificial atoms or single atomic-like emitters.

8997-24, Session 9

Quantum nonlinear optics using cold Rydberg atoms *(Invited Paper)*

Thibault Peyronel, Massachusetts Institute of Technology (United States); Ofer Firstenberg, Harvard Univ. (United States) and Technion-Israel Institute of Technology (Israel); Qi-Yu Liang, Massachusetts Institute of Technology (United States); Alexey Gorshkov, California Institute of Technology (United States); Mikhail D. Lukin, Harvard Univ. (United States); Vladan Vuletic, Massachusetts Institute of Technology (United States)

In conventional optical materials, the nonlinearities at light powers corresponding to single photons are negligibly weak. Using ensemble of laser-cooled atoms and Electromagnetically Induced Transparency (EIT) techniques, we created a medium in which slowly-traveling photons are coherently coupled to highly excited atomic Rydberg states. The large dipole-dipole energy shift between the Rydberg states effectively mediates strong interactions between single photons. In particular, this technique can be used to engineer strong dissipative interactions between photons and to create a quantum nonlinear optical medium exhibiting simultaneously large single photon transmission and strong two-photon absorption. We also demonstrated that the nature of the interaction can be tuned by introducing a finite detuning from the intermediate atomic state. In particular, it can take the form of an attractive force between the photons. In our effectively one-dimensional system, this attractive potential gives rise to a photonic bound state which governs the propagation dynamics of the photon pairs. We reconstruct the time-dependent two-photon wavefunction via quantum state tomography, and show that the interaction produces large deterministic nonlinear phase shifts and polarization entanglement.

8997-25, Session 9

Optical nonlinearity with few-photon pulses in a quantum dot/pillar cavity device *(Invited Paper)*

Loïc Lanco, Lab. de Photonique et de Nanostructures (France)

A single two-level system constitutes an extremely non-linear optical medium, where the interaction with a first single photon modifies the transmission probability for a second photon. The main difficulty to implement a single photon switch using this property is to ensure that a gate single photon will interact with the quantum emitter with a near-unity probability.

Here we demonstrate giant optical non-linearity in a micropillar cavity deterministically coupled to an InGaAs quantum dot. Using short-pulse excitation, we report a nonlinearity threshold at 8 incident photons per pulse. Furthermore, we have theoretically shown that nonlinearities can actually be obtained at the single-photon limit, if the photon extraction efficiency is also optimized. This paves the way for the near-future realization of all-optical switches and quantum logic gates operating with single-photon incident pulses.

In addition, we will present first results regarding the development of a spin-photon interface, using pillar cavities coupled to charged quantum dots.

8997-26, Session 10

Polariton devices and quantum fluids *(Invited Paper)*

Dario Ballarini, Milena L. De Giorgi, Giovanni Lerario, Istituto Italiano di Tecnologia (Italy); Emiliano Cancellieri, Ecole Normale Supérieure (France); Alessandro Cannavale, Istituto Italiano di Tecnologia (Italy); Alberto Bramati, Ecole Normale Supérieure (France) and Univ. Pierre et Marie Curie (France); Giuseppe Gigli, Istituto Italiano di Tecnologia (Italy) and Univ. del Salento (Italy) and Univ. degli Studi di Lecce (Italy); Fabrice P. Laussy, Univ. Autónoma de Madrid (Spain); Daniele Sanvitto, Istituto Italiano di Tecnologia (Italy) and National Nanotechnology Lab. (Italy)

Exciton-polaritons, which are composite particles resulting from the strong coupling between excitons and photons, have shown the capability to undergo condensation into a macroscopically coherent quantum state, demonstrating huge non-linearities and unique propagation properties. These strongly-coupled light-matter systems are promising candidates for the realization of semiconductor all-optical devices with fast time response and small energy consumption. Recently, quantum fluids of polaritons have been used to demonstrate the possibility to implement optical functionalities as spin switches, transistors or memories, but also to provide a channel for the transmission of information inside integrated circuits. On the other hand, the confinement of polariton fluids and the control over their propagation properties, crucial for the realization of polariton circuits, offer the unique possibility to study the fundamental new physics of out-of-equilibrium quantum fluids, opening the door to their implementation in future optical devices.

Here, the main differences with respect to other kinds of all-optical devices will be discussed, along with the presentation of the recent advances in the field of polariton devices. Moreover, the physics of polariton fluids will be presented from the point of view of quantum hydrodynamics.

8997-27, Session 10

The exciton-polariton microcavity as an optical transistor *(Invited Paper)*

Mark D. Steger, David W. Snoke, Univ. of Pittsburgh (United States)

Recent works have demonstrated the feasibility of exciton-polariton microcavities as optical transistor elements. The strong nonlinear response of the microcavity polariton makes it a promising choice for an optical switch: at moderate densities the exciton-exciton interactions and saturation of the exciton-photon coupling both lead to an increase of the lower polariton energy. Also, the unique dispersion relation of the polariton allows for a single-wavelength laser to be used as both signal and gate: by arranging the lasers at different angles one can be made resonant to the polariton while the other is off-resonant. Modulation of the gate intensity can cause the signal to be brought into or out of resonance with the polariton.

As the switching mechanism is dependent on a real population of carriers in the cavity, the speed of the switch is related to the lifetime of the polariton. Therefore the speed of switches can be partly engineered by changing the Q-factor of the microcavity since the polariton lifetime is a mixture of the cavity photon and exciton lifetimes. Results from current GaAs/AlAs microcavities allow for near THz frequency switching. Different geometries allow for different logical models to be assumed such as AND or NAND gates.

We will present current efficiencies and geometries being studied with these switches as well as present future avenues for improvement. We will also relate the underlying mechanism to related results based on the saturation of strong coupling in the microcavity polariton.

8997-28, Session 10

Nonlinear polariton resonant tunneling diode *(Invited Paper)*

Hai Son Nguyen, Lab. de Photonique et de Nanostructures (France) and Ctr. National de la Recherche Scientifique (France); Dmitry Vishnevsky, Clermont Univ. Blaise Pascal (France) and Institute Pascal (France); Felix Marsault, Chris Sturm, Dmitrii Tanese, Lab. de Photonique et de Nanostructures (France) and Ctr. National de la Recherche Scientifique (France); Dimitry Solnyshkov, Univ. Blaise Pascal (France) and Institute Pascal (France); Elisabeth Galopin, Aristide Lemaître, Isabelle Sagnes, Alberto Amo, Lab. de Photonique et de Nanostructures (France) and Ctr. National de la Recherche Scientifique (France); Guillaume Malpuech, Univ. Blaise Pascal (France) and Institute Pascal (France); Jacqueline I. Bloch, Lab. de Photonique et de Nanostructures (France) and Ctr. National de la Recherche Scientifique (France)

In this work, we report the realization of a polariton resonant tunneling diode (RTD) based on an innovative design of a wire cavity. Our sample consists in a high quality factor GaAs based microcavity operating in the strong coupling regime. Electron beam lithography and dry etching are used to fabricate 1D microwires with a microstructure defining the RTD: two constrictions delimits a 0D polariton island, with well-defined confined polariton states and coupled to the 1D regions on each side through two tunnel barriers. A monochromatic polariton flow sent onto this microstructure can undergo resonant tunneling, when its energy coincides with the energy of one of the confined modes within the island. We use a gate laser beam, focused onto the island, to tune the energy of the island level, and thus to modulate the polariton intensity transmitted through the microstructure. This laser beam locally injects a small exciton density in the island, and thus induces a blueshift of the island levels, thanks to polariton-exciton repulsive interactions. Finally we see strong influence of the polariton-polariton interactions in the device operation: this non-linearity is responsible for the asymmetric shape of the transmission peak, as well as for a bistable behavior of the RTD. This device is envisioned as the building block for more complex architecture circuits, like logic gates and optical memory.

8997-29, Session 11

Quantum dot spin-photon entanglement and photon-to-spin teleportation *(Invited Paper)*

Weibo Gao, Parisa Fallahi, ETH Zurich (Switzerland); Emre Togan, ETH Zurich (Switzerland) and Harvard Univ. (United States); Aymeric Delteil, Y. S. Chin, Javier Miguel Sanchez, Atac Imamoglu, ETH Zurich (Switzerland)

Entanglement plays a central role in fundamental tests of quantum mechanics as well as in the burgeoning field of quantum information processing. Particularly in the context of quantum networks and communication, a major challenge is the efficient generation of entanglement between stationary (spin) and flying (photon) qubits . Here, we report the observation of quantum entanglement between a semiconductor quantum dot spin and the color of a propagating optical photon. The demonstration of entanglement relies on the use of fast single-photon detection which allows us to project the photon into a superposition of its two frequency components. Our results extend the previous demonstrations of single-spin photon entanglement in trapped ions, neutral atoms and nitrogen vacancy centers to the domain of artificial atoms in semiconductor nano-structures that allow for on-chip integration of electronic and photonic elements. Our observation constitutes a key first step towards implementation of a quantum network with nodes consisting of semiconductor spin qubits.

Further more, we experimentally demonstrate transfer of quantum information carried by a photon to a semiconductor spin using quantum teleportation. In our experiment, a single photon in a superposition state is generated using resonant excitation of a neutral dot. To teleport this photonic qubit, we generate an entangled spin-photon state in a second dot located 5 meters away and interfere the photons from the two dots in a Hong-Ou-Mandel set-up. Thanks to an unprecedented degree of photon-indistinguishability, a coincidence detection at the output of the interferometer heralds successful teleportation, which we verify by measuring the resulting spin state after prolonging its coherence time by optical spin-echo.

8997-30, Session 11

Frequency conversion interfaces for photonic quantum systems *(Invited Paper)*

Kartik Srinivasan, National Institute of Standards and Technology (United States)

Manipulating the wavelength of quantum states of light is an important resource in the development of photonic quantum information technology, where it can be used to interface disparate physical systems, overcome fabrication-induced inhomogeneity, and allow for more optimal detection. In this talk, I will outline our laboratory's efforts at manipulating the color of single photon states. I will begin by briefly reviewing how we generate single photons from single semiconductor quantum dots embedded in guided wave nanophotonic structures. I'll then describe experiments in which we use such a single photon source in conjunction with three-wave-mixing in a nonlinear crystal to demonstrate telecom-to-visible conversion and produce identical photons from initially spectrally distinct sources. Finally, I will discuss efforts to develop quantum frequency converters in a scalable, chip-based platform, using both material nonlinearities (four-wave-mixing) and engineered nonlinearities based on radiation pressure coupling between photons and phonons (cavity optomechanics).

8997-31, Session 11

A variable plasmonic beam splitter tested with single photons

Alexander Huck, Shailesh Kumar, Niels I. Kristiansen, Jonas S. Neergaard-Nielsen, Ulrik L. Andersen, Technical Univ. of Denmark (Denmark)

The dimensions of optical components can be reduced far beyond the diffraction limit of light by the aid of metallic nano-structures and strongly confined surface plasmon polariton (SPP) modes propagating along them. Furthermore, due to the strong field confinement of SPP modes the spontaneous emission from a dipole emitter can be greatly enhanced and channelled into a well-defined spatial mode, which is a promising tool for building a light-matter interface and a bright on-demand single photon source.

In this contribution, we experimentally demonstrate and test with single photons the construction of a tunable plasmonic beam splitter based on evanescent adiabatic coupling between two SPP modes propagating along individual silver nanowires. The wet chemically prepared silver nanowires have a diameter of 88 nm. Using the tip of an atomic force microscope, we first couple a single nitrogen vacancy center hosted in a nanodiamond to the SPP mode propagating along one silver nanowire. After this, we partially couple the excited SPP to a second nanowire by positioning it close to the first nanowire with a minimum gap of 51.6±2.6 nm and an overlap of around 1 μm. With this configuration we obtain efficient evanescent coupling to the SPP mode of the second wire, which otherwise is not excited. By further reducing the inter wire gap we demonstrate variable power splitting ratios. For asymmetric cases the contrast exceeds values of 9:1. All experimental results agree well with finite element simulations which suggest the slow formation of silver sulphide and silver oxide over time.

8997-32, Session 11

Plasmonic Hong-Ou-Mandel interference

James Fakonas, Hyunseok Lee, California Institute of Technology (United States); Yousif A. Kelaita, Stanford Univ. (United States); Harry A. Atwater, California Institute of Technology (United States)

In this work we measure two-photon quantum interference (TPQI), also known as the Hong-Ou-Mandel effect, in plasmonic waveguides. A uniquely quantum phenomenon, Hong-Ou-Mandel interference occurs when two photons that arrive at adjacent inputs of a 50-50 beam splitter are always observed to exit the splitter together in one output port or the other, but never in separate outputs. According to quantum theory, this result is a consequence of destructive interference between the probability amplitudes of two processes: one in which both photons are transmitted at the splitter and the other in which both are reflected.

To measure this effect in a plasmonic system, we fabricate 50-50 directional couplers out of dielectric-loaded plasmonic waveguides. We integrate these with low-loss silicon nitride waveguides, which deliver pairs of single photons to and collect them from the plasmonic couplers. In preliminary experiments, we observe plasmonic Hong-Ou-Mandel interference with a visibility of 93% +/- 1%, a result that puts this measurement solidly in the quantum regime. We also extend the standard theory of the Hong-Ou-Mandel effect to account for loss in the 50-50 directional coupler and describe its effect on the visibility of the interference.

Conference 8998: Advances in Slow and Fast Light VII

Sunday - Wednesday 2 –5 February 2014

Part of Proceedings of SPIE Vol. 8998 Advances in Slow and Fast Light VII

8998-1, Session 1

Using slow light to reduce losses in plasmonics and metamaterials *(Invited Paper)*

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

Plasmonic and metamaterials are exciting fields with a host of potential applications. All of them are unfortunately impeded by high loss in the metals. The losses are associated with the fact that a significant part of energy is stored in the form of kinetic energy of free electrons in metals where it gets lost at high rate. In this talk we show that using highly dispersive media (usually associated with slow light) to augment the energy storage and this reduce or even completely eliminate the role of the metal can reduce the losses significantly. At the same time the field enhancement and Purcell factor also get reduced, but, as we hope to show, a careful optimization process can lead to combination of a decent (if not spectacular) field enhancement with low losses thus bringing plasmonics and metamaterials one step close to real applications.

8998-2, Session 1

Stopped-light plasmonic nanolasing *(Invited Paper)*

Ortwin Hess, Imperial College London (United Kingdom)

No Abstract Available

8998-3, Session 1

Plasmonic light matter Fano interactions in hot atomic vapors

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

The ability to control the response of light at the nano-scale using plasmonic devices has drawn much attention in the last few years. Amongst the different degrees of freedom, shaping spectral features is highly desired, and can be achieved, by coupling different building blocks together, establishing a new hybrid system with controlled spectral features due to the interference between these subsystems [1,2]. In the case of coupling a broad plasmonic resonance with a narrow spectral feature, a Fano resonance [3] is created. Specifically, the interaction of a plasmonic system with atomic vapor such as Rubidium is very appealing due to the vast experience in manipulating and controlling such vapors close to room temperature. Moreover, plasmonic and atomic vapor interactions hold a promise to shed light on the basic nature of light matter interactions between surfaces and atoms due to the unprecedented light concentration in plasmonic structures. Here, we demonstrate for the first time the evanescent interaction between a surface plasmon resonance (SPR) and Rubidium (85Rb) atomic vapor. We show that due to the Fano interplay between the atomic and plasmonic resonance, having five orders of magnitude difference in their spectral widths, the systems resonance changes dramatically while changing the coupling conditions. We apply to these results to a model, taking into account the plasmonic resonance, as well as the motion of the atoms, and find good agreement with our results. Finally, we discuss the different prospects of such an hybrid system.

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8998-4, Session 1

Slow-light plasmonic-enhanced emitters and detectors for on-chip interconnects *(Invited Paper)*

Meir Orenstein, Technion-Israel Institute of Technology (Israel)

No Abstract Available

8998-5, Session 1

Plasmonics: nonlocal response and light-matter interactions *(Invited Paper)*

Niels Asger Mortensen, DTU Fotonik (Denmark)

No Abstract Available

8998-6, Session 2

Nanophotonics, nanoplasmonics, and vapors-on-a-chip for slow-light applications *(Invited Paper)*

Uriel Levy, The Hebrew Univ. of Jerusalem (Israel)

No Abstract Available

8998-7, Session 2

Slow-light transmission in the metal-dielectric structure based on plasmon-induced transparency

Yundong Zhang, Harbin Institute of Technology (China); Jin Li, Harbin Institute of Technology (China) and Northeastern University (China); Hanyang Li, Harbin Institute of Technology (China); Chengbao Yao, Harbin Institute of Technology (China) and Harbin Normal University (China); Ping Yuan, Harbin Institute of Technology (China)

No Abstract Available

8998-8, Session 2

Tuning the transmission lineshape and time delay of a photonic-crystal slab guided resonance mode by polarization control *(Invited Paper)*

Ningfeng Huang, The Univ. of Southern California (United States); Luis Javier Martinez Rodriguez, The Univ. of Southern California

(Uruguay); Michelle L. Povinelli, The Univ. of Southern California (United States)

No Abstract Available

8998-9, Session 2

Photonic integrated circuits with slow light *(Invited Paper)*

Toshihiko Baba, Yokohama National Univ. (Japan)

No Abstract Available

8998-10, Session 2

Slow-light enhanced dark and bright soliton propagation in SOI photonic crystal channel waveguides

Swati Rawal, Ravindra K. Sinha, Delhi Technological Univ. (India)

Slow light is a promising technology for future all optical communication networks and can be used for the increase of light matter interaction and enhancement of nonlinear effects such as soliton propagation, two photon absorption etc. When optical pulses propagate through photonic crystal waveguides, their evolution in both time and frequency domain is governed by interplay of linear dispersion and nonlinearity. However soliton propagation will dominate in PhC waveguides when group velocity dispersion is slightly anomalous because of large waveguide dispersion. In the frequency region of normal dispersion, we find that dark solitons can compensate the effect of dispersion for choice of parameters that can be implanted in real world applications. In the present paper, the propagation of optical pulses is modeled through the nonlinear Schrodinger equation. We numerically investigate the impact of slow light enhanced nonlinear absorptions on the propagation of bright and dark solitons in silicon-on insulator photonic crystal channel waveguides. Evolution of the solitonic pulses is quantified by the misfit parameter which is found to be comparable to the lowest misfits obtained. The possible propagation loss due to higher order dispersion and nonlinear effects is also investigated. The performance of dark and bright soliton based optical delay line is further demonstrated which may have major implication in realizing integrated optical buffers.

8998-11, Session 3

Image rotation and optical forces based on slow and fast light *(Invited Paper)*

Robert W. Boyd, Univ. of Ottawa (Canada)

No Abstract Available

8998-12, Session 3

Dual cavity superluminal laser for precision metrology

Joshua Yablon, Zifan Zhou, Shih Tseng, Devin Hilleman, Selim M. Shahriar, Northwestern Univ. (United States)

No Abstract Available

8998-13, Session 3

Dispersion amplification *(Invited Paper)*

John C. Howell, Univ. of Rochester (United States)

No Abstract Available

8998-14, Session 3

Investigation on gain tuning fast-light effect of optical waveguide gyroscope

Hao Zhang, Zhisong Xiao, BeiHang Univ. (China)

Abstract:

Since large optical loss deteriorates the properties of passive optical ring resonator, a configuration of active gain ring resonator made of Er^{3+}:Yb^{3+} co-doped phosphate glass side-coupled to two straight passive optical waveguide is proposed in this paper. The active gain ring resonator made of Er^{3+}:Yb^{3+} co-doped in phosphate not only compensate the loss in the resonator but also control the structure in the fast light regime in which the group velocity of light is fast than that in vacuum or negative. The gain coefficient below the threshold of laser oscillation is tuned by the erbium and ytterbium concentration and pumping power at 980 nm through numerically rate equations and propagation equations. Theoretical analysis indicated that gain coefficient would control the dispersion relationship and the fast light introduced by anomalous dispersion can be produced to enhance the sensitivity of the ring resonator optical gyroscope at the same time with the optimized parameters such as the radius of the resonator, the coupled coefficient between resonator and straight optical waveguide, and the bias phase. We also compared and discussed the two situations: active gain ring resonator side-coupled to two straight passive waveguide and side-coupled to two straight active waveguide, which correspond to two different production processes. It implied that this configuration we proposed is potential for developing of high sensitivity integrated optical waveguide gyroscope.

8998-15, Session 3

Optimization of CROW gyroscopes *(Invited Paper)*

Michel J. F. Digonnet, Kiarash Zamani Aghaie, Stanford Univ. (United States)

No Abstract Available

8998-16, Session 4

Multimode quantum state tomography of slow light in rubidium vapor *(Invited Paper)*

Andrew M. Dawes, Pacific Univ. (United States)

No Abstract Available

8998-17, Session 4

Quantum noise limits in fast-light-enhanced gravitational wave detectors

Minchuan Zhou, Northwestern Univ. (United States); Jacob Scheuer, Tel Aviv Univ. (Israel); Joshua Yablon, Selim M. Shahriar, Northwestern Univ. (United States)

No Abstract Available

8998-18, Session 4

Quantum memories for light based on Raman scattering: noise and efficiency *(Invited Paper)*

Joshua Nunn, Univ. of Oxford (United Kingdom)

No Abstract Available

8998-19, Session 4

Quantum mutual information of an entangled state propagating through slow- and fast-light media *(Invited Paper)*

Ryan T. Glasser, Jeremy B. Clark, National Institute of Standards and Technology (United States); Quentin Glorieux, Universite Pierre et Marie Curie, Laboratoire Kastler Brossel (France); Ulrich Vogl, Max Planck Institute for the Science of Light (Germany); Paul D. Lett, National Institute of Standards and Technology (United States)

No Abstract Available

8998-20, Session 5

A comparison of different slow-light schemes *(Invited Paper)*

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

No Abstract Available

8998-21, Session 5

Ultraslow light in a hot Rubidium vapor using an indpendent control light *(Invited Paper)*

Byoung Seung Ham, Gwangju Institute of Science and Technology (Korea, Republic of)

No Abstract Available

8998-22, Session 5

Theoretical modeling of a DPAL-based superluminal laser and comparison with experiment

Zifan Zhou, Joshua Yablon, Ye Wang, Devin Hilleman, Shih Tseng, Selim M. Shahriar, Northwestern Univ. (United States)

No Abstract Available

8998-23, Session 5

Rb in photonic bandgap fibers *(Invited Paper)*

Alexander L. Gaeta, Cornell Univ. (United States)

No Abstract Available

8998-24, Session 5

Slow and fast light in a phase sensitive system *(Invited Paper)*

Yanhong Xiao, Fudan Univ. (China)

No Abstract Available

8998-25, Session 6

Detection of rotation using slow light with angular momentum *(Invited Paper)*

Yuri Rostovtsev, Univ. of North Texas (United States)

No Abstract Available

8998-26, Session 6

An eye-like ring resonator for highly-sensitive temperature sensing

Yundong Zhang, XiaoQi Liu, Xuenan Zhang, Ping Yuan, Harbin Institute of Technology (China)

We propose an “eye-like” ring resonator structure for highly sensitive temperature sensing. The output intensities of the proposed structure exhibit sharp asymmetric Fano-resonance line shapes around the resonance wavelength. The asymmetric Fano-resonance line shapes of the proposed structure is generated by adding a ring inside and coupling with the outer ring in a point-to-point manner to produce a nonlinear phase shift. Compared to the conventional single ring add-drop filter structure, the sensitivity of the proposed configuration is enhanced by 3 times. Utilizing the intensity interrogation, we analyze the effect of parameters on the sensitivity and the detection limit. This proposed structure enables highly sensitive, compact and stable temperature sensors.

8998-27, Session 6

Fast-light enhancement by polarization mode coupling in a single optical cavity *(Invited Paper)*

David D. Smith, NASA Marshall Space Flight Ctr. (United States); H. Chang, Ducommun Miltec (United States); Krishna Myneni, U.S. Army RDECOM (United States); Albert T. Rosenberger, Oklahoma State University (United States)

No Abstract Available

8998-28, Session 6

Superluninal laser using dual peak Raman gain

Ye Wang, Zifan Zhou, Joshua Yablon, Shih Tseng, Selim M. Shahriar, Northwestern Univ. (United States)

No Abstract Available

8998-29, Session 6

Interferometric measurements by using slow light in liquid crystal media *(Invited Paper)*

Stefania Residori, Umberto Bortolozzo, Institut Non Linéaire de Nice Sophia Antipolis (France); Jean-Pierre Huignard, jphopto (France)

No Abstract Available

8998-30, Session 7

Superluminal propagation and signal conversion via stimulated Brillouin scattering in optical fibers *(Invited Paper)*

Li Zhan, Shanghai Jiao Tong Univ. (China)

No Abstract Available

8998-31, Session 7

Variable delay of Gbit/s data using coded Brillouin dynamic gratings *(Invited Paper)*

Yair Antman, Avinoam Zadok, Bar-Ilan Univ. (Israel); Lior Yaron, Tomi Langer, Moshe Tur, Tel Aviv Univ. (Israel)

No Abstract Available

8998-32, Session 7

Broadening free SBS-based slow and fast light in optical fibers *(Invited Paper)*

Thomas Schneider, Andrzej Wiatrek, Hochschule für Telekommunikation Leipzig (Germany)

No Abstract Available

8998-33, Session 7

Slowing light with acoustic phonons in silicon photonics *(Invited Paper)*

Zheng Wang, The Univ. of Texas at Austin (United States)

No Abstract Available

8998-34, Session 8

Quantum-enhanced measurements with atomic vapor *(Invited Paper)*

Eugeniy E Mikhailov, The College of William & Mary (United States)

No Abstract Available

8998-35, Session 8

Observation of robustness in topological edge states of light *(Invited Paper)*

Mohammad Hafezi, Joint Quantum Institute (United States)

No Abstract Available

8998-36, Session 8

Electrically-tuned quantum light generation in silicon photonics: the role of slow light *(Invited Paper)*

Shayan Mookherjea, Univ. of California, San Diego (United States)

No Abstract Available

8998-37, Session 8

Highly-efficient photon-atom quantum interface based on electromagnetically-induced transparency *(Invited Paper)*

Shengwang Du, Hong Kong Univ. of Science and Technology (Hong Kong, China)

No Abstract Available

8998-38, Session 9

Effects of polarization mode coupling and superposition in a whispering-gallery microresonator *(Invited Paper)*

Albert T Rosenberger, Oklahoma State Univ. (United States)

No Abstract Available

8998-39, Session 9

Observation of EIT-like spectrum in the nested fiber ring resonator

Yundong Zhang, Changqiu Yu, Kaiyang Wang, Ping Yuan, Harbin Institute of Technology (China)

We demonstrate the electromagnetically induced transparency like spectrum in the nested fiber ring resonator with the transfer matrix theory, the system consists of two rings and two waveguides and four couplers which connected the two rings and two waveguides. The simulation results show that the tunable group delay can be realized by changing the coupling coefficients. At transmission window, the transmittance can achieve approximately 94% with the 1.12ns group delay. Through tuning the coupling coefficients, the group delay can vary from 1.12ns to 14.6ns and the bandwidth of the transparency window can vary from 124MHz to 66MHz.The ability for realizing such transparency resonance and for controlling the group delay or the bandwidth of such resonance is important for applications such as tunable bandwidth filter, as well as for switching and optical routing applications.

8998-40, Session 9

Slow light in high-contrast grating hollow-core waveguide *(Invited Paper)*

Tianbo Sun, Weijian Yang, Univ. of California, Berkeley (United States); Weimin Zhou, U.S. Army Research Lab. (United States); Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

No Abstract Available

8998-41, Session 9

Ultra-fast repeated frequency conversion of light trapped in a microcavity

Emre Yüce, Georgios Ctistis, Univ. Twente (Netherlands); Julien Claudon, Emmanuel Dupuy, Commissariat à l'Énergie Atomique (France); Allard P. Mosk, Univ. Twente (Netherlands); Jean-Michel Gérard, Commissariat à l'Énergie Atomique (France); Willem L. Vos, Univ. Twente (Netherlands)

Manipulating nanophotonic structures such as photonic crystals and cavities in time enables to trap or release [1,2], slow-down [3], phase and amplitude modulate light signals that is confined on-chip [4]. In particular, the phase modulation of light leads to a change of the frequency of light [5]. Previously, the color of light has been changed on demand inside microcavities within 70 to 300 ps by inducing a refractive index change via the excitation of free carriers [1,5].

Here, we investigate and demonstrate how light trapped in an ultra-fast switched microcavity is frequency shifted either to red or blue. To this end we switch the cavity via the electronic Kerr effect on femtosecond time scales while avoiding absorption and carriers. Each time a pump pulse hits the cavity we observe reversible switching of the cavity resonance frequency. Consequently, we observe color-change of the trapped probe light as a result of the ultrafast phase modulated probe light due to refractive index change. The light trapped in the cavity is frequency shifted to frequencies that are not resonant with the cavity. Hence this frequency change is not-adiabatic and not limited. We investigate repeated frequency conversion by shining pump pulses separated by less than 1 ps on the cavity. We generate both blue- and red-shifted pulses at THz repetition rates due to the repeated switching of the cavity [6]. Our results offer novel opportunities for fundamental studies of frequency conversion in cavity QED and in optical information processing.

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control of light on a silicon chip," Nature 431, 1081 (2004).

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8998-42, Session 9

Management of slow light dispersion in complex microresonator devices *(Invited Paper)*

Misha Sumetsky, Aston Institute for Photonics Technologies (United Kingdom)

No Abstract Available

8998-43, Session 10

Experimental observations of the transition from fast light to slow light in a side-coupled ring resonator *(Invited Paper)*

Yundong Zhang, Xuenan Zhang, Xiaoqi Liu, Kaiyang Wang, Ping Yuan, Harbin Institute of Technology (China)

No Abstract Available

8998-44, Session 10

Dynamical behave of optomechanical-induced transparency in a silica microresonator

Chunhua Dong, Chang-Ling Zou, Guang-Can Guo, Univ. of Science and Technology of China (China)

For the transient OMIT experiment, optical fields in a whispering gallery mode (WGM) of a silica microsphere with diameter around 200 micron were coupled to the Brillouin mechiancal modes of the microsphere. The WGM was excited through the evanescent field of a tapered single mode fiber. A strong driving optical laser pulse tuned to a red transition of a micro-optomechanical system leads to destructive interference for the excitation of an intracavity signal field, inducing a tunable transparency window for the probe beam. The light storage is achieved using a readout pulse at red transition with 3 microsecond delay after the driving pulse. The time-gated heterodyne detection was used to measure the temporary OMIT spectra which shown the OMIT process evolved toward the steady state. And the transient OMIT behaviors observed are in good agreement with theoretical calculations based on the coupled-oscillator model. Specifically, the characteristic time scale for establishing the OMIT process is determined by the optomechanical cooperativity as well as the mechanical damping rate. The coherent interconversion

accelerates with increasing optomechanical coupling rates, providing an effective mechanism for tailoring the temporal profile of the retrieved pulse in a mechanical oscillator. Experimental studies on both OMIT and light storage under nearly the same conditions also illustrate the connections between these two closely related processes.

8998-45, Session 10

Slow-light optical amplifiers: opportunities and fundamental limitations *(Invited Paper)*

Per Lunnemann Hansen, Jesper Mørk, Technical Univ. of Denmark (Denmark)

No Abstract Available

8998-46, Session 10

Perfect absorption and reflection in slow-light waveguides *(Invited Paper)*

Andrey A. Sukhorukov, The Australian National Univ. (Australia); Nadav Gutman, Y. D. Chong, C. Martijn de Sterke, The Univ. of Sydney (Australia)

No Abstract Available

8998-47, Session 11

2D and WDM correlators using tunable optical delays *(Invited Paper)*

Alan E. Willner, The Univ. of Southern California (United States)

No Abstract Available

8998-48, Session 11

Coupled microrings data buffer using fast light *(Invited Paper)*

Jacob Scheuer, Tel Aviv Univ. (Israel); Selim M. Shahriar, Northwestern Univ. (United States)

No Abstract Available

8998-49, Session 11

Slow light and optical information processing due to an intramolecular coherence

Igor V. Melnikov, Svetlana V. Nazarenko, Anastasia A. Vinogradova, Georgy L. Alfimov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

In the past two decades there has been a great deal of interest in the study of both Bragg and Laue diffraction of optical spatial solitons. There are a diversity of fascinating phenomena pertinent to photonic-crystal 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 1D Laue-type photonic crystals show different linear properties like anomalous diffraction when compared to continuous media, in the nonlinear regime these have shown analogous behavior where the self- and cross-phase modulation interactions allows the formation of discrete optical solitons. The dynamics of these crystals has been modeled by the discrete nonlinear Schrödinger equation (DNLSE), which reduce the bangap structure into a system of individual waveguides coupled with adjacent waveguides as a set of ordinary differential equations.

In a nonlinear photonic crystal, the high degree of light localization can enhance the nonlinear optical processes and for instance, Raman-type nonlinearity can provide an effective tool for exploiting nonlinear interactions in switching devices. These predictions have been experimentally verified in nonlinear photonic crystals based on AlGaAs and LiNbO3, demonstrating soliton interactions such as time-gating, blocking, routing, and other logic functions due to the cubic nonlinearity.

The monoclinic optical crystal KGW offer a high n2 nonlinear coefficient with low two photon absorption. Besides, KGW is a highly Raman-active crystal, with prominent Stokes vectors at 768 cm-1 and 901 cm-1 which are ideal for wavelength conversion from 1.3 ?m to the 1.5 ?m telecommunications band. The KGW crystal has a short Raman relaxation time T2 making it ideal for short picosecond Raman lasers. When using a material such as KGW for waveguide arrays, the presence of a Raman term in the Maxwell-Bloch equations offers a method of light storage due to the low-frequency, intramolecular coherence that, in turn, is able to couple the fundamental beam and a Stokes-shifted wavelength. Planar waveguides have been fabricated in KGW using both light ion and swift-heavy ion irradiation techniques, and show excellent promise for the fabrication of waveguide arrays with strongly preserved nonlinear properties in the guiding region.

In this report we propose, to our best knowledge for the first time, to employ the Raman nonlinearity that also may be combined with the Kerr effect for Raman soliton localization in both 1- and 2D photonic crystals. We present numerical modeling of coherent- and non-coherent interactions in a nonlinear, Raman-active material, such as potassium gadolinium tungstate KGd(WO4)2 (KGW), illustrating the storage, blocking, switching, and retrival for a set of wavelengths. With the availability of new highly nonlinear and Raman efficient materials such as KGW, as well as new techniques in creating photonic crystals with these materials, there is much promise shown for applications of all optical and logic functionality.

8998-50, Session 11

Photonic crystal slow-light waveguides: useful disorder and applications in integrated quantum circuits *(Invited Paper)*

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

No Abstract Available

8998-51, Session 11

Resonant four-wave mixing in a ring cavity

Gleb Romanov, Eugeniy E Mikhailov, Irina Novikova, The College of William & Mary (United States)

No Abstract Available

8998-52, Session 12

Rotational sensitivity enhancement in a ring laser gyroscope using Raman gain *(Invited Paper)*

Sean M. Spillane, Los Gatos Research, Inc. (United States); Selim M. Shahriar, Northwestern Univ. (United States)

No Abstract Available

8998-53, Session 12

Optical loss effect on fast-light enhanced integrated on-chip laser gyroscope based on slot-waveguide structure

Long Zhao, Zhisong Xiao, BeiHang Univ. (China)

We propose a configuration of fast-light enhanced integrated gyroscope consisting of several passive ring resonators to achieve high absolute rotational sensitivity. In this paper, the slot-waveguide passive resonators are introduced to improve the system performance since the high capability of light strong confinement and integration. Importantly, to achieve same enhancement factor, the low-refractive-index waveguide can effectively decrease the optical path such as the number of passive resonators, and promote the structure working on the fast-light enhanced area after theoretical calculation. On the other hand, Optical loss effect on this slot-waveguide structure as well as sensitivity enhancement factor are thoroughly discussed, which manifests that, in lossless condition, the more passive rings the higher rotational sensitivity in structure can be achieved while working on fast-light area. However, in practical condition which loss has actually impacted the whole structure performance, that the enhancement factor can be increased when the propagation loss is lower than the threshold that depends on size, through coefficient, etc. Therefore, the low-loss slot waveguide has great potential to improve system sensitivity and realize highly integrated on-chip structure. The number of resonators is optimized to achieve best performance on rotational sensitivity. Actually, this enhancement means smaller occupied area and high efficiency of limited area to realize integrated. The fast-light enhanced gyroscope showed here will have broad prospect in highly integrated on-chip applications, especially aeronautic and astronautic area.

8998-54, Session 12

Theoretical design of a superlumianl ring laser gyroscope using novel coupled passive resonators *(Invited Paper)*

Tianliang Qu, National Univ. of Defense Technology (China)

No Abstract Available

8998-55, Session 12

A subluminal ring laser: modeling, stability, and applications

Zifan Zhou, Joshua Yablon, Minchuan Zhou, Selim M. Shahriar, Northwestern Univ. (United States)

No Abstract Available

8998-56, Session 12

Performance assessment of a solid-state ring laser gyro *(Invited Paper)*

Sylvain Schwartz, Gilles A. Feugnet, François Gutty, Jean-Paul Pocholle, Thales Research & Technology (France); Thomas Lauprêtre, Univ. Paris Sud 11 (France); Fabienne Goldfarb, Fabien Bretenaker, Lab. Aimé Cotton (France); Rupamanjari Ghosh, Jawaharlal Nehru Univ. (India); Iacopo Carusotto, Univ. degli Studi di Trento (Italy)

No Abstract Available

8998-57, Session 13

Investigations of AC stark shift in pulsed Raman-Ramsey interaction for vapor-cell clock development *(Invited Paper)*

Gour S. Pati, Delaware State Univ. (United States)

No Abstract Available

8998-58, Session 13

Resonance fluorescence from a single atom and slow light *(Invited Paper)*

Frank A. Narducci, Naval Air Systems Command (United States); Jon P. Davis, Naval Air Warfare Ctr. Aircraft Div. (United States)

No Abstract Available

8998-59, Session 13

Atomic polarization decoherence of Zeeman levels in rubidium filled hollow-core photonic crystal fiber *(Invited Paper)*

Fetah A. Benabid, Univ. of Bath (United Kingdom); Ekaterina Ilinova, XLIM Institut de Recherche (France)

No Abstract Available

8998-60, Session 13

Electromagnetically-induced transparency with diamond photonic devices *(Invited Paper)*

Victor M. Acosta, Hewlett-Packard Labs. (United States)

No Abstract Available

8998-61, Session 13

High-storage efficiency EIT-based optical memory *(Invited Paper)*

Yi-Hsin Chen, Meng-Jung Lee, I-Chung Wang, National Tsing Hua Univ. (Taiwan); Shengwang Du, The Hong Kong University of Science and Technology (Hong Kong, China); Yong-Fan Chen, National Cheng Kung University (Taiwan); Ying-Cheng Chen, Institute of Atomic and Molecular Sciences, Academia Sinica (Taiwan); Ite A Yu, National Tsing Hua Univ. (Taiwan)

No Abstract Available

8999-1, Session 1

Optical action at mesoscales *(Invited Paper)*

Aristide C. Dogariu, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

The interaction between light and complex material systems can be controlled by manipulating the coherence and polarization properties of electromagnetic fields. Harnessing light at scales comparable with the wavelength offers distinctive possibilities not only for sensing material or radiation properties [1-3] but also for controlling the mechanical action induced by light [4-6]. At such dimensions, photonic phenomena include scale-specific modifications of the structure so that a passive interpretation of the reciprocal action is inadequate and a description including dynamics of the light-medium interaction is necessary [7]. We will review both passive and active applications where the continuous reconfiguration of the electromagnetic field in space and time leads to unique nonequilibrium dynamics.

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8999-2, Session 1

Negative optical radiation forces and singular optics

Davit Hakobyan, Etienne Brasselet, Univ. Bordeaux 1 (France)

Optical forces and torques are two available mechanical spatial degrees of freedom to manipulate matter with light, on which rely optical tweezing strategies. In contrast to the Keplerian intuition that objects should be pushed downstream an incident photon flux, the concept of so-called negative optical forces has been recently unveiled and triggered both fundamental and applicative research enthusiasm. Here we report on a counterintuitive negative complex optical forces spatial distribution when light-matter interaction takes place in presence of singularities, both for the light field and the material system. Such a negative optomechanical effect is experimentally retrieved and theoretically described. A quantitative agreement between experimental data and simulations is obtained. These results complete the state-of-the-art negative optomechanical toolbox and could promote a new era of optical micromanipulation.

8999-3, Session 1

Single-beam trapping using laser beams focused by low and high numerical apertures: angular spectrum approach

Martin Siler, Oto Brzobohat?, Petr Jákl, Vitezslav Karasek, Pavel Zemánek, Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic)

Generally, it is assumed that the single beam optical tweezers hold particles behind the focal plane due to the highly focused laser beam. However, even moderately focused beams may stably confine particles of high refractive index contrast and sizes up to half wavelength.

This is caused by the fact that the light structure near focus is complex even for such moderately focused beams.

The intensity profile consists of several axial oscillations as well as off-axis lobes or rings which enhance trapping.

Moreover, side lobes provide another multiple trapping sites for small sized particles.

The properties of these traps will be analyzed theoretically by means of Generalized Lorenz-Mie Scattering theory.

8999-4, Session 1

Near-field waveguide trapping and tracking of particles using fluorescence imaging

Balpreet S. Ahluwalia, Petter Brox, Øystein Helle, Jean-Claude Tinguely, Olav G. Hellesø, Univ. of Tromsø (Norway)

The evanescent field from an optical waveguide is used for near-field trapping and transporting of fluorescent microspheres. The waveguide trapping is combined with fluorescence imaging to track the particle in three-dimensions. A single laser (532 nm) can be used both to propel and to excite fluorescence via evanescent excitation. Alternatively, a separate laser (532 nm) from the top can be used for fluorescence in addition to the trapping beam (1070 nm). Out-of-focus images of the trapped particle are captured and analysed to find the radius of the outermost diffraction ring. A calibration is done to determine the relationship between the z-coordinate and this radius. The x and y coordinates are found by determining the centre of the fluorescent image. This gives a precise measurement of the position of the particle in three dimensions with nanometre precision (<100 nm). Movies of trapped particles are then recorded and analysed to find the position of a trapped particle with time. Results of trapping and tracking with different waveguide designs will be demonstrated, e.g. strip waveguides, rib waveguides and waveguide loop with a gap. The gap on the far side of a loop can be used to precisely trap a particle at a fixed position. A strip waveguide provides high field gradients sideways and thus tight optical trapping, whereas rib waveguide ease the requirement for single-mode condition and induces less propagation losses associated with the sidewall roughness. Optical waveguides are made of tantalum pentaoxide (Ta2O5) and fabrication steps are optimized to reduce propagation losses.

8999-5, Session 2

Attractive optical forces from blackbody radiation *(Invited Paper)*

Monika Ritsch-Marte, Matthias Sonnleitner, Innsbruck Medical Univ. (Austria); Helmut Ritsch, Univ. Innsbruck (Austria)

Optical traps utilize optical dipole forces: A spatially varying intensity translates into a spatially dependent AC Stark shift of the energy levels, and thus the atoms or molecules can minimize their energy by seeking out high-intensity regions such as the focus spot of an optical tweezers system. Typically coherent laser light is utilized to build the optical trap.

Here we demonstrate that under certain conditions incoherent broadband light may give rise to similar attractive optical forces that can overcome the repulsive radiation pressure forces. Specifically we have studied hydrogen atoms in the ground state that are exposed to the black-body radiation emitted from a spherical object at some distance. In analogy to laser trapping the forces originate from a spatial inhomogeneity in the intensity, in our case of the black-body radiation emitted from a finite-sized object. The effect is proportional to the fourth power of the temperature and induces a force decaying with the third power of the distance from the object. For ground state hydrogen atoms we find that it can surpass the repulsive radiation pressure and actually pull the atoms against the radiation energy flow towards the object's surface with a force stronger than gravity.

Radiation pressure forces are included in many astrophysics approaches modeling gas or dust clouds in the presence of radiation emanating from hot objects, but the dipole force seems to have always been discarded. Based on our findings we believe that the "black-body force" may turn out to be relevant in a variety of astrophysical scenarios studying the aggregation of matter.

8999-6, Session 2

Clustering of aerosols in a single potential-well trap

Jeremy Moore, Univ. of Michigan (United States); Leopoldo L. Martin, Univ. de La Laguna (Spain); Kyu Hyun Kim, Hengky Chandrahalim, Univ. of Michigan (United States); Matt Eichenfield, Sandia National Labs. (United States); Inocencio J. Martin, Univ. de La Laguna (Spain); Tal E. Carmon, Univ. of Michigan (United States)

Pioneering work in optical clustering [1] in air includes 1D clustering of aerosols in a trap where they cling slightly to interference fringes [2]. Here we investigate an optical trap that is much larger than the aerosol and contains a weak single local minimum in the trap potential in which multiple aerosols can cluster.

Our experimental setup consists of a 1.5µm laser coupled to a single-mode optical fiber as suggested in [1] for preventing transverse irregularities in the trap. The beam is weakly focused through a lens to create a vertical single potential-well trap. The trap contains no counter propagating beam, so that the trap has no fringes along the propagation direction. We suspend silica particles sized 2 to 25 microns. Clustering of several particles is photographed in 1D when the beam is narrow and in 3D clustering is observed when the trap is broad relative to the particle. Surprisingly, clustering is versatile as it occurs also when non-spherical particles that are formed from attached spheres are suspended from above and clustered in various configurations. While an extensive model can be employed [1] to explain this behavior, we briefly note that each sphere acts as a ball lens that focuses the light to facilitate trapping of an additional sphere.

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8999-7, Session 2

Optical binding in anisotropic colloids

Simon Hanna, Stephen H. Simpson, Univ. of Bristol (United Kingdom); Philip H. Jones, Univ. College London (United Kingdom); Onofrio M. Maragó, Istituto per i Processi Chimico-Fisici (Italy)

The optical binding forces and torques acting between anisotropic colloidal particles are examined theoretically. Previous work in this field has focused on binding between spherical particles. The geometric anisotropy of the particles adds a rotational dimension to the more conventionally considered systems of spheres. We will examine the equilibrium configurations of pairs of ellipsoidal particles, as a function of the aspect ratios and symmetries (uniaxial or biaxial) of the particles. The dynamical behavior of sets of spheroidal particles will also be investigated, demonstrating the formation of aligned chains along which rotational and translational disturbances are able to propagate. Comparisons will be drawn with recent experimental results and the potential for self organization of novel structures will be discussed.

8999-8, Session 2

Optical trapping of non-spherical plasmonic nanoparticles

Oto Brzobohat?, Martin Siler, Lukas Chvatal, Vitezslav Karasek, Pavel Zemánek, Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic)

Laser manipulation with plasmonic nano-particles is a rapidly growing field with various practical applications stretching beyond physics towards biology and chemistry. For example gold nano-particles can be employed as local heat source, probes for surface enhanced Raman spectroscopy with a sensitivity going down to a single molecule or contact-less probe in scanning near-field optical microscope. A single tightly focused laser beam – optical tweezers – was also employed to three-dimensional trapping of gold and silver nano-particles with diameters between 20 to 250 nm. However, theoretical models assuming the spherical shape of a nano-particle predict spatial confinement only for particles with diameter lower than 100 nm. Our results indicate this discrepancy is caused by ignoring particles shape which is very important for understanding of light-matter interaction.

8999-9, Session 2

Highly-focused structured light beams for optical trapping

Alexander B. Stilgoe, Daryl C. Preece, Timo A. Nieminen, Halina H. Rubinsztein-Dunlop, The Univ. of Queensland (Australia)

Structured light fields under high-numerical aperture optics can be used to organise particles into arrays and functional solids. These light fields are often constructed out of beam modes in the paraxial regime. Paraxial beam modes have a simple representation and can readily be transformed between different bases. Once paraxial modes enter a high-numerical aperture system vector effects absent from the paraxial formulation, such as the axial-component of the electric field or radial and azimuthal polarisations begin to play a part and the relevant physics changes. Using the known relationships between the Laguerre—Gauss, Hermite—Gauss, and Ince—Gauss modes we relate the three bases to the vector spherical harmonic symmetries. We look at how the resulting full wave modes differ under a high-numerical aperture system including how well the resulting fields obey the Gouy phase shift. We calculate the optical forces in such beams in order to investigate the localization of trapped particles within the pattern produced by the beam. Possible applications include particle sorting and structural formation of functional solids in optical tweezers. We investigate both beam-like (self-Fourier, so shape-preserving) modes and non-beam-like (not self-Fourier) modes.

8999-10, Session 3

Angular momentum radio *(Invited Paper)*

Bo Thidé, Swedish Institute of Space Physics (Sweden) and Scuola Galileiana di Studi Superiori, University of Padua (Italy)

Hithtero, radio communication applications have almost exclusively been based on the manipulation of translational electromagnetic (EM) degrees of freedom, typically one-dimensional oscillating currents along linear antenna elements, and the pertinent EM fields. Physically, these translational processes are described in terms of the mechanical linear momentum carried by the particles and the inherently single-state linear momentum carried by the associated EM field. In recent wireless communication experiments at optical frequencies it has been demonstrated that the utilization of the inherently multi-state EM angular momentum describing the rotational EM degrees of freedom makes it possible to enhance the spectral density over and above what is possible with linear momentum methods.

We present the fundamental properties of the EM angular momentum physical layer that make it possible to enhance the spectral capacity of a radio communication link with one single transmitting and one single receiving monolithic antenna over and above what is possible with linear momentum single-antenna links. We also describe how the angular momentum link capacity can be further enhanced by the use of multiple transmitting and receiving antennas and make a comparison with systems that use multiple linear momentum antennas, also known as multiple-input-multiple-output (MIMO) systems.

8999-11, Session 3

Generation, manipulation, and applications of Airy plasmons *(Invited Paper)*

Dragomir N. Neshev, The Australian National Univ. (Australia)

Airy waves enchant observers by their unusual properties resembling a magic trick: a beam bending in a homogeneous space without presence of any force. Importantly, in a planar system, the Airy function is the only nondiffracting self-accelerating solution in the paraxial approximation [1]. As such, Airy plasmons demonstrate many remarkable properties: they do not diffract while propagating along parabolic trajectories, and they recover their shape after passing through obstacles. However, even for the near-infrared-frequency range, the propagation length of Airy plasmons at a gold–air interface is only a few tens of microns, due to the strong losses in metal. The short propagation of the plasmons presents a significant challenge for the observation and the implementation of Airy plasmon beams. It means that high beam acceleration is required to achieve both significant curvature over the propagation length and strong confinement to the metal interface.

Nevertheless, experimental demonstrations of Airy plasmons utilizing different excitation methods were presented almost simultaneously by three different research groups [2-4]. This talk reviews the basic physics of Airy plasmons and describes the experimental methods for their generation on plane metal surfaces. Furthermore we present our results on the control of the Airy plasmon trajectories, as well as the interference of two Airy plasmons and hot-spot generation. Finally, we will discuss many useful applications utilizing the unusual properties of Airy plasmons, including plasmonic circuitry and surface particle manipulation.

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8999-12, Session 3

Tuning vector vortex in spatially coherent supercontinuum multicolored optical beam using q-plate

Yisa Rumala Jr., Sebastião Pratavieira, Giovanni Milione, Thien An Nguyen, Zabir Hossain, The City Univ. of New York (United States); Daniel A. Nolan, Corning Incorporated (United States); Ebrahim Karimi, Sergei Slussarenko, Lorenzo Marrucci, Univ. degli Studi di Napoli Federico II (Italy); Robert R. Alfano, The City Univ. of New York (United States)

Spatially coherent vector beams consisting of multiple colors are generated using a photonic crystal fiber supercontinuum light source and tunable liquid crystal q-plate. The polarization topology of the multicolored beam is mapped, and the feasibility of the device as an optical spectral filter is demonstrated through detailed analysis of multicolored optical mode. A hybrid mode-wavelength division multiplexer (HMWDM) scheme is proposed. In this scheme, information is encoded in the wavelength of light, and the spatial mode and polarization modulation about optical mode is used to turn on and off different frequency channels, i.e. an optical switch. Potential applications include device multiplexing for broadband high speed optical communication, ultradense data networking, and super resolution microscopy.

8999-13, Session 3

Unveiling orbital angular momentum of light of order up to twenty through diffraction by a square aperture

Alcenisio J. de Jesus Silva, Univ Federal de Alagoas (Brazil); Juarez G. Silva, Univ. Federal de Alagoas (Brazil); Márcio A. R. C. Alencar, Univ. Federal de Sergipe (Brazil); Jandir M. Hickmann, Univ. Federal do Rio Grande do Sul (Brazil) and Univ. Federal de Sergipe (Brazil); Eduardo J. da Silva Fonseca, Univ. Federal de Alagoas (Brazil)

In the diffraction of light with orbital angular momentum by a square aperture a perfect square optical intensity lattice takes place only for even values of the topological charge. In this letter, despite of this fact, we showed that in the Fraunhofer plane, the number of intensity maxima in the side of the square pattern could give us the topological charge modulus of a light beam. Surprising, the square aperture outperforms the triangular aperture for more than two times the maximum value measured in the triangular aperture. We present measurements, computer simulations, and a heuristic argument that explains the observations. A square pattern cannot be used to determine the topological charge sign. However, we showed that it is possible to measure modulus and sign for even and odd topological charges combining patterns of the triangular and square apertures. Finally, we explained this behavior using properties of the pattern from each aperture. When we increase the TC from m=10 to m=20, the phase along the slit evolves from being approximately linear with increasing inclination to being nonlinear. This effect will distort the single slit pattern shift associated with each aperture side. However, it affect much more the triangular slit than the square slit, due to two main reasons. First, the side of the triangular Fraunhofer diffraction pattern is 40% bigger than the side of the square Fraunhofer diffraction pattern. Second, roughly there is, two times more points in the side of the triangular diffraction pattern than in the side of the square diffraction pattern. This was used to explain the persistent truncation in the Fraunhofer diffraction patterns of orbital angular momentum beams by a square aperture.

8999-14, Session 3

Short-link capacity increase powered by the orbital angular momentum of light

Mario A. Usuga Castaneda, Idelfonso Tafur-Monroy, DTU Fotonik (Denmark)

No Abstract Available

8999-15, Session 3

Propagation and wavefront ambiguity of linear nondiffracting beams

Rüdiger Grunwald, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Martin Bock, Max-Born-Institute for Nonlinear Optics and Short-Pulse Spectroscopy (Germany)

Nondiffracting waves are stationary solutions of wave equations for electromagnetic waves (Helmholtz equation, Maxwell's equations) and the quantum mechanical wave function. A well-known kind of localized beam is the Bessel beam. Ultrashort-pulsed Airy beams with curved trajectories gain much attention and are interpreted as linear light bullets. Common to all nondiffracting pulsed wave fields is the presence of a broad frequency spectrum and a conical angular distribution resulting in characteristic spatio-temporal interference patterns. Usually, the appearance of interconnected intensity profiles is considered as a "propagation" and Bessel or Airy beams are thought to "propagate" between distant coordinates. A more detailed analysis, however, shows that this picture does not go far enough. The situation becomes clear if the angular spectrum is represented by rays or Poynting vectors. Nondiffracting beams are caustics of ray bundles ("straight world lines" in the quantum mechanical case discussed by Berry and Balazs in 1979). This picture is even applicable to Bessel beams which at each plane are generated from rays originating from different annular zones on an axicon. Their angular spectra form intensity rings in the far-field. Shack-Hartmann sensors decompose the field into Poynting vectors and show that the local wavefront is ambiguous (all points crossed by rays propagating in different directions). Therefore, energy flux related concepts are not appropriate to completely describe all aspects of propagation and wavefront. For particular applications like optical communication or spectroscopy, alternative descriptions are required. Here, an approach based on information transport and Fourier domain analysis is proposed.

8999-16, Session 4

From q-plates to the photonic gear: tailoring the rotational properties of light *(Invited Paper)*

Lorenzo Marrucci, Univ. degli Studi di Napoli Federico II (Italy); Fabio Sciarrino, Univ. degli Studi di Roma La Sapienza (Italy)

The rotational properties of a light beam are controlled by its spin and orbital angular momentum (SAM and OAM). The q-plate, a liquid crystal device that can give rise to a coupling of these two quantities, was introduced a few years ago, leading to several applications in classical and quantum photonics.

Very recently, in particular, a specific kind of q-plate was used to generate rotational-invariant states of single photons, that were then employed for performing a demonstration of quantum key distribution without the need for establishing a common reference frame between the transmitting and the receiving units. This result may find applications in future satellite-based quantum communication.

By a similar approach, photonic states having a strongly enhanced rotational sensitivity, as opposed to rotational invariance, can be generated by using q-plates with very high topological charge. Photons in these states can be obtained starting from light having a uniform linear polarization and, after a physical rotation, can be then converted back into light having uniformly linear polarization. As a result, one obtains linearly polarized light whose polarization plane rotates by an angle that is proportional to the angle of physical rotation between the generation and detection stages, with a very large proportionality constant. This effect of rotational amplification, which we named "photonic gear", leads to a sort of "super-resolved Malus' law", potentially useful for measuring mechanical angles with very high precision.

8999-17, Session 4

Mapping of all polarization-singularity C-point morphologies

Enrique J. Galvez, Xinru Cheng, Kory Beach, Colgate Univ. (United States)

We present a study of polarization singularities that appear in optical beams in non-separable superpositions of polarization and spatial modes. In particular, we present our recent mapping of all types of C-points, which include monstars. We found that all the morphologies of C-points can be represented by points on a sphere, as specified by two angles. The C-point sphere contained three regions of specifying the three morphologies: lemon, monstar and star. The advantage of this representation is that it is amenable to be verified by direct laboratory implementation: the poles of the sphere are the symmetric forms of the lemon and the star, and all other points of the sphere, except for the equator, correspond to asymmetric C-points. Points along the equator contain the modes that have shear singularities, with their own morphology. Represented this way, any morphology represented by a point on the sphere could be specified as a superposition of two morphologies that are antipodes on the sphere, in analogy to the Poincare' sphere.

In the laboratory we prepared beams with any desired morphology via superpositions of Laguerre-Gauss (LG) beams with topological charges of +1 and -1, in the state of right circular polarization, with a fundamental Gaussian beam in the state of left circular polarization. The weighting of the two LG modes specified the latitude on the sphere, and their relative phase specified the longitude. We used a spatial light modulator to encode the spatial modes, and imaging polarimetry to diagnose them. The experimental results are in agreement with the theory. We found that specific morphologies were very sensitive to experimental parameters, such as relative phases and beam overlap.

8999-18, Session 4

Vector light beams propagation and scattering in turbid medium

Igor V. Meglinski, Alexander Doronin, Univ. of Otago (New Zealand); Giovanni Milione, Robert R. Alfano, The City College of New York (United States)

Recently, due to its high sensitivity to subtle alterations in medium morphology the vector light beams have gained much attention in the area of photonics. This leads to development of a new free space communication methods and non-invasive optical technique for tissue diagnostics. Conceptual design of the particular experimental systems requires careful selection of various technical parameters, including beam structure, polarization, coherence, wavelength of incident optical radiation, as well as an estimation of how the spatial and temporal structural alterations in free space in clouds and fog and biological tissues can be distinguished by variations of these parameters. Therefore, an accurate description of vector light beams propagation within turbid and tissue-like media is required. To simulate and mimic the propagation of vector light beams within the turbid scattering media a stochastic Monte Carlo (MC) technique is developed. In current report, the use of vector light beams for polarization based optical biopsy as well as fog is discussed. The results of MC simulation of vector light beams propagating and undergoing anisotropic scattering in turbid media are presented including a comparison with plane wave light beams. Additionally, several physical phenomena associated with the anisotropic scattering of vector light beams in turbid media are discussed including the mutual influence of light's polarization and its trajectory, i.e. the spin-orbit interaction of light, and the conservation of light's spin and orbital angular momentum.

8999-19, Session 4

Generating and measuring non-diffracting vector Bessel beams

Angela Dudley, CSIR National Laser Ctr (South Africa); Yanming Li, North Carolina State Univ. (United States); Thandeka I. Mhlanga, CSIR National Laser Ctr. (South Africa); Michael J. Escuti, North Carolina State Univ. (United States); Andrew Forbes, CSIR National Laser Ctr. (South Africa)

We demonstrate how to create non-diffracting vector Bessel beams by implementing a spatial light modulator (SLM) to generate scalar Bessel beams which are then converted into vector fields by the use of an azimuthally-varying birefringent plate, known as a q-plate. The orbital angular momentum (OAM) of these generated beams is measured by performing a modal decomposition on each of the beam's polarization components. This is achieved by separating the circular polarization components through a polarization grating (PG) before performing the modal decomposition. We investigate both single charged Bessel beams as well as superpositions and the results are in good agreement with theory.

8999-20, Session 5

Field tracing for simulation of locally-polarized light fields and fs pulses *(Invited Paper)*

Frank Wyrowski, Friedrich-Schiller-Univ. Jena (Germany)

In field tracing electromagnetic fields are traced through optical systems. That allows to overcome limitations of ray tracing in source modeling, physical accuracy of light propagation and definition of detector functions. In the talk we present a brief introduction to field tracing. The electromagnetic field representation enables the investigation of complex light fields. We will demonstrate that for two examples: (1) The effect of field propagation and interference on the local state of polarization is considered in different simulations. (2) Field tracing allows fs pulse simulation. This is demonstrated for spatiotemporal pulse shaping (SSTF).

8999-21, Session 5

Topological aspects of polarization structured beams

Nirmal K. Viswanathan, Vijay Kumar, Univ. of Hyderabad (India)

Topological structures are universal and can provide quantitative measure of the physically observable quantities independent of the system. The fundamental generic topological structures of a tensor field are lemon, star and monstar with half-integer index (+/- 1/2) and are spiral, node and saddle with integer index (+/- 1) for a vector field. In optics both these topological structures can be realized in the same system via phase and polarization engineering. For example, superposition of orthogonal circular polarized plane and helical waves give rise to half-integer topologies of tensor field corresponding to polarization ellipse orientation and integer-index topologies of Poynting vector field.

Controllable realization of Poynting vector and angular momentum densities is a challenging problem of recent interest. Polarization-engineered light beams offer one possible solution to this problem as the half- and integer-index topological structures are interconnected and one can influence the other. Paraxial Poynting vector density can be decomposed into orbital and spin densities. The orbital density is directly proportional to the product of intensity and phase gradient whereas the spin density is directly proportional to the spin gradient. In polarization-engineered beams or vector-vortex beams the phase as such has no meaning; therefore the Poynting vector can be expressed in terms of component phases. Via controllable movement of component vortices to the desired beam intensity position we can control the Poynting vector density and consequently the angular momentum density. We demonstrate that polarization structured light beams can be an effective method for controllable realization of tunable angular momentum density.

8999-22, Session 5

Encoding information with vector vortex beams

Giovanni Milione, Thien An Nguyen, The City College of New York (United States) and New York State Ctr. for Complex Light (United States); Daniel A. Nolan, Corning Incorporated (United States) and New York State Ctr. for Complex Light (United States); Robert R. Alfano, The City College of New York (United States) and New York State Ctr. for Complex Light (United States)

We experimentally investigate the ability to encode information with vector vortex beams. Vector vortex beams are light beams with spatially inhomogeneous states of polarization such as radial or azimuthal polarization. Vector vortex beams are another basis in the Hilbert space of light's spin and orbital angular momentum eigenstates, e.g., circular polarized scalar vortex beams. In contrast to encoding information with circular polarized scalar vortex beams it is shown with vector vortex beams it is possible to manipulate the entire Hilbert space by simply manipulating their polarization. Additionally, we experimentally investigate a method to decode vector vortex beams by manipulating a higher-order pancharatnam-berry phase whereby, for example, radial and azimuthal polarization can be separated from other vector vortices. The connection of vector vortex beams to so-called classical entanglement will be discussed.

8999-23, Session 5

Polarization and coherence Stokes parameters in diffraction and interference

Ari T. Friberg, Tero Setälä, Jani Tervo, Jari Turunen, Univ. of Eastern Finland (Finland)

The classic (one-point) Stokes parameters specify the polarization state and the newly introduced two-point Stokes parameters the coherence properties of random electromagnetic fields. We show that in diffraction and interference an insightful connection exists between these two sets of quantities. More specifically, we show first that in radiation from spatially incoherent, partially polarized sources each far-zone coherence Stokes parameter is proportional to the Fourier transform of the corresponding source polarization Stokes parameter. This result amounts to the electromagnetic van Cittert – Zernike theorem [1]. The normalized coherence parameters give the electromagnetic degree of coherence [2]. For sources whose polarization state is uniform, the far-field electromagnetic degree of coherence is determined by the source degree of polarization and the Fourier transform of the source shape [1]. We further show that an incoherent, unpolarized source produces paraxially the same far-zone electromagnetic degree of coherence as an opening in a blackbody cavity [3]. These results have applications in modeling field propagation from incoherent radiators. Conversely, in Young's two-pinhole setup each coherence Stokes parameter at the openings contributes on interference only to the corresponding polarization Stokes parameter [2]. Their modulation contrasts yield the electromagnetic degree of coherence and the degree of polarization of the illumination.

[1] J. Tervo, T. Setälä, J. Turunen, and A.T. Friberg, Opt. Lett. 38, 2301 (2013).

[2] T. Setälä, J. Tervo, and A.T. Friberg, Opt. Lett. 31, 2208 (2006); ibid 31, 2669 (2006).

[3] K. Blomstedt, T. Setälä, J. Tervo, J. Turunen, and A.T. Friberg, Phys. Rev. A 88, 013824 (2013).

8999-24, Session 5

Incoherent polarized white-light optical vortex from a q-plate

Thien An Nguyen, The City College of New York (United States) and New York Ctr. for Complex Light (United States); Giovanni Milione, The City College of New York (United States) and Graduate Ctr.of the City Univ. of New York (United States) and New York Ctr. for Complex Light (United States); Yisa Rumala Jr., The City College of New York (United States) and New York Ctr. for Complex Light (United States); Daniel A. Nolan, Corning Incorporated (United States) and New York Ctr. for Complex Light (United States); Ebrahim Karimi, Sergei Slussarenko, Univ. degli Studi di Napoli Federico II (Italy) and CNR-SPIN (Italy); Lorenzo Marrucci, Univ. degli Studi di Napoli Federico II (Italy) and CNR-SPIN (Italy) and New York Ctr. for Complex Light (United States); Robert R. Alfano, The City College of New York (United States) and The City Univ. of New York (United States) and New York Ctr. for Complex Light (United States)

Incoherent polychromatic optical vector vortex is generated using a lamp and tunable liquid crystal q-plate via spin-orbit conversion. The contrast ratio of the incoherent optical vortex as it propagates in space is about 0.30 and decreases to 0.13 with propagation distance. The examination of the e?ects of different states of polarizations on the output beam indicates that the incoherent optical vortices beams are polarization maintaining. A comparison of the incoherent optical vortex and the coherent optical vortex is discussed.

8999-25, Session 6

Laguerre-Gaussian mode generation by nanoarrays with a tailored geometry

Mathew D. Williams, Matt M. Coles, David S. Bradshaw, David L. Andrews, Univ. of East Anglia (United Kingdom)

Light generated with orbital angular momentum, commonly known as an optical vortex, is widely achieved by modifying the phase structure of a conventional laser beam through the utilization of a suitable optical element. In this research, a process is introduced that can produce electromagnetic radiation with a helical wave-front directly from the vacuum. The chirally driven optical emission originates from a hierarchy of tailored nanoscale chromophore arrays arranged with a specific propeller-like geometry and symmetry. For example, a nanoarray composed of three particles requires each component to be held in a configuration with a rotation and associated phase shift of 2/3 pi radians with respect to its neighbor. Following initial electronic excitation, each such array is capable of supporting delocalized doubly degenerate excitons, whose azimuthal phase progression is responsible for the helical wave-front. Under the identified conditions, relaxation of the electronically-excited nanoarray produces the structured light in a spontaneous manner. It is determined that nanoarrays of escalating order, i.e. those containing an increasing number of components, enable access to a set of topological charges of higher order. Practical considerations for the development of this technique are discussed, and potential new applications are identified.

8999-26, Session 6

Controlling light in multimode waveguides: new challenges

Martin Ploschner, Univ. of Dundee (United Kingdom); Tomas Tyc, Masaryk Univ. (Czech Republic); Kishan Dholakia, Univ. of St. Andrews (United Kingdom); Tomá? Ci?már, Univ. of Dundee (United Kingdom)

Transmission of light within multimode waveguides introduces randomization of laser beam amplitude, phase and polarization. However, it was shown recently that using holographic techniques for wavefront optimization one can quantify this randomization by acquiring a transformation matrix of this optical system, giving a direct relation between the input and the output optical modes. This also allows one to generate an arbitrary optical field propagating from the waveguide within the accessible field of view and range of spatial frequencies. Such possibilities were also exploited in a number of exciting applications. Examples include optical manipulation of colloidal particles or various imaging modalities such as bright-field or fluorescence microscopy.

Nevertheless the technology still suffers with numerous limitations that restrain its broader outreach. This paper focuses on the most important issues:

- The calibration procedure (acquiring of the transformation matrix) is currently very time consuming. We discuss the enhancement of GPU driven experimental system together with a series of simplifications leading to significantly faster measurements.

- The transformation matrix is very sensitive to the deformation of the waveguide and has to be repeated for every time the waveguide is moved. Hence no bending and looping of the waveguide can be realized during imaging which renders flexible multimode fibre-based endoscopy with the current approaches impossible. We discuss our first experimental observations suggesting that mixing between propagating modes may not be entirely random, which could allow further major simplification of the calibration procedure.

8999-27, Session 6

Spin-controlled optical radiation pressure

Georgiy V. Tkachenko, Etienne Brasselet, Univ. Bordeaux 1 (France)

Optical radiation forces are the mechanical manifestation of the transfer of the linear momentum of light to matter, which basically occurs when light is reflected, refracted, scattered or absorbed in the course of its propagation. Here we report on the full control of the optical radiation pressure at fixed photon flux and incident angle by controlling the photon helicity. The experimental demonstration is achieved by using transparent microspheres with typical size of 10 micrometers that enable a strong coupling between linear and angular degrees of freedom of a light field. As result the spin of photons can be used to fully control optomechanical effects driven by the radiation pressure of light. A careful analysis of the possible contribution of the usual optical scattering force is considered and an experimental arrangement is proposed to cancel its contribution in our experiments. This allows us to present an unambiguous demonstration that is quantitatively validated analytically with a good agreement. Moreover, envisioned applications are discussed and experimental proofs-of-principle are presented. These results should contribute to the development of optofluidics and application potential is expected, for instance for the pharmaceutical industry, angular momentum driven nanoactuation or optical sailing.

8999-28, Session 6

Vitality of optical vortices

Filippus S. Roux, CSIR National Laser Ctr. (South Africa)

Stochastic optical fields generally contain numerous optical vortices. Being topologically stable, such vortices cannot be removed or destroyed by local perturbations. They can only be created and annihilated in pairs of opposite topological charge. This presents a challenge when light becomes severely distorted due to propagates through a random medium such as turbulence. For weak scintillation the distortion can be corrected using adaptive optics, but for strong scintillation the distortions cause optical vortices, which cannot be removed by the deformable mirrors in adaptive optics. One way to remove them would be to coerce them to annihilate in pairs. To this end, it would be helpful to identify which vortex pairs will disappear by themselves and which pairs need additional processing to force them to annihilate.

In this talk we present a method to distinguish between annihilation and creation events. We study the properties of optical fields in the vicinity of these events and use this knowledge to derive a quantity that distinguishes between points of annihilation and those associated with pair creation. This quantity, which we call the optical vortex dipole vitality, is composed of the first and second order transverse derivatives of the optical field. Numerical simulations of optical speckle fields are used to aid the discussion and to demonstrate the ability of the vitality to distinguish between vortex pairs that are about to be annihilated and those that have just been created.

8999-29, Session 6

Density of optical degrees of freedom: intensity, linear, and angular momentum

Michael Mazilu, Univ. of St. Andrews (United Kingdom)

For any optical system, optical eigenmodes describe solutions of Maxwell's equations that are orthogonal to each other. In their simplest free space form, these modes correspond, for example, to Bessel, Laguerre-Gaussian or Hermite-Gaussian beams. However, the orthogonality property is not limited to the intensity of the optical field but more generally the optical eigenmode decomposition can be applied to the linear and angular momentum arising from complex coherent beams. These modes can be seen as describing the independent degrees of freedom of the optical system and are characterized by the mode their density and coupling efficiency. It is interesting to study the effect of different optical systems on the density of the optical degrees of freedom propagating through them. Here, we look at systems containing different elements such as: dielectric, plasmonic, meta-material, photonic crystal and random lenses. Using the optical eigenmode decomposition, we determine their density in the different cases and discuss the origin of the variations observed. Further, we study the overall number of optical degrees of freedom accessible including linear and angular momentum of optical beams.

8999-30, Session 6

The role of vortices in the generation of optical lift

Simon Hanna, Stephen H. Simpson, Univ. of Bristol (United Kingdom); Grover A. Swartzlander Jr., Rochester Institute of Technology (United States)

When a linearly polarised plane wave is incident on a semi-cylindrical lightfoil, an optical "lift" force may be generated, which has many potential applications including the driving of micromachines, biological transport or improved designs of solar sails for interstellar space travel [1,2]. The lightfoil also experiences an optically induced torque until it reaches a stable orientation. Torque generation and lift are associated with the production of optical phase singularities, which change in position and number as the orientation of the lightfoil changes relative to the incident wave, and as the symmetry and chirality of the lightfoil is altered. In this paper we examine the link between the formation of phase singularities and the generation of mechanical torque and lift in such systems, using a combination of analytical and computational approaches.

[1] G.A. Swartzlander Jr. et al., "Stable optical lift," Nature Photonics 5, 48-51 (2011).

[2] S.H. Simpson et al., "Optical lift from dielectric semicylinders," Optics Letters 37, 4038- 4040 (2012).

8999-52, Session PWed

Scaling law with random electromagnetic fields

Tero Setälä, Timo Hassinen, Jani Tervo, Jari Turunen, Ari T. Friberg, Univ. of Eastern Finland (Finland)

Spectroscopy is a widely used technique in the characterization of light sources, nanoparticles, material objects, etc. Two decades ago it was found that due to the partial spatial coherence of the source the normalized spectrum of the far field may significantly differ from that of the source introducing a new aspect to the spectral measurements [1]. At the same time, within the scalar-field treatment, the so-called scaling law was established which ensures spectral invariance, i.e., that the normalized far-field spectrum in every direction is the same as the source spectrum. In this work we formulate an electromagnetic extension of the scaling law which holds for finite, statistically homogeneous, partially polarized, planar sources [2]. The electromagnetic scaling law covers also situations of wide angle emission from sources having in general three field components and it is more general than that put forward previously in the literature. We illustrate the formalism with three examples. First, the radiation emanating from an aperture in a blackbody cavity is shown to be consistent with the scaling law. Second, we construct a paraxial source whose individual field components satisfy the scalar scaling law but the total spectrum does not. Third, we show a situation in which the transverse field components do not obey the scaling law whereas the total field does. The results of this work find applications in spectroscopy, materials research and modeling of energy transport from random light sources.

[1] E. Wolf, Phys. Rev. Lett. 56, 1370 (1986).

[2] T. Hassinen et al., submitted.

8999-53, Session PWed

Encoding mutually-unbiased bases in orbital angular momentum for quantum key distribution

Angela Dudley, CSIR National Laser Ctr. (South Africa); Mhlambululi Mafu, Sandeep K. Goyal, Univ. of KwaZulu-Natal (South Africa); Daniel Giovannini, Univ. of Glasgow (United Kingdom); Melanie G. McLaren, CSIR National Laser Ctr. (South Africa); Thomas Konrad, Univ. of KwaZulu-Natal (South Africa); Miles J. Padgett, Univ. of Glasgow (United Kingdom); Francesco Petruccione, Univ. of KwaZulu-Natal (South Africa); Norbert Lütkenhaus, Univ. of Waterloo (Canada); Andrew Forbes, CSIR National Laser Ctr. (South Africa)

We encode mutually unbiased bases (MUBs) using the higher-dimensional orbital angular momentum (OAM) degree of freedom and illustrate how these states are encoded on a phase-only spatial light modulator (SLM). We perform (d - 1)-mutual unbiased measurements in both a classical prepare and measure scheme and on entangled photon pairs for dimensions ranging from d = 2 to 5. The calculated average error rate, mutual information and secret key rate show an increase in information capacity as well as higher generation rates as the dimension increases.

8999-54, Session PWed

Spatial superpositions of Gaussian beams

Darryl Naidoo, Council for Scientific and Industrial Research (South Africa); Thomas Godin, FEMTO-ST (France); Michael Fromager, Kamel Ait-Ameur, Ecole Nationale Supérieure d'Ingenieurs de Caen et Ctr. de Recherche (France); Andrew Forbes, CSIR National Laser Ctr. (South Africa)

We explore an interferometric beam shaping technique that considers the coaxial superposition of two Gaussian beams. This technique is traditionally implemented in a Mach-Zehnder interferometer; however, to avoid phase shift drift due to vibrations and thermal effects we employ amplitude and phase modulation with an SLM to achieve the beam shaping. We consider two Gaussian beams of equal but opposite curvature that possess the same phase and width incident on a focusing lens. At the plane of the lens we obtain a multi-ringed beam with a central intensity maximum which develops into a multi-ringed beam with a central null at the focal plane of the lens. The interesting feature of this beam is that it possesses two focal spots on either side of the focal plane of the lens. We investigate obstructing the beam at the focal plane of the lens and by carefully selecting the free parameters we obtain an unobstructed second focus while the equivalent Gaussian beam is sufficiently obstructed.

8999-55, Session PWed

Application of geometric phase to wavefront sensing for astronomical adaptive optics

Eric E. Bloemhof, National Science Foundation (United States)

Modern adaptive optics systems give extremely high performance, in terms of Strehl ratio (degree of correction) and increasingly in terms of field of view. Arguably the most important subsystem is the wavefront sensor, which extracts the deviation from flatness of a fiducial wavefront that has been perturbed by the turbulent atmosphere, and then provides the command signals to an actuated surface for compensation. An essential practical requirement of a wavefront sensor to achieve high sensitivity is that it perform over a broad spectral bandwidth. With that in mind, wavefront sensors are considered here in which use is made of the geometric phase, which has the property that the value of the phase is independent of wavelength. System designs and simulated performance are discussed.

8999-31, Session 7

Ultrafast and ultra-broadband optical-vortex pulse generation and characterization *(Invited Paper)*

Ryuji Morita, Keisaku Yamane, Hokkaido Univ. (Japan) and JST CREST (Japan); Zhili Yang, Hokkaido Univ. (Japan); Yasunori Toda, Hokkaido Univ. (Japan) and JST CREST (Japan)

An optical vortex has unique and interesting properties of possessing a phase singularity in its center and doughnut-like intensity profile, carrying well-defined orbital angular momentum (OAM). The features originate in the phase distribution linearly depending on the azimuthal angle, which offers us a new controllable parameter of light wave in spatial domain. The optical vortices have attracted much attention because of their applications to quantum information processing, laser ablation, optical tweezers, etc. Although, in most of the applications, (quasi-)continuous-wave light sources have been utilized so far, optical vortex generation well-combined with light control techniques in frequency or time domain such as femtosecond technology is a reasonable extension. Ultrashort optical-vortex pulses generated by this new scheme enable us to carry out ultrafast nonlinear spectroscopy and high-peak power interactions with matter.

We demonstrate the generation of ultrashort and ultra-broadband optical-vortex pulses (pulse energy: several tens of uJ) in few-cycle regime, by using an axially-symmetric waveplate (ASWP) and optical parametric amplification. In addition, instead of using an ASWP, we employ a computer-generated hologram incorporated in 4-f system and performed an amplification. This configuration overcomes the low-throughput drawback of the vortex converter, simultaneously compensating for the angular dispersion. It also gives flexibilty of OAM- or topological-charge control. Thus, we succeed in generation of ultra-broadband optical-vortex pulses (~740 - ~ 870 nm) with a programmably-controlled topological charge. Moreover, we experimentally exhibit a high-precision method for measuring frequency-resolved OAM spectrum of femtosecond ultra-broadband optical-vortex pulses on the basis of electric-field reconstruction in spatial domain.

8999-32, Session 7

Optical vortices in a six-wave mixing mechanism

Matt M. Coles, Mathew D. Williams, David L. Andrews, Univ. of East Anglia (United Kingdom)

Optical vortex light engendered with integer units of orbital angular momentum (OAM) may be involved in frequency upconversion. Second harmonic generation is usually forbidden in isotropic media due to parity constraints, but it becomes allowed by six-wave mixing. Here, we present a rigorous quantum analysis for the case of a Laguerre-Gaussian input beam comprising photons endowed with a single unit of OAM. Such a process gives rise to the acquisition of OAM by the two emergent photons; it emerges that the mechanism delivers a harmonic output whose polarization is essentially parallel to the incident radiation. On derivation of the quantum amplitudes for this six-wave nonlinear mechanism, utilizing a state-sequence procedure, our investigation ascertains the character of the emission and discovers an entangled distribution to the conserved total orbital momentum. From the latter it is resolved that higher order modes arise, corresponding to the generation of structured light with OAM greater than unity. A distinctive conical spread of OAM, originating from the entangled distribution in the emission pair, affords a potential means to determine the individual angular momenta.

8999-33, Session 7

Propagation of an LP11 mode in a few mode elliptical core optical fiber

Giovanni Milione, Thien An Nguyen, The City College of New York (United States) and New York State Ctr. for Complex Light (United States); Daniel A. Nolan, Corning Incorporated (United States) and New York State Ctr. for Complex Light (United States); Robert R. Alfano, The City College of New York (United States) and New York State Ctr. for Complex Light (United States)

We experimentally investigate the propagation of an LP11 (Hermite-Gaussian) and LP01 (Gaussian) mode in a few mode elliptical core optical fiber. In the single mode regime an elliptical core optical fiber is well know for its ability to impose birefringence onto the two

orthogonal polarizations of the LP01 mode and act as a polarization maintaining optical fiber. In the few mode regime the purposeful elliptical deformation of the optical fiber core results in significant splitting of the LP11 and LP01 propagation constants as well as their orthogonal polarization imposing birefringence onto both the LP11 and LP01 modes. Remarkably, it is shown a few mode elliptical core optical fiber can maintain the propagation of both the LP01 and LP11 modes as well as their polarization without mixing up to ~50 meters even when the optical fiber is significantly bent. The use of a few mode elliptical core optical fiber for spatial mode division multiplexing to increase optical fiber information capacity as well as the preservation of the entanglement of higher-order modes will be discussed.

8999-34, Session 7

Controlling the acceleration of rotating Bessel beams

Andrew Forbes, Angela Dudley, CSIR National Laser Ctr. (South Africa); Christian Schulze, Friedrich-Schiller-Univ. Jena (Germany); Filippus S. Roux, CSIR National Laser Ctr. (South Africa); Michael Duparré, Friedrich-Schiller-Univ. Jena (Germany)

We present a method for encoding superpositions of non-canonical optical vortices, characterized by their anisotropy and referred to as the morphology parameter, on a spatial light modulator (SLM). We implement this technique to create superimposed, non-canonical, higher-order Bessel beams and investigate the propagation of the resulting field. Although it is already known that the intensity profile of the resulting field experiences an angular rotation, we show that by tuning the morphology parameter, the rate of rotation will either accelerate or decelerate as a function of the propagation distance. We also experimentally and theoretically show that these accelerating and decelerating sections in the intensity profile experience a transfer of energy between them. The experimentally produced fields are in good agreement with those calculated theoretically.

8999-35, Session 7

Bandwidth analysis of the principal states superimposed from vortex modes propagating in an optical fiber

Daniel A. Nolan, Corning Incorporated (United States); Giovanni Milione, Robert R. Alfano, The City College of New York (United States)

We expand our principal states analysis of vortex modes propagating in an optical fiber for super dense optical network to include the wavelength width over which these states are valid. Again the theory is formulated using SU(N) group theory and an eigen analysis to determine the modal expansion coefficients. Specifically we characterize the principal states of LP11 mode. These states are a superposition of four vector vortex modes including the radial, azimuthal and two HE21 vortex modes. To first order, the principal states are frequency and wavelength independent; however dependencies develop away from the frequencies at which the specific expansion coefficients are determined. These wavelength dependencies result from the mode coupling that occurs within the link. The vector modes from which the principal states are formed are to a much lesser extent wavelength dependent.

The higher order Poincare sphere is used to show the evolution of these orthogonal states as a function of wavelength as well as the link length and the mode coupling. This analysis reduces to that previously used to characterize the propagation of the two principal states of the fundamental LP01 mode in an optical fiber. Important here is the polarization mode dispersion of this mode and the bandwidth over which it is valid. In this case, the standard Poincare can be used to show the evolution of these principal states including the bandwidth . This work is important to characterize the bandwith limitions on the horizon using spatial modes for super dense optical networks.

8999-36, Session 7

Theory of interference with multiple OAM states in a spiral phase plate etalon: thick-plate and thin-plate approximation

Yisa Rumala Jr., The City College of New York (United States) and The City Univ. of New York (United States) and New York State Ctr. for Complex Light (United States)

A spiral phase plate is a transparent device used to generate orbital angular momentum. When reflections from the surface of the device is taken into account, the device becomes a spiral phase plate (SPP) etalon. The transmitted optical intensity profile from device is characterized by a periodic azimuthal intensity modulation. This work provides an analytic description of the device which applies to both the high finesse and low finesse regimes. Two approximations are considered: the thin-plate approximation and thick-plate approximation. In the thin-plate approximation, the angle between the flat surface and azimuthally increasing surface is not explicitly taken into account, while in the thick-plate approximation, this angle is explicitly taken into account. For the case of the low finesse regime, the device is accurately described by the thin-plate approximation, however, in the high finesse regime, this approximation is expected to breakdown. A triangular wedge in which the thickness of the wedge varies as a function of azimuthal angle is used to understand the problem from a ray optics perspective. From the calculations, a few properties of the SPP etalon are immediately apparent: (1) the thick-plate approximation reproduces thin-plate approximation in appropriate limit, (2) the transmitted strong Fabry-Perot azimuthal intensity modulation peaks decreases as the reflectivity is increased due to geometry of device, (3) In addition to the strong Fabry-Perot azimuthal intensity modulation which varies as a function of angle, there are smaller azimuthal intensity modulations close to these strong Fabry-Perot etalon peaks. These items are quantified in analytic calculations.

8999-37, Session 8

Shaping electromagnetic fields for THz plasmonics *(Invited Paper)*

André Edelmann, Stefan F. Helfert, Jürgen Jahns, FernUniv. Hagen (Germany)

The field of plasmonics deals with electromagnetic waves, which propagate at the interface between a dielectric and metallic medium. These electromagnetic waves are called surface plasmon polaritons (SPPs). We discuss propagation and excitation of SPPs at optical and terahertz (THz) frequencies and their potential in integrated systems.

Plasmon propagation at optical frequencies will be considered in laterally and longitudinally periodic metallic waveguides. Lateral periodicity leads to the well-known self-imaging phenomenon, which may be used for plasmonic beam splitting. Longitudinal periodicity was investigated in order to implement filter characteristics and in an effort to improve propagation properties (as expressed by the field extension and attenuation). To implement nanoplasmonic devices into integrated systems we discuss the coupling of free-space to plasmonic fields (and vice versa). Plasmonic grating coupling is used to excite the SPP at certain angles of incidence to the metallic surface. End-fire coupling allows the excitation of a plasmon at the front facet of the metallic waveguide. We discuss both methods in the optical and the terahertz regime. In particular the coupling of THz-waves to metallic wires is discussed by using the end-fire method. The THz-SPP propagates with low attenuation along a cylindrical wire. In the optical domain we consider free-space coupling via gratings to plasmonic waveguide

structures. Finally we explore the potential of the discussed plasmonic devices to integrated optical systems, e.g., into planar integrated free space optics (PIFSO) to merge the benefits of both technologies.

8999-38, Session 8

The shot noise limit of light control through random nanophotonic media

Hasan Yilmaz, Willem L. Vos, Allard P. Mosk, Univ. Twente (Netherlands)

We study the effect of experimental noise on the control of of coherent light propagation through random nanophotonic media using wavefront shaping. The control of light propagation in a wavefront shaping experiment is quantified by the enhancement factor which is the ratio of the intensity of the focused light behind the sample on a selected position to the ensemble averaged intensity of the light. Ideally, the number of degrees of freedom on the wavefront determines the enhancement factor. However, noise limits the amount of control in an experiment. The noise causes measurement errors in the phase of the transmitted field which reduces the enhancement factor. Here, we show the effect of noise on the enhancement factor in a wavefront shaping experiment. We found a general expression for the enhancement factor which includes three different noise contributions; namely camera read-out noise, the shot noise, and the laser excess noise. We use a two-step optimization procedure to suppress the camera read-out noise. We conclude that even using a low-end camera and a noisy laser, the fundamental limitation of the enhancement factor in a two-step wavefront shaping experiment is the photodetection shot noise.

8999-39, Session 8

Ultrasensitive force detection of photonic phenomena with tuning-fork-based frequency modulation

Aaron Lewis, The Hebrew Univ. of Jerusalem (Israel); Hesham Taha, Andrey Ignatov, Alina Stinkovski, Ori Avayu, Patricia Hamra, Nanonics Imaging Ltd. (Israel)

The standard method that is used with atomic force microscopy to monitor mechanical properties of materials such as elasticity and adhesion is based on laser beam bounce technology. With such an approach there are two major problems one is jump to contact and the other is adhesion ringing. Numerous methods have evolved for trying to resolve these problems from methods called pulsed force mode to peak force. However, what is desired is a smooth approach and retract from a surface or molecule where force measurements need to be implemented. Over the last few years it has been realized that the best method of force feedback in atomic force microscope is based on tuning fork force modulation but there have been few studies implementing these advances into the realm of force spectroscopy. In this paper force spectroscopic analysis is implemented based on tuning forks and it is demonstrated that there is close to single pN force sensitivity. These efforts use the pioneering theory of Sader and Jarvis that has shown theoretically that it is possible to derive accurate formulas for the force versus frequency in such Frequency Modulation methods [J. E. Sader and S. P. Jarvis, "Accurate formulas for interaction force and energy in frequency modulaton force spectroscopy" Appl. Phys. Lett. 84, 1801 (2004)]. It will be further shown that such normal force tuning fork based force spectroscopy can readily be integrated with other photonic, chemical and structural tools such as Raman microSpectroscopy and Scanning Electron Microscopy.

8999-40, Session 8

Combining focusing properties of a single diatom valve with optical eigenmodes in ultra-shrinking of light

Luigi Lavanga, Edoardo De Tommasi, Istituto per la Microelettronica e Microsistemi (Italy); Anna Chiara De Luca, Consiglio Nazionale delle Ricerche (Italy); Principia Dardano, Istituto per la Microelettronica e Microsistemi (Italy); Mario De Stefano, Univ. degli Studi di Napoli Federico II (Italy); Luca De Stefano, Ivo Rendina, Istituto per la Microelettronica e Microsistemi (Italy); Kishan Dholakia, Michael Mazilu, Univ. of St. Andrews (United Kingdom)

It is known that a properly arranged distribution of nanoholes on a metallic slab is able to produce, in far field conditions, light confinement at sub-diffraction and even sub-wavelength scale [1]. This same effect can also be implemented by the use of Optical Eigenmode (OEi) technique [2]. In this case, a spatial light modulator (SLM) encodes phase and amplitudes of N probe beams whose interference is able to lead to sub-wavelength confinement of light focused by an objective [3]. The OEi technique has been already used in a wide range of applications, such as photoporation, confocal imaging, and coherent control of plasmonic nanoantennas. Here, we describe the application of OEi technique to a single valve of a marine diatom. Diatoms are ubiquitous monocellular algae provided with an external cell wall, the frustule, made of hydrated porous silica which play an active role in efficient light collection and confinement for photosynthesis [4]. Every frustule is made of two valves interconnected by a lateral girdle band. We show that, applying OEi illumination to a single diatom valve, we can achieve unprecedented sub-diffractive focusing for the transmitted light beating the resolution limit by a factor of 2.4.

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8999-41, Session 9

Weak measurements with non-integer orbital angular momentum states *(Invited Paper)*

Jörg B. Götte, Max-Planck-Institut für Physik komplexer Systeme (Germany)

Weak measurements typically require two non-orthogonal states, which are not eigenstates of an observable. This is why weak values of the orbital angular momentum (OAM) operator seem counterintuitive or involve additional auxiliary observables, such as polarization. We show how the use of non-integer (OAM) states circumvents these problems and how weak values can be rigorously related to the position of phase singularities in the optical field of the pointer. This establishes firmly the connection between singular optics, and in particular singularimetry, and the enhancement techniques common for weak values.

8999-43, Session 9

Recovery of quantum-entanglement after encountering an obstruction

Melanie G. McLaren, CSIR National Laser Ctr. (South Africa) and Stellenbosch Univ. (South Africa); Mary Jacquiline Romero, Univ. of Glasgow (United Kingdom); Thandeka Mahlanga, Filippus S. Roux, CSIR National Laser Ctr. (South Africa); Miles J. Padgett, Univ. of Glasgow (United Kingdom); Andrew Forbes, CSIR National Laser Ctr. (South Africa) and Stellenbosch Univ. (South Africa)

Quantum entanglement of Bessel-Gaussian (BG) modes in the orbital angular momentum (OAM) basis offers a number of advantages over the more commonly used Laguerre-Gaussian (LG) modes. Unlike the LG modes, the continuous scalable radial parameter of the BG modes allows greater control over quantum state preparation and a greater number of OAM modes to be measured, thereby potentially increasing the state dimensionality. We demonstrate entanglement in terms of the BG modes by performing a Bell-type experiment and showing a violation of the Clauser-Horne-Shimony-Holt inequality for qubits. We show that in terms of the BG modes, the OAM bandwidth becomes wider and flatter, allowing for higher state dimensionality. Using quantum state tomography, we compare the high-dimensional density matrices measured in the BG basis to those measured in the LG basis.

We also use the well-documented reconstruction property of BG beams to show the recovery of quantum entanglement of a state after encountering an obstruction. We calculate the concurrence of the entangled state for different positions of the obstruction along the path of propagation and show that the original unobstructed value can be salvaged in the BG basis.

8999-44, Session 9

The evolution of OAM-entanglement between two qutrits in turbulence

Alpha Hamadou Ibrahim, Council for Scientific and Industrial Research (South Africa); Filippus S. Roux, CSIR National Laser Ctr. (South Africa); Melanie G. McLaren, Council for Scientific and Industrial Research (South Africa); Sandeep K. Goyal, Thomas Konrad, Univ. of KwaZulu-Natal (South Africa); Andrew Forbes, CSIR National Laser Ctr. (South Africa)

The use of higher-dimensional entangled systems have been proved to significantly improve many quantum information tasks. For instance, it has been shown that the use of higher-dimensional entangled systems provides a higher information capacity and an increased security in quantum cryptography. The orbital angular momentum (OAM) state of light is a potential candidate for the implementation of higher-dimensional entangled systems and has thus been considered for free-space quantum communication. However, atmospheric turbulence severely affects the OAM state of photons. In this work, we study the evolution of the OAM entanglement between two qutrits (three-dimensional quantum systems) in atmospheric turbulence both numerically and experimentally. The qutrits are photons entangled in their orbital angular momentum (OAM) states generated by spontaneous parametric down conversion. We propagate one of the photons through turbulence while leaving the other undisturbed. To compare our results with previous work, we simulate the turbulent atmosphere with a single phase screen based on the Kolmogorov theory of turbulence and we use the tangle to quantify the amount of entanglement between the two qutrits. We compare our results with the evolution of OAM entanglement between two qubits. It is found that the OAM entanglement between qutrits decays faster.

8999-45, Session 9

The implementation of quantum walks using classical light

Thomas Konrad, Sandeep K. Goyal, Univ. of KwaZulu-Natal (South Africa); Filippus S. Roux, Andrew Forbes, CSIR National Laser Ctr. (South Africa)

We study the notion of classical entanglement at the example of a quantum walk implemented by means of the orbital angular momentum and the polarization degree of freedom of a classical light beam. The scheme makes use of a ring interferometer containing a quarter wave plate and a q plate. While the polarization serves here as the coin to determine the direction of the walk in each step, the orbital angular momentum represents the position of the walker which increases or decreases depending on the polarization due to the action of the q plate. The coupling of both optical degrees of freedom leads to optical states which are reminiscent of entangled states of quantum systems and are called classically entangled. The generation of classically entangled states is a prerequisite to mimic coined quantum walks. We compare the physics of paraxial optics and quantum mechanics and address the question whether other quantum information tasks can be implemented with classical light.

Reference: S. Goyal et al., PRL 110, 263602 (2013).

8999-46, Session 10

State characterization and proof of entanglement in clouds of ultracold atoms

Wolfgang A. Ertmer, Carsten Klempt, Jan Peise, Frank Deuretzbacher, Luis Santos, Leibniz Univ. Hannover (Germany); Augusto Smerzi, Luca Pezze, European Lab. for Non-linear Spectroscopy (Italy); Philipp Hyllus, Géza Tóth, Univ. del País Vasco (Spain)

Entanglement, one of the most intriguing features of quantum mechanics, is nowadays a valuable resource for quantum engineering. For instance, an entangled input state can improve the sensitivity of an interferometer beyond the shot noise limit. Most prominently, quadrature-squeezed and spin-squeezed states are useful for this application.

In our experiment, we use spin dynamics in a Rb-87 Bose-Einstein condensate to produce up to 10,000 entangled atoms in two different spin modes – a process analogous to optical parametric down-conversion. Ideally, this process produces a superposition of Dicke states- an interesting alternative to squeezed states which can be used to achieve Heisenberg-limited sensitivity in an interferometric apparatus.

We experimentally demonstrate that the state is useful for sub-shot-noise interferometry. However, it is difficult to characterize the produced state, since a full state tomography is not feasible for such large particle numbers. Here we show that inequalities for the total spin projections and their variances can be applied to directly prove that the generated state is entangled. Furthermore, the depth of entanglement can be estimated, i.e. how many atoms are at least in the largest non-separable subset of particles.

8999-47, Session 10

Optical trapping of 100nm nanoparticle on extended slow Bloch mode cavity

Laurent Milord, Institut National des Sciences Appliquées de Lyon (France); Emmanuel Gerelli, Cécile Jamois, Abdelmounaim Harouri, Céline Chevalier, Christian Seassal, Pierre Viktorovitch, Taha Benyattou, Univ. de Lyon (France) and Institut des Nanotechnologies de Lyon (France) and Institut National des Sciences Appliquées de Lyon (France)

Nanoplasmonic devices and Photonic crystal (PC) are two major approaches for optical nanotwezeers. In both cases, state of the art devices can trap nanoparticles of 100 nm diameter or less. However, these approaches rely on subwavelength nanocavity with a very small capture cross section. Our original work consists in the use of extended slow Bloch modes PC resonant cavities whose cross section is larger (one order of magnitude). This is a key point for microfluidic applications. Moreover, our cavity is designed for direct free space excitation using low NA microscope objective.

First, we will present a new approach based on double period PC to engineer the slow Bloch mode. The quality factor can be easily tuned by simple geometrical aspects. We show theoretically and experimentally that Q's of several thousands are easily achievable.

Secondly, we will present the trapping application. Bloch modes devices are very interesting for trapping applications. Indeed, the period of these modes is equal to the period of the PC (300 nm) which induces very strong gradient forces. We expect an increase of one order of magnitude (for the same quality factor) as compared to the usual extended cavities, such as micro disks.

Using 5x5 µm? cavities on SOI we successfully trap 100 and 200 nm particles with an excitation power of 30 mW and a waist of 2µm. They remain confined within an area of 60x60 nm?. This is a very promising result for the future integration of these devices in a microfluidic system.

8999-48, Session 10

Nanostructured fibre tip for trapping of nanoparticles

Jean-Claude Tinguely, Univ. of Tromsø (Norway); Ming Ding, Gilberto Brambilla, Univ. of Southampton (United Kingdom); Andreas Hohenau, Joachim R. Krenn, Karl-Franzens-Univ. Graz (Austria); Olav G. Hellesø, Univ. of Tromsø (Norway)

To trap a nanoparticle it is necessary to confine light to the nanoscale and to generate strong field gradients to overcome the Brownian motion of the particle. This has previously been demonstrated with nanoapertures in metal films. However, metal films do not provide the flexibility of normal optical tweezers to trap particles in 3D and maneuver them anywhere within a volume. We propose to use a metal coated and nanostructured optical fibre for trapping of nanoparticles. The fibre provides easy coupling to a light source, a nanoaperture or a more complex nanoantenna can be fabricated on the tip of a tapered-fibre, and the device can be moved as an NSOM-probe. We have done extensive simulations of the field distribution and the optical forces for the device, using the finite element method. Based on the simulations, we will show what kind of particles can be trapped and compare various designs. Fibre tapers have been produced using etching with hydrofluoric acid (HF) and using a micropipette puller. Information will be provided on the nanostructuring of the tip, using a focused ion beam. Preliminary results of optical trapping with the device will be presented.

8999-49, Session 10

Influence of multiple particles in optical tweezers on the trapping efficiency

Thomas Weigel, Reza Ghadiri, Cemal Esen, Gustav Schweiger, Andreas Ostendorf, Ruhr-Univ. Bochum (Germany)

Since the early times of Arthur Ashkins groundbreaking experiments on optical tweezers, a great number of theoretical works was dedicated to this subject. Most of them treated the optical trapping of single spherical or elliptical particles. In the last years optical tweezers have become more and more a tool for assembling three dimensional structures using single microspheres as building blocks. For this purpose a large number of particles has to be moved simultaneously. All structures and particles inside the light beams influence the properties of the traps. For this reason, we investigated theoretically the influence of additional single particles and particle arrays on the properties of optical traps. Techniques using wave theory usually lack the flexibility to be used for different particle shapes and numbers. For this reason a geometrical optics based model is used with the inherent flexibility to be applied for various shapes and particle numbers.

8999-50, Session 10

Diffractive beam shaping, tracking and coupling for wave-guided optical waveguides (WOWs)

Mark Jayson M. Villangca, Andrew Rafael M. Bañas, Technical Univ. of Denmark (Denmark); Thomas Aabo, Technical University of Denmark (Denmark); Darwin Palima, Jesper Glückstad, Technical Univ. of Denmark (Denmark)

We have previously proposed and demonstrated the targeted-light delivery capability of wave-guided optical waveguides (WOWs). This ability can be enhanced by coupling a nanoantenna which can be used for stimulation and sensing. The full strength of this structured-mediated paradigm can be harnessed addressing multiple WOWs and manipulating them to work in tandem. We propose the use of diffractive techniques to create multiple focal spots that will couple into the WOWs. This is done by using a spatial light modulator to project the necessary phase to generate the multiple coupling light spots. Among other techniques we can apply the simple and fast diffractive approach of multiple lenses and gratings to move the light spots around to accommodate the different orientations and positions of each WOW. We also perform optimization on the light coupling to the WOWs and achieve adiabatic focusing at the tip. We finally consider creating special optical landscapes along the free-standing waveguides for different applications such as drug delivery (i.e. micro-injection).

8999-51, Session 10

Rotation-induced cooling of an optically-trapped micro-gyroscope in vacuum

Yoshihiko Arita, Michael Mazilu, Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

Quantum state preparation of mesoscopic objects is a powerful playground for the elucidation of many physical principles. These quantum regimes can only be achieved through laser cooling and by minimizing the state decoherence. Here, we present a trapped, levitated rotating microparticle confined in an optical potential, that is well isolated from the thermal environment – a micro-gyroscope in vacuum. Rotation of microparticles is achieved by trapping a birefringent spherical vaterite crystal (4.40 microns in diameter) with a circularly polarized, tightly focused trapping laser beam operating at 1064nm. We show rotation rates exceeding 5MHz, which represents the fastest "man-made" rotating object to date. An optically trapped and simultaneously rotated particle in vacuum offers original perspectives on particle dynamics. At low rotation rates (1kHz), we see evidence of parametric coupling between the rotational and translational degrees of freedom of the trapped particle. Indeed, the trap stiffness varies slightly for different orientations of the particle and this orientation changes as the particle rotates and precesses. As the particle rotates faster (>10kHz), the particle motion around the particle axis is stabilized by the gyroscopic effect, which leads to a stabilization of the lateral (translational) motion of the particle. We show that fast rotation at 78kHz stabilizes and effectively cools the particle position to an effective temperature of 40K for all three translational directions. This trapped micro-gyroscope presents a powerful and original route to explore new directions in cavity optomechanics and is a major step towards measuring rotational quantum frictional forces.

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9000-1, Session 1

Device applications of cryogenic optical refrigeration

Seth D. Melgaard, Air Force Research Lab. (United States) and The Univ. of New Mexico (United States); Denis V. Seletskiy, Univ. Konstanz (Germany); Dana Sills, Richard I. Epstein, Thermodynamic Films (United States); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

With the coldest solid-state temperatures (ΔT >185K from 300K) achievable by optical refrigeration, it is now timely to apply this technology to cryogenic devices. Along with thermal management and pump absorption, this work addresses the most key engineering challenge of transferring cooling power to the payload while efficiently rejecting optical waste-heat fluorescence. We discuss our optimized design of such a thermal link, which shows excellent performance in optical rejection and thermal properties.

9000-2, Session 1

Effect of impurities on cooling efficiency in fluoride crystals *(Invited Paper)*

Alberto Di Lieto, Alberto Sottile, Azzurra Volpi, Zhonghan Zhang, Mauro Tonelli, Univ. di Pisa (Italy)

We present the measurement relative to cooling efficiency of LiYF4 crystals doped with Yb-ions. We studied samples with doping levels between 5% and 10%, grown from different raw powders, and we correlate cooling efficiency both spectroscopic and chemical analysis.

9000-3, Session 1

Preparation of high-purity LiF, YF3, and YbF3 for laser refrigeration *(Invited Paper)*

Markus P. Hehlen, William L. Boncher, Steven P. Love, Los Alamos National Lab. (United States)

Transition-metal impurities currently present the key limitation for achieving solid-state laser cooling to <100 K. Some transition-metal ions have strong and spectrally broad optical absorptions at the 1020 nm pump-laser wavelength used to excite Yb-doped laser-cooling materials. The impurity ions are excited either by direct absorption of the pump laser light or, at high Yb concentrations, by energy transfer from Yb-ions. The subsequent non-radiative decay of the excited transition-metal ions causes parasitic heating even at trace amounts. A correlation between the background absorption coefficient and the iron impurity concentration has recently been found experimentally for Yb3+-doped YLiF4 crystals (YLF:Yb). Metal impurities are present in the starting materials and can be introduced during the crystal growth. The former route likely dominates and can be addressed by targeted purification techniques. The present work builds on earlier efforts on preparing high-purity fluoride glasses (ZBLAN:Yb). The solvent-based purification presented here involves binding and extraction of transition-metal ions in a two-phase liquid system using a chelating agent. We report on progress in purifying LiF, YF3, and YbF3 starting materials used for the subsequent growth of ultra-pure YLF:Yb crystals for laser cooling.

9000-4, Session 1

Intracavity optical refrigeration to 130K using high-power vertical external-cavity surface-emitting lasers (VECSELs)

Mohammadreza Ghasemkhani, Alexander R. Albrecht, The Univ. of New Mexico (United States); Seth D. Melgaard, The Univ. of New Mexico (United States) and Air Force Research Lab. (United States); Denis V. Seletskiy, The Univ. of New Mexico (United States) and Univ. Konstanz (Germany); Jeffrey G. Cederberg, Sandia National Labs. (United States); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

Using anti-Stokes fluorescence principle, a Yb:YLF crystal is laser cooled to 130 K from room temperature in an intracavity arrangement for enhancing the pump absorption. The laser is a high power InGaAs/GaAs MQW VECSEL, tuned to 1020 nm (linewidth <0.5 nm) using a 4 mm thick birefringent filter in the cavity. The pump laser is a 70 W fiber-coupled diode laser at 808 nm. The crystal thickness is an important parameter for achieving low temperatures and is determined based on the optimal loss in the cavity which is about 5% in this case. The setup is inside a vacuum chamber and is pumped down to 10-5 torr to lower the convective heat load. To reduce the conductive heat load the crystal sits on two very thin microscope cover slips. The fluorescence emitted by the crystal is utilized to measure it's temperature using differential luminescence thermometry method. This is the lowest temperature achieved in the intracavity geometry to date and presents a major progress towards realizing an all-solid-state compact optical cryocoolers.

9000-5, Session 2

p x n-Type transverse thermoelectrics: an alternative Peltier refrigerator with cryogenic promise *(Invited Paper)*

Chuanle Zhou, Matthew Grayson, Yang Tang, Northwestern Univ. (United States)

The concept of band-engineered transverse thermoelectrics with p-type Seebeck in one direction and n-type orthogonal is introduced, possessing off-diagonal terms that drive heat flow transverse to electrical current. Such materials are named p x n ("p-cross-n") type transverse thermoelectrics. Whereas thermoelectric performance is normally limited by the figure of merit ZT, transverse thermoelectrics can achieve arbitrarily large temperature differences in a single leg Peltier cooler even with inferior ZT by being geometrically tapered. Similarly, a single meander line geometry can result in large Seebeck voltage generation, exceeding the optimal performance of a rectangular leg of standard thermoelectric. An intuitive microscopic model is introduced to explain the transverse thermoelectric effect in p x n materials. Because the Peltier cooling mechanism is intrinsic, p x n thermoelectrics can operate at cryogenic temperatures where standard longitudinal thermoelectrics fail. A band-structure engineering strategy is described, whereby alternating InAs and GaSb layers in a wide-period superlattice can give rise to the desired p x n Seebeck tensor. A literature survey shows some anisotropic bulk semiconductors also have the necessary p x n–type Seebeck behavior.

9000-6, Session 2

Electro-luminescent cooling in the deep sub-bandgap bias regime

Parthiban Santhanam, Massachusetts Institute of Technology (United States)

Electro-luminescent cooling, in which electrons and holes absorb heat from the lattice and subsequently release it as incoherent radiation, was recently observed in infrared light-emitting diodes at very low power density. These results utilized the low-bias regime in which the electrical energy qV is much smaller than the thermal energy kBT. Other investigations into electro-luminescent cooling have focused on much higher bias operation where qV is within a few kBT of the bandgap energy, but has been hampered by the associated requirement of very high quantum efficiency. We find that redesigning devices for the intermediate deep sub-bandgap bias regime, where kBT < qV < Egap-3kBT, could enable electro-luminescent cooling with higher power density, lower lattice temperature, and emitting shorter wavelength light. At near-infrared wavelengths, a quantum efficiency of 75% could provide milliwatts of room-temperature cooling power per cm^2, roughly 10^4 times the highest reported figures at any temperature to date.

9000-7, Session 2

Near-infrared up-conversion for photovoltaics: progress and challenges *(Invited Paper)*

Bryce S. Richards, Sean K. W. MacDougall, Aruna Ivaturi, Jose Marques-Hueso, Heriot-Watt Univ. (United Kingdom); Karl W. Krämer, Univ. Bern (Switzerland); Jonathan A. S. Morton, Georgios E. Arnaoutakis, Eliyas D. Mammo, Heriot-Watt Univ. (United Kingdom)

The upper efficiency limit of a single junction solar cell can be significantly increased by harvesting sub-band-gap photons via up-conversion (UC). External quantum efficiencies of such devices have improved steadily over the last few years and now significant UC photocurrents are being reported. For silicon photovoltaic devices, emphasis has been placed on determining both the photoluminescent quantum yield (PLQY) of Er3+-doped ?-NaYF4 via ~1500nm excitation. Internal PLQYs up to 10.7% and 8.5% for broadband (1480-1560nm, 2 MWm-2) and monochromatic (1523nm, 970 Wm-2) illumination have been achieved. External PLQYs for both scenarios are limited to ~6.5% due to weak absorption.

9000-8, Session 2

Spontaneous Raman cooling of solids

Matthew R. Tomes, Tal E. Carmon, Univ. of Michigan (United States)

Here we design a Raman refrigerator. Following recent demonstration of Brillouin cooling, a question arises if similar cooling is possible by Raman scattering. Raman cooling is expected to have 1000-times higher cooling efficiency compared to Brillouin cooling due to the ratio between optical- and acoustical-phonon frequencies. The major hurdle in the demonstration of Raman cooling is prevention of Stokes scattered light that creates phonons and heats the system. Though the Plank distribution implies that Stokes scattering is preferred, we design a three-dimensional photonic crystal with a bandgap that inhibits spontaneous emission to the Stokes line. An additional requirement is the anti-Stokes photon lifetime should be less than the phonon (picosecond) lifetime. This constrains the photonic crystal dimensions to be less than 200-um. Finally, absorption should be sufficiently low. As one of ten million photons per cm is expected to be anti-Stokes scattered, and cool at 20% quantum efficiency, absorption should be lower than one per fifty million per cm. Fortunately, materials such as CaF2 can in theory offer absorption of one per ten billion per cm when operating between the UV-resonance and multi-photon absorption regimes. The continuous trend of improving highly-transparent materials and photonic crystal fabrication techniques together with our calculation suggest that Raman cooling of solids is possible despite many challenges. The small cross section of Raman cooling can be mitigated by resonantly enhancing the pump (e.g. Fabry-Perot) and GeO2 might be preferred as it is highly transparent while having a high refractive index as needed for 3D bandgaps.

9000-9, Session 2

Laser cooling of dense atomic gases by collisional redistribution of radiation and spectroscopy of molecular dimers in a dense buffer gas environment

Anne Sass, Ralf Forge, Stavros Christopoulos, Katharina Knicker, Peter Moroshkin, Martin Weitz, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany)

We report on experiments investigating laser cooling of atomic gases by collisional redistribution of fluorescence, a technique applicable to ultradense atomic alkali- noble gas ensembles. The cooled gas has a density of more than ten orders of magnitude above the typical values in Doppler cooling experiments of dilute atomic gases. In frequent collisions with noble gas atoms in the dense gas mixture, the energy levels of the alkali atoms are shifted, and absorption of far red detuned incident radiation becomes possible. Redistribution of fluorescence takes place as the subsequent spontaneous decay occurs close to the unperturbed resonance frequency. The emitted photons have a higher energy than the incident ones, and the dense atomic gas ensemble is cooled. We here describe recent experiments of a rubidium-noble gas mixture and on the dependency of the cooling effect as a function of several experimental parameters; i. e. buffer gas pressure and species, incident laser power and wavelength. Our experimental findings are compared to simulations of the expected temperature distribution. Latest results indicate a temperature drop down to room temperature, initially starting from 700 K, a temperature required to reach sufficiently high alkali vapour density.

For the future, we expect that redistribution laser cooling can also be applied to molecular gas samples. We here describe two different approaches, working with alkali dimers on one hand, as well as the production of SrH molecules by laser ablation in dense buffer gas environment.

9000-23, Session PWed

Spectroscopic evaluation of Tm-doped potassium lead halides for 2um laser-cooling applications

Eric Kumi-Barimah, Uwe H. Hömmerich, EiEi Brown, Hampton Univ. (United States); Sudhir B. Trivedi, Brimrose Corp. of America (United States)

Tm3+ doped materials (Tm3+: ZBLANP [1,2], Tm3+: BaY2F8 [3]) have shown promising results for laser cooling applications at IR wavelengths of ~2µm with possible improvements in cooling efficiencies compared to Yb3+ based materials operating at ~1µm. The extended IR fluorescence of the involved Tm3+ transition (3H6->3F4), however, limits the choice of host materials due to increased non-radiative decay rates due to multi-phonon emission. For efficient 2um fluorescence, Tm3+ ions need to be doped into hosts with lower maximum phonon energies than typical found in oxide crystals (hwmax: ~700-1000 cm-1). In this work we explored the low-phonon energy materials KPC (hw<200cm-1) and KPB

(hw<140cm-1) as hosts for Tm^{3+} ions and evaluated their absorption and fluorescence properties for optical cooling. Results of the materials synthesis, crystal growth, and optical spectroscopy will be reported at the conference. Initial results of laser cooling experiments using the 1.907µm output of a Tm fiber laser will also be reported.

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9000-24, Session PWed

Light-up conversion versus light-down conversion in radiative cooling of semiconductors

Volodymyr K. Malyutenko, V. Lashkaryov Institute of Semiconductor Physics (Ukraine)

Aimed to shed more light at practical application of light conversion processes for radiative cooling of solids, we consider experimental results and compare operation principles and fundamentals of recently demonstrated two all-optical approaches to make semiconductors cooled through photo excitation of free carriers, light up conversion and light down conversion cooling processes. In the case of light up conversion, cooling is due to anti-Stokes (near-bandgap) luminescence in direct-band semiconductors with extremely high internal quantum efficiency following near-bandgap laser excitation (Nature 493, 504, 2013). In the case of light down conversion, cooling occurs due to the enhancement of thermal emission with overall energy of multiple (below-bandgap) photons escaping an indirect-bandgap semiconductor with low internal quantum efficiency exceeds the energy of a single pumped photon (J. Appl. Phys. 108, 073104, 2010; APL 102, 241102, 2013). The latter is the result of linear light down conversion process with >>100 % power conversion efficiency fueled with thermal energy (PRB 76, 113201, 2007). We also discuss the possibility to perform radiative cooling of semiconductor with over bandgap incoherent light pump. Figures of merit of our concern shall be the material band structure, cooling power, cooling and power conversion efficiencies, cooling temperature range, and entropy limitations.

9000-25, Session PWed

Thermal study of laser cooling in rhodamine dye using a Bragg grating

Sébastien Loranger, Ecole Polytechnique de Montréal (Canada); Elton Soares de Lima Filho, Bibl. UdeM - École Polytechnique de Montréal (Canada); Galina A. Nemova, Raman Kashyap, Ecole Polytechnique de Montréal (Canada)

Laser cooling of solids through anti-Stokes fluorescence (ASF) has attracted great attention recently, since it is a new promising technologyfor refrigeration. Another way of implementing cooling through ASF is to use liquids in which a highly fluorescent agent, such as dyes or quantum dots are dissolved, which have the advantage of flexibility in the geometry, ease of thermal contact and faster cooling cycle in comparison with rare earth. Although cooling through ASF was first demonstrated in liquids with Rhodamine as the fluorescent molecule[1], this first experiment was not fully acknowledged as there were significant doubts raised over theaccuracy of the temperature measurement. A few follow-up experiments have been realized, although always showing the same difficulties in temperature measurement. Here we propose the use of an FBG as a low thermal mass, transparent sensor, which constitutes a sensitive technique which overcomes most of the earlier difficulties. FBG temperature sensors are highly sensitive with mK resolution, while being able to monitor temperature in real-time. Here, we show the results of a thermal study in Rhodamine dyes with their pump wavelength dependence, to determine the optimal cooling conditions.The external efficiency of the studied Rhodamine solution is reported. This thermal study was done with a solution of Rhodamine encapsulated in a glass capillary in which the FBG sensor is co-located, directly in contact with the solution. The solution is side pumped as well as directly pumped with a large core multi-mode fiber inserted inside the solution.

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9000-10, Session 3

Can we laser cool a semiconductor single crystal? *(Invited Paper)*

Qihua Xiong, Jun Zhang, Chiyuan Zhang, Nanyang Technological Univ. (Singapore)

Laser cooling of semiconductors has recently been realized in II-VI nanoribbons. In order to scale up for practical optical refrigerator applications, it is critical to ask whether laser cooling is achievable in thin film or bulk crystal counterparts. In this talk, we will discuss the laser cooling potential in a series of bulk crystals, such as CdS, ZnTe, CdSe and ZnSe, commercially available or home-made, which are comprehensively evaluated by studying the absorption, anti-Stokes photoluminescence and resonance Raman spectra at different temperature and excitation wavelengths. The energy levels of all intrinsic defects including donor-acceptor pair (DAP), vacancies, interstitial defects and anti-site defects were assigned by comparing experimental results and ab-initio calculations. Commercial bulk crystals exhibit a broad anti-sites emission which eliminates any possible cooling, while those defects should be in extrinsic nature. We therefore develop crystal growth techniques to eliminate such anti-site defects. Our preliminary data indeed suggest that those defects in commercial crystal are extrinsic, which could be eliminated in the crystals we grew in laboratory. Our work suggests that bulk crystal is a promising way to scale up the right materials towards semiconductor optical refrigerators.

9000-11, Session 3

Laser cooling of CdS nanobelts: thickness matters

Dehui Li, Jun Zhang, Qihua Xiong, Nanyang Technological Univ. (Singapore)

Laser cooling of semiconductors has been recently demonstrated in CdS nanobelts. It is expected that the laser cooling of CdS nanobelts depends on their thickness since the emission peak, absorption band tail and external quantum efficiency all show thickness dependent behaviors. On the one hand, investigations on the thickness dependent laser cooling can help to clarify the mechanism of laser cooling. On the other hand, the knowledge about the thickness dependent cooling can guide us to select nanobelts with proper thickness for practical applications such as cooling of nanoelectronic devices. We have investigated the thickness dependence of laser cooling in CdS nanobelts pumping by a 532 nm laser. We find that nanobelts with a thickness around 80-120 nm show an efficient cooling. No net cooling for those belts with thicknesses below 65 nm can be observed for a 532 nm pumping, which is mainly due to the nearly zero absorption at 532 nm and the small external quantum efficiency induced by the large surface nonradiative recombination in the thinner nanobelts. Above 110 nm, both the reduction of the mean emission energy and the decrease of the external quantum efficiency due to the reabsorption contribute to the decrease of the normalized cooling

temperature. The modeling of the thickness dependent normalized temperature change has been carried out as well, which are consistent with the experimental results. If tunable wavelength laser (500 nm – 520 nm) is available, small net cooling is possible for nanobelts below 60 nm. Our finding can help to choose nanobelts with proper thickness for practical applications such as cooling of nanoelectronic devices.

9000-12, Session 3

Laser cooling based on nitride structures *(Invited Paper)*

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

We summarize what we have accomplished on GaN-based films and nanostructures. When the anti-Stokes and Stokes photon energies are far below the resonances of GaN, the ratio of the anti-Stokes and Stokes Raman intensities is 1/35 ≈ 0.029 at room temperature. In our recent experiment, we significantly improved this ratio to 0.5 in a GaN/AlN nanostructure. Recently, by exploiting the resonance of the bound-exciton transition, we increased the ratio of the anti-Stokes photoluminescence intensity and Stokes Raman intensity to 3.7 in GaN, which is significantly larger than 1. This implies that we may have reached the threshold for laser cooling in GaN. We will discuss all the relevant issues on laser cooling based on anti-Stokes Raman scattering and anti-Stokes photoluminescence.

9000-13, Session 3

Wide band gap semiconductors for optical refrigeration: an overlook

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

While laser refrigeration of solids doped with rare earth atoms has seen significant successes, the experiments performed with semiconductors have not achieved net cooling until recent experiments with CdSe nano ribbons. This points out to the wide bandgap semiconductors, such as nitrides and II-VI compounds as a possible solution. Wide bandgap semiconductors are characterized by low Auger recombination, large phonon energy, and strong electron-phonon coupling – all highly desirable features for laser cooling. In this talk we shall perform the assessment of different wide bandgap materials and identify the optimum strategy for efficient cooling of semiconductors.

9000-14, Session 3

High-performance cavity end mirrors based on substrate-transferred compound semiconductor heterostructures *(Invited Paper)*

Garrett D. Cole, Vienna Ctr. for Quantum Science and Technology, Univ. of Vienna (Austria) and Crystalline Mirror Solutions GmbH (Austria); Wei Zhang, Michael J. Martin, JILA (United States); Johannes Pohl, Ferdinand-Braun-Institut (Germany); Moritz Nagel, Evgeny V. Kovalchuk, Humboldt-Univ. zu Berlin (Germany); Alexei L. Alexandrovski, Stanford Photo-Thermal Solutions (United States); Markus Weyers, Ferdinand-Braun-Institut (Germany); Achim Peters, Ferdinand-Braun-Institut (Germany) and Humboldt-Univ. zu Berlin (Germany); Jun Ye, JILA (United States); Markus Aspelmeyer, Vienna Ctr. for Quantum Science and Technology, Univ. of Vienna (Austria)

Narrow-linewidth lasers and precision interferometers require mirrors that simultaneously exhibit excellent optical and mechanical performance. The current bounds of stability and sensitivity in these systems are dictated by the mechanical damping, and corresponding Brownian thermal noise, of the high-reflectivity coatings that comprise the cavity end mirrors. Recent work in the field of cavity optomechanics has shown that monocrystalline semiconductors, specifically AlGaAs-based heterostructures, are capable of significantly reduced mechanical damping, while achieving competitive reflectivity when compared with state-of-the art dielectric coatings. However, the implementation of such materials in a high-finesse cavity presents a number of challenges. Direct deposition onto typical optical substrates is precluded by lattice matching constraints, or in the case of amorphous substrates, by the lack of a crystalline template for seeded growth. Additionally, high-quality epitaxy is incompatible with curved surfaces required for a stable resonator design. Overcoming these obstacles, we have developed a microfabrication technique that enables the transfer of monocrystalline multilayers onto essentially arbitrary optical surfaces. Employing our "crystalline coatings" as end mirrors in a Fabry-Pérot cavity, we observe a thermally-limited noise floor consistent with a tenfold reduction in mechanical damping, paving the way for the next generation of ultrastable interferometers. While the demonstrated optical properties (finesse of 150,000 at 1064 nm) are sufficient for most applications, there are various benefits associated with further enhancements in the ultimate reflectivity. Along these lines, we describe our efforts in realizing parts-per-million levels of optical absorption in semiconductor Bragg mirrors, with the goal of achieving finesse values approaching 1,000,000 in the near-infrared.

9000-15, Session 4

Optical refrigeration in multi-level systems *(Invited Paper)*

Steven R. Bowman, U.S. Naval Research Lab. (United States); Christopher G. Brown, Sotera Defense Solutions (United States); Joseph Ganem, Loyola Univ. Maryland (United States)

Optical cooling has been demonstrated in a number of solid-state materials using anti-Stokes emission in two-level systems such as ytterbium. This approach relies on thermal broadening to maintain the spectral separation required for effective optical pumping. While effective at elevated temperature, this approach rapidly looses effectiveness as temperatures decrease. Here we examine the potential for optical cooling via Stokes emission generated by non-resonant cross relaxation in multi-level electronic systems. By providing an intrinsic energy mismatch, these systems have the potential to maintain effective pump absorption and cooling for cryogenic operation. A theoretical comparison with two-level systems and analysis of promising candidate materials will be presented.

9000-16, Session 4

Temperature dynamics of laser cooling of solids with Yb3+ ions

Galina A. Nemova, Raman Kashyap, Ecole Polytechnique de Montréal (Canada)

Laser cooling of solids is one of promising areas of laser physics. The interest to this area is caused first of all by the development of an all solid-state optical cryocooler, which is compact, free from mechanical vibrations, moving parts and liquids. It is based on high reliable diode pump systems and does not introduce electro-magnetic interference in the cooling area. The idea of cooling solids with anti-Stokes fluorescence was proposed in 1929 [1] and experimentally realized for the first time with the Yb3+:ZBLANP sample in 1995 [2]. In 2013, laser cooling to 119K, below NIST cryogenic temperature of 123K with Yb3+:YLF crystal, was announced [3]. Since the first experimental observation in 1995 laser cooling of solids with anti-Stokes fluorescence has been observed with Yb^{3+}, Tm^{3+}, and Er^{3+} rare-earth (RE) ions doped in wide variety of low-phonon glass and crystal hosts. Today Yb^{3+} ions look like the most suitable and promising for cooling application since they are the only RE ions, which have only two manifolds: the ground (2F7/2) and excited (2F5/2) manifolds. Two level Yb^{3+} ions are free from excited state absorption, which is a source of undesirable heat generation mitigating cooling. Although some theoretical estimations concerning cooling with Yb^{3+} ions have already been reported, we present a comprehensive theoretical investigation of cooling in a host system doped with Yb^{3+} ions. The temperature dependences on all parameters, such as absorption and emission cross sections, mean fluorescence wavelength as well as the interaction of Yb^{3+} ions with impurities for different concentrations of Yb^{3+} ions in the host are taken into account and investigated. We can see how the temperature dependences of these parameters influence on the efficiency of cooling and the minimum achievable temperature. This understanding of cooling is very useful for the design of an optical cryocooler.

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9000-17, Session 4

Direct measurement of laser cooling of Yb:YAG crystal at atmospheric pressure using a fiber Bragg grating

Elton Soares de Lima Filho, Bibl. UdeM - École Polytechnique de Montréal (Canada); Galina A. Nemova, Sébastien Loranger, Raman Kashyap, École Polytechnique de Montréal (Canada)

Although Yb:YAG has been cooled in a vacuum environment [1], we report for the first time an experimental demonstration of optical cooling at atmospheric pressure. A Yb:YAG crystal is supported on thin silica fibers, inside a matt-black chamber with air at atmospheric pressure, and pumped at 1029 nm, in pulsed and CW regime. Direct measurement of the crystal surface temperature during pumping was made possible by using a low-mass, transparent fiber Bragg grating (FBG) sensor. The FBG interrogation system has sufficient sensitivity to measure the background absorption of the sample, and bulk cooling at pump power as low as 17 mW. The dynamical measurement of the temperature allows the determination of the overall heat transfer coefficient of the sample in the air of 22 W/(m2-K). A temperature drop of 8.8 K from the chamber temperature is observed in the Yb:YAG crystal in air when pumped with 4.2 W at 1029 nm, close to the value of 8.9 K observed in vacuum [1]. A background absorption α_b = 2.9x10-4 cm-1 is estimated with a pump wavelength at 1550 nm. Simulations predict further cooling when the sample's cross sectional area and the pump power are optimized, considering absorption saturation effects. The choice of an efficient geometry, the use of a readily available temperature sensor in less controlled environments, should simplify implementation of laser cooling systems and the development of commercial devices.

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9000-18, Session 5

Next generation optical refrigerators *(Invited Paper)*

Richard I. Epstein, The Univ. of New Mexico (United States) and ThermoDynamic Films (United States); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

Advances over the last few years has made optical refrigeration the first solid-state technology that can cool from room temperatures to cryogenic temperatures. At the current operation temperatures of near 100K, optical refrigeration be used for a range of applications the value the absence of vibrations and compactness that this technology offers. These applications include cooling conventional electronics such as low-noise amplifiers and high-purity germanium gamma ray spectrometers and pre-cooling other vibrationless cryocoolers such as Joule-Thomson devices that go to much lower temperatures. Improvements in the materials and designs of future optical refrigerators will lead to optical refrigerators that can cool to below 70 K with coefficients of performance above 10. These next generation optical refrigerators would be able to cool high-temperature superconductor electronics and provide replacements for stirling cycle cryocooler and other mechanical coolers that are more compact and efficient as well as producing no vibrations. In this talk I will outline the steps needed to achieve this next generation. The challenges to achieving these goals include developing new high-performance cooling materials and high-efficiency lasers at the appropriate wavelength and modifying the architecture of the optical refrigerators so that they recycles the waste fluorescent light.

9000-19, Session 5

All-optical photon-waste recycling in laser cooling of solids

Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

It has been shown that luminescence recycling using photovoltaic power convertors could drastically enhance the wall-plug efficiency in optical refrigeration. Analysis and methods for achieving this in an all-optical manner (i.e. without photovoltaics) will be presented here. The cooling chamber essentially consists of a thermally-isolated two-body system: an anti-Stokes upconversion material (cold side) and a Stokes down-convertor (hot side).

9000-20, Session 5

Progress in optical cooling using integrated all-fiber Tm-doped glass fibers and Tm-doped fiber lasers

Dan T. Nguyen, Rajesh Thapa, Jie Zong, Dan L. Rhonehouse, NP Photonics, Inc. (United States); Nai-Hang Kwong, College of Optical Sciences, The Univ. of Arizona (United States); Rolf Binder, College of Optical Sciences, The Univ. of Arizona (United States) and College of Optical Sciences, The Univ. of Arizona (United States); Arturo Chavez-Pirson, NP Photonics, Inc. (United States)

Theoretical and experimental progress toward all-fiber optical cooler using Tm-doped glass fibers as optical cooler and Tm-doped glass fiber laser as a pumping source are presented. Important achievements include that glasses for fabrication of cooling fiber have been purified with all transition metals less than 1ppm, and in particular OH-absorption is reduced from tens of dB/m to currently ~ 0.2dB/m at the peak of OH absorption near 3.3 microns. Net cooling in isolated Tm-doped tellurite glass fibers has been demonstrated experimentally. Furthermore, experimental efforts of utilizating the cooling power in single- and multiple-fiber configurations to cool a heat source are underway, and their results will be reported. Theoretical modeling of heat transfer between the cooling fiber and heating source help to understand and optimize the cooling experiments. The numerical cooling simulations are based on the solution of the heat transport equation and include effects of thermal conduction as well as convective and radiative coupling to the ambient. The all-fiber optical cooling is potentially applicable in many device applications due to its light weight, compact, vibration-less and micro-scale design and the potential for long lifetimes even in harsh space conditions. The cooling fiber can be easily integrated to an optical fiber system that can transfer part of the heat to a remote location.

9000-26, Session 5

Exploring Coulomb Interaction in Piezoelectric Materials for Assisting the Laser cooling of Solids

Iman Hassani Nia, Hooman Mohseni, Northwestern Univ. (United States)

Coulomb interaction among photoexcited carriers in spatially separated states can lead to interesting quantum phenomena. In this paper we demonstrate how coulomb interaction could be utilized to facilitate the laser cooling of piezoelectric materials. In this kind of materials, the electrostatic potential is associated with a piezoelectric stress. Therefore the force exerted on the atoms can be controlled by changing the electrostatic potential. We explain how the coherent piezoelectric force on the atoms caused by the change of carrier density can assist cooling or heating (phonon amplification) in a properly designed MQW structure. Numerical investigations (by solving self consistent Poisson and Schrodinger equations) show that the efficiency of this mechanism can be significantly higher than Anti-Stokes process. To demonstrate the advantage of this method even further, we present simulations by using experimentally reported parameters of GaN and In0.15Ga0.85N, in order to conclude that the net cooling is indeed possible even with current III-nitride growth technology. The dependency of cooling efficiency on the laser intensity and wavelength is explained in detail. At optimum conditions the threshold Shockley-Reed-Hall recombination rate for net cooling can be enhanced by two orders of magnitude for the structure under consideration. Owing to the high efficiency of this mechanism, the next step is to investigate it in other strong piezoelectroic semiconductors such as III-V quantum dots.

9000-27, Session 5

Upconversion lasing, heat transfer and stimulated cooling in solids

K. Sandner, Helmut Ritsch, Univ. of Innsbruck (Austria)

A laser can be understood as a thermodynamic engine converting heat to a coherent single mode field close to Carnot efficiency. To achieve lasing, spectral shaping of the excitation light is used to generate a higher effective temperature on the pump than on the gain transition. Here, using a toy model of a quantum well structure with two suitably designed tunnel-coupled wells kept at different temperatures, we predict that lasing can also occur on an actual spatial temperature gradient between the pump and gain regions. Gain and narrow band laser emission require a sufficiently large temperature gradient and resonator quality. Lasing appears concurrent with amplified heat flow between the reservoirs and points to a new form of stimulated solid state cooling. In addition, such a mechanism could reduce intrinsic heating and thus extend the operating regime of quantum cascade lasers by substituting phonon emission driven injection by a phonon absorption step.

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9001-20, Session PWed

Chaos synchronization and encrypted communication systems as an application of VCSELs

Masanori Hisatomi, Wakao Sasaki, Doshisha Univ. (Japan)

In this work, we have proposed electro-optical nonlinear delayed feedback systems (NDFS's) using the VCSEL's for the first time which have high potential to perform more sensitive chaotic dynamics for an improvement of the secure communications quality. Sensitive dependence on initial conditions can be kept by using VCSEL's, and it has been able to be varying chaotic output dynamically by the slight difference of initial value in NDFS's. We have proposed chaos synchronization system using the two identical NDFS's. We have realized chaos synchronization linked simple direction of Master-Slave model by injecting a part of the LD driving voltage of the Master System into the Slave System as a synchronization signal. Where, feedback gain and delay time are the parameters, which are able to be utilized as the secret encryption key when performing the secure communications. In this system, we have demonstrated the reduction of robustness to prevent tapping by someone else attaining higher correlation only if the feedback gain is just the same value, and also demonstrated the variations of correlation if feedback gain has the slight difference, as well. Moreover, we also have demonstrated applications to secure communications using VCSEL's. As a consequence of the chaotic synchronization experiment, correlation coefficient over 0.9, up to about as much as 0.98 has been attained if the feedback gains of both systems are just the same. In addition, the correlation reduction rate of about 65% has been accomplished with only 10% difference of the feedback gain. In conventional edge emitting type LD, if the injection ratio of the synchronization signal from master to slave is considerably large e.g. about 50%, the reduction of robustness is come to be very difficult because even more than 10% difference in the feedback gain could not reduce the correlation coefficient of the chaotic synchronization by 10%. In our present work using VCSEL, the high correlations could be seen only if feedback gain is just the same value between master and slave, and thus more secure communications have been achieved. As a consequence of the secure communications, accuracy above 90% restoration of the original information signal has been realized if the feedback gain was the same value. So that possibility of application to encrypted communications by VCSEL's is suggested, because it could be difficult to tapping the information signal if feedback gains between master and slave have 10% difference.

9001-1, Session 1

28-Gbps 850-nm oxide VCSEL development and manufacturing progress at Avago *(Invited Paper)*

Thomas R. Fanning, Avago Technologies Ltd. (Singapore); Jingyi Wang, Avago Technologies Ltd. (United States); Zheng-Wen Feng, Avago Technologies Ltd. (Singapore); Mark R. Keever, Avago Technologies Ltd. (United States); Chen C. Chu, Aaditya Sridhara, Avago Technologies Ltd. (Singapore); Cesare F. Rigo, Avago Technologies Srl (Italy); Hairong Yaun, Terry E. Sale, Avago Technologies Ltd. (Singapore); Laura Giovane, Avago Technologies Ltd. (United States)

Avago's 850nm VCSEL for applications requiring modulation at 25-28Gbps have been designed for -3dB bandwidths in excess of 19GHz over the extended temperature range of 0-85°C. The DBR mirrors have been optimized to minimize optical losses and thermal and electrical resistance. The active region is designed to provide superior differential gain for high optical bandwidth. In this paper we will describe the design for performance and manufacturability of Avago's high speed 25-28Gbps VCSEL. Analysis of the high-speed modulation characteristics and results of wear out reliability studies will be presented. We will also discuss the manufacturability of this next generation of high performance, reliable lasers. The challenges of epitaxial growth and wafer fabrication along with the associated process control technologies will be described.

9001-2, Session 1

Energy-efficient oxide-confined high-speed VCSELs for optical interconnects *(Invited Paper)*

Philip Moser, Philip Wolf, Gunter Larisch, Hui Li, James A. Lott, Technische Univ. Berlin (Germany); Dieter H. Bimberg, Technische Univ. Berlin (Germany) and King Abdulaziz Univ. (Saudi Arabia)

Energy efficient oxide-confined vertical-cavity surface-emitting lasers (VCSELs) emitting at 850 and 980 nm that are particularly well suited for optical interconnects are presented. Error-free operation (bit error ratio < 1E-12) up to 40 Gb/s in a back-to-back configuration and at 25 Gb/s across up to 1 km of multimode optical fiber is demonstrated with ~100 fJ dissipated energy per bit. Trade-offs between oxide-aperture diameter, cavity photon lifetime, current-density, and energy efficiency are demonstrated and discussed.

9001-3, Session 1

1060nm 28-Gbps VCSEL developed at Furukawa

Toshihito Suzuki, Masaki Funabashi, Hitoshi Shimizu, Shinichi Kamiya, Kazuya Nagashima, Akihiko Kasukawa, Furukawa Electric Co., Ltd. (Japan)

With the progress of data centers and supercomputers, parallel optical interconnect plays an important role, in which VCSELs are used as high speed and energy-saving light sources. To improve system performance further, an increasing number of VCSELs with higher speed, lower power consumption, and enhanced reliability are required.

This paper presents recent development results of our 28-Gbps VCSELs featured with double intra-cavity structures and a lasing wavelength of 1060nm. The double intra-cavity realizes very low cavity loss due to undoped semiconductor bottom DBR and dielectric top DBR layers. Compressively strained InGaAs MQW provides high differential gain that contributes to low power consumption and high reliability.

Based on our 10-Gbps VCSEL structure, we carefully optimized MQW, selective oxide structure, cavity length, and doping profile in order to achieve high speed operation while maintaining high reliability and other laser performances. The developed VCSELs exhibit modulation bandwidth exceeding 20GHz and D-factor of 10GHz/(mA)1/2. Typical threshold current and slope efficiency are 0.5mA and 0.5W/A, respectively.

The paper also discusses static and dynamic characteristics of VCSELs with various oxide aperture sizes simultaneously fabricated on the same wafer. For a longer transmission distance and better optical coupling to a multimode fiber, lateral confinement is precisely controlled to reduce spectral width as well as far field pattern (FFP). Clearly opened eye diagrams are obtained at multiple bit rates up to 28-Gbps. Bit error rate (BER) tests are also performed and 25-Gbps error free transmission has been confirmed over 300m multimode-fiber optimized for 1060nm with a PRBS pattern length of 2^31-1.

9001-4, Session 1

VCSEL arrays for high-aggregate bandwidth of up to 1.34 Tbps

Martin Grabherr, Roger King, Steffan Intemann, Stefan Wabra, Roland Jäger, Michael Riedl, Philipp Gerlach, Philips Technologie GmbH U-L-M Photonics (Germany)

Even though the lane speed of VCSEL based AOC and transceivers has reached 25 Gbps and beyond, parallel optics are getting even more important in order to meet the required aggregate bandwidths for upcoming applications, among others, 100 Gigabit Ethernet, Infiniband EDR, or EOM (embedded optical modules).

As 100 GB can be achieved by, e.g., 4 times 25 Gbps using standard QSFP footprint, different approaches are using large scale 2D VCSEL arrays operating at lower lane speeds. In 2013 Compass EOS has introduced a 1.34 Tbps core router solution that incorporates 2D VCSEL arrays of 12 times 14 emitters, each operated at 8 Gbps, designed and manufactured by Philips U-L-M Photonics. The VCSEL array is mounted face down onto a CMOS ASIC, directly on top of the analog area. Emission wavelength of 1000 nm allows for substrate side emission and thus for flip-chip mounting as well as integration of 2D microlens arrays.

(Reference: Kobi Hasharoni et al., “A high end routing platform for core and edge applications based on chip to chip optical interconnect”, OTu3H.2, OFC/NFOFC, 2013).

We introduce the different VCSEL technologies that address lane speeds of 25 Gbps and beyond and 2D VCSEL arrays designed for most compact assembly technology. Performance and reliability aspects for the respective products are discussed and focus is set on the very low power consumption achieved by both concepts.

9001-5, Session 1

Ultrafast direct modulation of transverse-mode coupled-cavity VCSELs far beyond the relaxation oscillation frequency

Hamed Dalir, Fumio Koyama, Tokyo Institute of Technology (Japan)

VCSELs have grown highly in popularity and their capability has been increased in various applications. The merits of VCSELs include low small footprint, low power consumption and so on. VCSELs have been used in short-reach datacom and mainly deployed in optical interconnects for data centers and supercomputers. The maximum speed of directly modulated VCSELs is limited by the intrinsic limitation of relaxation oscillation frequencies and their parasitic capacitance. There have been various reports on the bandwidth enhancement of VCSELs, which includes injection-locking, coupled cavity, modulator-integration and so on. We have been working on the optical feedback to enhance the modulation bandwidth of VCSELs. While there have been difficulties in VCSELs in terms of their stability in making external cavities. Recently, we proposed a transverse-optical-feedback scheme for increasing the modulation bandwidth of VCSELs and predicted 60% enhancement in their small signal modulation bandwidth.In this paper, TCC scheme for enhancing bandwidth of VCSELs is demonstrated. Our measured results show that the 3-dB bandwidth for aperture diameter of 8.5?8.5um^2 can go beyond 29 GHz of the photo-detector limitation, which is 3 times larger than a conventional VCSEL without optical feedback. To the best of our knowledge, this is currently the world’s fastest 980nm VCSEL. Also, we achieved 36Gbps clear eye opening with 4dB extinction ratio and PRBS of 2^31-1. Using smaller aperture diameters enables us to have single mode operation while a small signal bandwidth of 18-20GHz and large signal modulations of 30-32 Gbps are demonstrated.

9001-6, Session 2

Tunable MEMS-VCSEL with >140-nm tuning range using SiO/SiC-based MEMS-DBR

Christian Gierl, Karolina Zogal, Sujoy Paul, Franko Küppers, Technische Univ. Darmstadt (Germany)

MEMS-VCSEL are aiming for applications such as gas spectroscopy, fiber Bragg-sensors and telecommunications. Their inherently short cavity enables a wide continuous single mode tuning of the emitted wavelength due to the short cavity related large free spectral range. Their low power consumption, on wafer-testability and small beam divergence make them attractive for the mentioned applications.

In this paper we propose a SiO/SiC-based material system for the movable DBR-membrane utilized by MEMS-VCSEL. With an refractive index contrast of Δn=1,1 only 11 alternating layers of SiO and SiC are needed to achieve the same maximum reflectivity of R=99,7% (at 1550 nm) as it is achieved by 23 layers of the material system SiO/SiN, which has been used for the up to date world record electrical pumped MEMS-VCSEL with a continuous tuning of 100 nm.

Compared to the SiO/SiN-DBR, the smaller number of pairs reduces the total thickness of the mirror membrane by a factor of three and thus the stiffness by a factor of 27. This enables the reduction of the overall size of the MEMS and thus a reduction of the total laser resonator length. It is shown that the new short-cavity devices will be able to be continuously tuned over more than 140 nm. Due to the high refractive index contrast between SiO/SiC, the spectral width of the reflectivity for R>99,5 % is improved to 330 nm compared to 140 nm achieved with the SiO/SiN DBR. This additionally supports the much larger tuning range of 140 nm.

9001-7, Session 2

In-plane integration of VCSEL with photo-detector by using laterally coupled cavities

Hamed Dalir, Fumio Koyama, Tokyo Institute of Technology (Japan)

VCSELs have been widely used for wide variety of applications such as datacom and optical sensing. The unique features of VCSELs including low small footprint, wafer-scale testing, low-cost packaging, low power consumption and easy of fabrication into arrays have been already proven. The in-plane integration of other optical devices offers new functionalities. In this paper, an in-plane photo-detector integrated VCSEL using transverse-coupled-cavity (TCC) scheme is demonstrated for the first time. A bow-tie shape oxide aperture was fabricated in order to form two cavities laterally coupled with each other. One-cavity functions as a VCSEL by pumping and the other one can be used as a photo-diode by applying a reverse bias voltage of -1 V. Ion-implantation was carried out in order to reduce the current leakage. The electrical isolation is over 1 MOhm. The aperture diameter of each cavity is 6x6µm2 with 4µm joint width connection. The threshold current is as low as 0.7mA. We obtained continuous tracking of the VCSEL output and the photo-current of the integrated detector in the VCSEL current range of 0.7- 10mA. A photo-detector monitor sensitivity of 0.25 A/W is attained. The integrated photo-detector can offer high-speed response thanks to low parasitic capacitance, which may open up new functionalities of VCSEL-based photonic integrated circuits.

9001-8, Session 2

Heterogeneously-bonded VCSEL arrays and electro-thermal modeling

Kent D. Choquette, Hyejin Jeong, Univ. of Illinois at Urbana-Champaign (United States)

A post-fabrication bonding technique for integrating semiconductor vertical cavity surface emitting lasers (VCSELs) onto hybrid substrates is demonstrated. This approach provides flexibility regarding the choice of device fabrication and hybrid substrate materials. Light output versus injected current and applied voltage characteristics of lasers are measured before and after the transfer process onto Si, polyethylene terephthalate, and Cu substrates. We present a simple VCSEL electro-thermal model and agreement is obtained between simulation and experiment for lasing wavelength with varying laser diameter. Using this model, the thermal limitations of the VCSEL output on different substrates is discussed.

9001-9, Session 2

Triggering of guiding and antiguiding effects in GaN-based VCSELs

Seyed Ehsan Hashemi, Jörgen Bengtsson, Johan S. Gustavsson, Martin Stattin, Chalmers Univ. of Technology (Sweden); Marlene Glauser, École Polytechnique Fédérale de Lausanne (Switzerland); Gatien Cosendey, Nicolas Grandjean, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Marco Calciati, Michele Goano, Politecnico di Torino (Italy); Åsa Haglund, Chalmers Univ. of Technology (Sweden)

In electrically-injected GaN-based VCSELs, several realization schemes of current apertures have been developed by different groups. We show that many of these lead to unintentional optical antiguiding, resulting in high lateral leakage loss, causing the threshold gain to increase by more than a factor of two. Moreover, a nanometer-sized structural change can be sufficient to trigger the transition from a guiding to an antiguiding cavity, or vice versa, causing a variation in the lateral leakage loss by orders of magnitude. The transition point can be precisely predicted using a computationally efficient quasi-2D effective index method. Physically, the transition is explained as the opening/closing of a channel of efficient lateral leakage through resonance in the peripheral part of the cavity. Notably, for strong enough antiguiding the lateral leakage decreases so that the threshold gain values might be tolerable. In the past, operation in this regime has been suggested to achieve single mode VCSELs, since a very strong modal discrimination has been forecasted. However, rather than a previously predicted fourfold increase in lateral leakage loss for the first higher order mode compared to the fundamental mode, our simulations indicate a much more moderate 50-100% increase. The smaller difference in loss values implies that the discrimination between the modes is less effective than previously thought. Finally, current simulations of a realistic cavity showed that the temperature increase caused by the electric pumping spatially modifies the refractive index distribution to such an extent that the optical guiding, and thereby threshold gain, may be influenced.

9001-10, Session 2

Optimizing the energy efficiency, bit rate, and modal properties of VCSELs for very-short-to-medium-reach optical interconnects

Hui Li, Philip Moser, Vladimir Kalosha, Philip Wolf, Technische Univ. Berlin (Germany); Alexey S. Payusov, Ioffe Physico-Technical Institute (Russian Federation); Gunter Larisch, James A. Lott, Technische Univ. Berlin (Germany); Dieter H. Bimberg, Technische Univ. Berlin (Germany) and King Abdulaziz Univ. (Saudi Arabia)

We experimentally and numerically analyze multiple design variations of GaAs-based vertical cavity surface emitting lasers (VCSELs) containing AlGaO “oxide” layers using our in-house-developed 1D to 3D numerical software tools and our nanophotonics device processing and high frequency analysis laboratories. We present VCSEL designs that independently maximize energy efficiency, bit rate, transmission distance, and selected intrinsic device figures-of-merit. We also study practical design trade-offs seeking to optimize the overall bandwidth density performance of VCSELs for applications in very-short-reach (up to ~10 mm) to medium-reach (up to ~2 km) optical interconnects. We solve the vector eigenvalue wave equation including material layer index dispersion for various VCSEL epitaxial structures with variations in the number, placement, and thickness of selectively-oxidized AlGaAs layers. We further vary the VCSEL cavity photon lifetime and other VCSEL design parameters by tuning the physical parameters of selected VCSEL epitaxial layers. We compare our numerical results to our experimental VCSEL results, including state-of-the-art VCSELs operating at bit rates of 25-to-40 Gbit/s with dissipated heat energies of below 100 fJ/bit.

9001-11, Session 3

Evolution of VCSELs *(Invited Paper)*

Jim A. Tatum, Finisar Corp. (United States)

Over the last 20 years, nearly 1 billion VCSELs have been shipped, the vast majority of them emitting at 850nm using GaAs active regions, and primarily used in data communications and optical tracking applications. Looking to the future, the ever increasing speed of data communications is driving VCSEL to evolve with more complex active regions, optical mode control, and alternate wavelengths to meet the more stringent requirements. We will discuss the current state of VCSELs for 28Gbps, and higher speeds, focusing on evolution to more complex active regions and alternate wavelength approaches, particularly as the market evolves to more active optical cables. Other high volume applications for VCSELs are driving improvements in single mode and optical power characteristics. We will present several evolving market trends and applications, and the specific VCSEL requirements that are imposed. The ubiquitous 850nm, GaAs active region VCSEL is evolving in multiple ways, and will continue to be a viable optical source well in to the future.

9001-12, Session 3

Progress towards commercialization of 25-Gb/s VCSELs

Li Wang, Chuan Xie, Neinyi Li, Shenghong Huang, Sumitomo Electric Device Innovations, U.S.A., Inc. (United States)

In this talk, we will present the development progress of 850-nm vertical-cavity surface-emitting lasers (VCSELs) operating at 25 Gb/s and beyond at Sumitomo Electric Device Innovations USA. To obtain high performance, low-power consumption and reliable VCSELs for EDR and 32GFC applications, it is necessary to optimize both wafer growth and VCSEL structures with indium-containing quantum well materials. We will present the recent progress towards commercialization of the new device, such as 30% reduced current density for 25 to 28 Gb/s operations. In addition, we will also discuss simulation results for structure optimization.

9001-13, Session 3

Progress on vertical-cavity surface-emitting laser arrays for infrared illumination applications

Delai Zhou, Jean-Francois Seurin, Guoyang Xu, Alexander Miglo, Daizong Li, Qing Wang, Mukta Sundaresh, Sam Wilton, Joe Matheussen, Chuni Ghosh, Princeton Optronics, Inc. (United States)

Infrared illumination (808nm – 1064nm) is broadly used in commercial and defense markets for surveillance and security operations. Compared with LED and edge emitters, vertical cavity surface-emitting lasers (VCSEL) provide combined advantages such as high efficiency, low diverging circular beam, narrow emission spectrum and low-cost manufacturability that include wafer level test and array integration. In addition, the emission of these VCSEL-based illuminators is speckle-free with no interference patterns. VCSELs can also operate at high temperatures, thereby meeting the harsh environmental requirements of many illuminators. The efficiency and brightness of these VCSELs also reduce the requirements of the power supply compared to, for example, an LED approach.

We report our progress on high-power high-efficiency two dimensional (2D) VCSEL arrays for such illumination applications that emit from a few watts up to several thousand watts. GaAs based VCSEL wafers are grown by MOCVD and processed into top emitting devices with selective wet oxidation, due to the strong substrate absorption. CW operations with output of >100W and efficiency of > 45% are recorded. Results from both single devices and arrays will be presented with special focus on array level device optimization. The GaAs substrate is removed for high power large size arrays (such as 5x5mm array for long distance illumination) to improve its heat dissipation. However, substrates are kept at ~100um for smaller arrays with lower power requirement (such as a few watts, for less than a few hundred meter distance illumination purpose).

9001-14, Session 3

Optimized VCSELs for high-power arrays

Holger Moench, Johanna S. Kolb, Philips Technologie GmbH (Germany); Andreas P. Engelhardt, Univ. Kassel (Germany); Philipp Gerlach, Roland Jäger, Jens Pollmann-Retsch, Ulrich Weichmann, Philips Technologie GmbH (Germany); Bernd Witzigmann, Univ. Kassel (Germany)

High power VCSEL systems with multi kilowatt output power require a good electro-optical efficiency at the point of operation i.e. at high temperature. The large number of optimization parameters can be structured in a way which separates system and assembly considerations from the minimization of electrical and optical losses in the epitaxially grown structure. A fit to the experimental data describes the properties of a single VCSEL depending only on diameter, current and temperature. This includes temperature dependent functions for gain parameters, internal losses and injection efficiency. Diameter dependent effects like current spreading and temperature dependent voltage drops over hetero-interfaces in the DBR mirrors are taken into account. By evaluating experimental measurements of the light output and voltage characteristics over a large range of temperature and diameter wafer-characteristic parameters are extracted allowing to predict the performance of VCSELs in a different configuration made from the same material. This approach has several beneficial outcomes: First, it gives a general description of a VCSEL independent of its geometry, mounting and detuning, second, insights into the structure and the underlying physics can be gained that lead to the improvement potential of the structure and third the performance of a structure in arrays and modules can be predicted. Experimental results will be presented which validate the approach and demonstrate the significantly improved VCSEL efficiency. The design and performance of exemplary high power systems based on this improved material will be presented.

9001-15, Session 4

Coherent switching of polarization oscillations in spin-polarized vertical-cavity surface-emitting lasers

Henning Höpfner, Markus Lindemann, Nils C. Gerhardt, Martin R. Hofmann, Ruhr-Univ. Bochum (Germany)

Spin polarized lasers, especially spin polarized vertical-cavity surface-emitting lasers (VCSEL) provide improved performance when compared to conventional, purely charge-based lasers. Advantages of these spin-enhanced devices lie in their reduced laser threshold, increased emission intensity, amplification of spin information, chirp control and possibilities for ultrafast modulation due to their faster dynamics.

Utilizing a commercially available conventional VCSEL and additional spin polarized optical pumping we are able to enhance the modulation dynamics of a conventional VCSEL with new spin effects. Our experiments show polarization oscillations in the spin-photon system that result in oscillations of the circular polarization of the VCSEL emission. The resulting polarization oscillations are of significantly higher frequency than the direct modulation bandwidth of the VCSEL and persist for durations longer than the spin lifetime in the active region. Simulations based on a rate-equation model show that with an improved VCSEL layout it should be possible to reach oscillation frequencies well above 100 GHz.

Here, we show that with multiple optical spin polarized pulses these oscillations can be coherently excited, amplified and also stopped. Using this excitation scheme, polarization oscillations faster than the purely charge-based dynamics can be achieved with half cycle to multi cycle duration.

Various influences of unpolarized electrical bias, optical excitation power and delay between pulses will be discussed both theoretically and experimentally. Additionally, we analyze the qualification of this new concept for ultrafast optical communication.

9001-16, Session 4

Spatial mode discrimination in anti-guided arrays of long-wavelength VCSELs

Tomasz Czyszanowski, Maciej Dems, Technical Univ. of Lodz (Poland); Robert P Sarzala, Lodz Univ of Technology (Poland); Vladimir Iakovlev, Nicolas Volet, Elyahou Kapon, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Anti-guided mode schemes are analysed as a confinement mechanism in wafer-fused InAlGaAs/InP 1300 nm VCSEL arrays. They provide larger side mode suppression ratio (SMSR) than any other waveguiding schemes. The anti-guided optical apertures are defined by low refractive index discs introduced by patterning the interface between the cavity and the top GaAs/AlGaAs DBR. We apply the three dimensional, fully vectorial Plane Wave Admittance Method and perform an exhaustive analysis of the modal gain of all confined modes as a function of the array parameters such as distance between emitters and their aperture size. We found two distinct aperture sizes (6 and 8 micro m), which assure high level of modal gain of the HE11 mode and strong higher order modes discrimination in the case of the single emitter.

We analyse the emitted wavelengths and modal gains of the transversal modes as the function of the distance between the emitters for both aperture sizes in the case of 2x1, 3x1 and 4x1 arrays. The arrays reveal periodic dependence of the desired properties: large modal gains, large

SMSR and in-phase emission with the change of the distance between the emitters. The increase of the distance between the emitters leads to the resonance between successive higher order modes and the array. We determine the optimal geometrical parameters which assure desirable properties. Finally we provide the explanation for the competition between the lateral modes and analyse the modes evolution driven by the change of the distance between the emitters.

9001-17, Session 4

Resonance detuning in coherently-coupled vertical-cavity surface-emitting laser arrays

Kent D. Choquette, Matthew T. Johnson, Dominic F. Siriani, Univ. of Illinois at Urbana-Champaign (United States)

The physical interactions between coupled photonic oscillators gives rise to a rich diversity of interactions that can be harnessed in photonic applications. One area of coupling that has been pursued for nearly three decades is that between semiconductor lasers, such as vertical cavity surface-emitting lasers (VCSELs). Coherently-coupled VCSEL arrays have many features that make them viable candidates for high radiance and optical beam steering applications. Beam steering with coherent VCSEL arrays offers a fundamentally different approach because the array acts as both the source and phase shifting mechanism, allowing maximum compactness and electro-optical efficiency. We report the novel beam steering mechanism which, in contrast to all other methods, is based on a temporal phase shift between array elements at the quantum well active region. This temporal phase shift is shown to be introduced by a resonance detuning between the array elements. Coherently coupled VCSEL arrays are thus shown to harness a fundamentally unique phase-shifting mechanism, which allows record-high beam steering speeds and phase sensitivity to current injection and can also be naturally extended into two dimensions.

9001-19, Session 4

Numerical analysis on current and optical confinement of III-nitride vertical-cavity surface-emitting lasers

Ying-Yu Lai, Tien-Chang Lu, Tsung-Lin Ho, Shen-Che Huang, Shing-Chung Wang, National Chiao Tung Univ. (Taiwan)

Recently, the current injection III-nitride based vertical-cavity surface-emitting lasers (VCSELs) and AlN-buried high Q microcavity light emitters have been demonstrated. But most of them still suffer from several issues to limit the device performance. In this study, we report on the numerical analysis of the electrical and optical properties of current-injected III-N based VCSELs with three types of current confinement schemes, conventional planar-Indium Tin Oxide (ITO) type, AlN-buried type without ITO, and hybrid type. The proposed hybrid structure, combined an ITO layer and a buried AlN aperture, exhibits not only a uniform and concentrated current distribution but also an enhanced lateral optical confinement. Thus, the hybrid type design shows a remarkably better performance including lower threshold current and series resistance compared with planar-ITO type and AlN-buried type. The index guiding of buried AlN aperture will induce multi-transverse modes to compete the electronic gain, so we also optimize the radius of AlN apertures for single transverse mode operation. The threshold current of hybrid type could be deduced to lower than half of that of planar-ITO and AlN-buried type. Such design provides a powerful solution for high performance III-N based VCSELs and is also viable using current state of art processing techniques.

9002-1, Session 1

Engineering opto-electronic properties of molecular beam epitaxy grown quantum dot structures

Abdul Majid Mohammed, Hala Alhashim, King Abdullah Univ. of Science and Technology (Saudi Arabia); Maxime Hugues, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France); David T. D. Childs, The Univ. of Sheffield (United Kingdom); Dalaver H. Anjum, Dongkyu Cha, Boon S. Ooi, King Abdullah Univ. of Science and Technology (Saudi Arabia); Richard A. Hogg, The Univ. of Sheffield (United Kingdom)

Engineering the quantum dot (QD) inhomogeneity, density, composition, aspect ratio for plethora of applications from broadband applications to telecom is not new to the research community in opto-electronic devices. For broadband applications a superluminescent diode (SLD) requires highly inhomogenous dots in the intrinsic region, where as inhomogeneity is a significant issue for QD laser, as those QDs outside the homogeneous line-width of the lasing energy do not merely fail to contribute to lasing, but are parasitic. In the first part of the paper, a systematic study of key MBE parameters such as QD growth temperature, QD InAs deposition amount and growth rate for broadband and telecom applications indicating a clear boundary of optimized parameters for telecom lasers and broadband devices will be discussed.

In the second part engineering of the low-growth temperature (LGT) component of the spacer layer thickness is discussed. Earlier report on the optimization of the LGT of p-doped laser/ SLD structures have shown a significant improvement in the device performance but at the expense of the blueshift (~40-50 nm) of peak emission wavelength. In this paper we demonstrate the improved performance of multi-layer dot-in-well (DWELL) structures (quantum dot laser, multi-section devices and superluminescent diode) with "no blushift" in peak emission by engineering the thickness of the LGT component of GaAs spacer layers between dot layers. High resolution transmission electron microscope (HRTEM) micrograph (strain and composition) for optimized structure indicated that a very low density of big coalesced dots (defective) are selectively healed (reduce strain), without disturbing the overall dot distribution and hence no blueshift in peak emission. These results are significant for 'laser dots', for optical telecoms applications where peak emission wavelength is most important. Further the above studies will be substantiated by multi-section modal gain, absorption measurement (improvement in internal loss) and spontaneous emission measurements from 77K to 300K.

9002-2, Session 1

Fabrication and optical properties of GaN quantum dots for coherent control *(Invited Paper)*

Yasuhiko Arakawa, Mark Holmes, Kihyun Choi, Munetaka Arita, Satoshi Kako, The Univ. of Tokyo (Japan)

To date, the majority of quantum dot coherent control experiments have been performed on QDs formed in the III-As semiconductor system, with which a 2-qubit CROT logic gate has also been realized using exciton and biexciton states. However, there have been no reports on the successful coherent optical manipulation of III-Nitride QDs, which emit in the UV to visible regions. The III-Nitride system is promising as it can sustain room-temperature stable excitons in single GaN QDs; a property which enabled the realization of a single photon emitter operating at 200K[1].

Recently, in order to control the site of such QDs, we have developed the selective area growth of nanowires containing single QDs [2] by metal organic chemical vapor deposition (MOCVD). Figure1(a) and (b) show SEM image of a single GaN/AlGaN nanowire containing a GaN quantum dot and Schematic view of the nanowire/QD structure.Our high-quality GaN QDs exhibit a very large biexciton binding-energy[3], fine structure splitting[4], and a strong phonon interaction [5]. Moreover, the presence of the excited states in single GaN QDs was evidenced by means of photoluminescence excitation (PLE) measurements[6]. We recently succeeded in an experimental demonstration of excited state Rabi rotation, where damped oscillation has been observed in the power dependent spectra of the quantum dot ground state upon resonant pumping of an excited state[7]. Figure2 shows power dependenent Rabi oscillations observed in the excitonic ground state emission upon resonant excitation of the excited state. The inset shows a simplied energy level diagram of the system.

In this presentation, we discuss histtorical overview of GaN-based quantum dots and recent progress in the growth and optical properties of GaN quantum dots embedded in site-controlled GaN/AlGaN nanowires. The discussion includes an obervation of enhanced biexciton binding energy and demonstration of excited state exciton Rabi rotation in a single GaN quantum dot.

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9002-3, Session 1

Development of broad spectral bandwidth hybrid QW/QD structures from 1000-1400 nm

Negin Peyvast, Siming Chen, Kejia J. Zhou, Nasser Babazadeh, Amilia Ahmed Khozim, Ziyang Zhang, David T. D. Childs, Osamu Wada, The Univ. of Sheffield (United Kingdom); Maxime Hugues, EPSRC National centre for III-V Technologies (United Kingdom); Richard A. Hogg, The Univ. of Sheffield (United Kingdom); Takeo Kageyama, Kenichi Nishi, Keizo Takemasa, Mitsuru Sugawara, QD Laser, Inc. (Japan)

Broad spectral line-width light sources are required in optical coherence tomography (OCT) in the biological "window" ~1000-1350 nm. This region is well served by GaAs based quantum well and quantum dot materials. The resolution of the OCT system is governed by the coherence length of the source, Lc ~0.44 λ2/Δλ, (λ is the central wavelength, Δλ is the spectral width). Enhancing spectral coverage (both spontaneous emission and gain) to e.g. 300nm, centered at 1200nm provides a theoretical OCT resolution for a Gaussian shaped emission of

~2?m, promising the prospect of sub-micron imaging of skin tissue using a semiconductor light source.

Here we describe the development of hybrid quantum well/quantum dot active elements to achieve broad spectral bandwidth spontaneous emission and gain. We have previously reported that the placement of the quantum well within the active element is a critical factor in obtaining broad spectral bandwidth emission.

Here we describe results from a new series of samples, utilizing QD layers of higher areal density, higher state separation, and narrower inhomogeneous linewidth. We describe the effect of emission energy of the quantum well, quantum dot layer number, and modulation p-doping. We go on to describe the further enhancement of the spectral emission bandwidth from the device through the introduction of higher order quantum well transitions (e1hh2,3) through the use of an asymmetric quantum well, along with QD layers with different emission wavelength. Utilizing self-heating and state-filling, a spontaneous emission of 350nm is obtained. Gain data will also be discussed.

9002-4, Session 1

Wavelength tunable quantum dot laser operating at 1550-nm band

Kouichi Akahane, Naokatsu Yamamoto, Atsushi Kanno, Toshimasa Umezawa, Tetsuya Kawanishi, National Institute of Information and Communications Technology (Japan); Atsushi Kanemori, Hiroshi Takai, Tokyo Denki Univ. (Japan)

Semiconductor quantum dots (QDs) grown using self-assembly techniques in the Stranski–Krastanow (S-K) mode have potential applications in high-performance optical devices such as QD lasers. Considerable research has been conducted with the aim of developing high-performance QD lasers with a low threshold current, temperature stability, high modulation bandwidth, and low chirp. To realize these high-performance devices, the surface QD density should be increased by fabricating a stacked structure. We have developed a growth method based on the strain-compensation technique that enables the fabrication of a high number of stacked InAs QD layers on an InP(311)B substrate. In this study, we employed the proposed method to fabricate wavelength tunable QD external cavity laser and investigated the characteristic of wavelength tunability. The ultra-high density, high-quality InAs/InAlGaAs QD optical gain medium for the 1550 nm waveband was obtained using a strain compensation technique on InP(311)B substrate. 20 QD layers were stacked without any degradation of crystal quality in which the total density of QDs reached to 1E13 /cm^2. A wide wavelength tunability of 1491–1550 nm was successfully achieved using a compact and robust external cavity system constructed with multiple optical band-pass and etalon filters for active optical mode selection.

9002-5, Session 1

Colloidal II-VI compound quantum dot lasers: spanning the red, green, and blue by single material *(Invited Paper)*

Arto V. Nurmikko, Kwangdong Roh, Joonhee Lee, Brown Univ. (United States); Cuong H. Dang, Nanyang Technological Univ. (Singapore)

Colloidal CdSe-based and related II-VI compound quantum dots have emerged recently as viable bright luminescent materials for displays, with single material composition spanning across the entire visible range using nanocrystal size control. With high luminescence efficiencies exceeding 90%, might thin solid films yield sufficient optical gain for achieving stimulated emission in the red, green, and blue (RGB)?

Synthesis of CQDs typically requires thin nm-scale outer organic layers to eliminate nonradiative surface states as a dielectric shell. Consequently, optical pumping (e.g. by compact solid state lasers) is a useful starting point rather than direct diode heterostructures. One physical attribute discovered in CQDs is that, when engineered to enable the initial solution be spin-cast as closely-packed self-assembled thin films, gain can be extracted, and used for stimulated emission, from single exciton states with their commensurately large optical cross section. The self-assembled films (thicknesses in the 100-200 nm range, i.e. tens of stacked CQD monolayers), can be optically homogeneous and smooth (nm scale RMS surface roughness), for measuring e.g. gain spectra and fabricating basic laser structures. For example, we have achieved vertical cavity surface emitting laser action in the red and the green with high spatial and spectral coherence. More recently, we have demonstrated spatially coherent lasing across the RGB spectra in distributed feedback (DFB) geometries, where the self-assembled films are conformally deposited on quartz grating substrates. Although still limited to optically pulsed operation, steady progress has been made to reach a quasi-cw regime at room temperature.

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9002-6, Session 2

GaAsBi/GaAs semiconductor lasers: initial laser characteristics and future prospects

Stephen J. Sweeney, Igor P. Marko, Shirong Jin, Konstanze Hild, Zahida Batool, Univ. of Surrey (United Kingdom); Peter Ludewig, Wolfgang Stolz, Kerstin Volz, Philipps-Univ. Marburg (Germany)

The incorporation of bismuth (Bi) atoms into standard III-Vs such as GaAs or InP provides several attractive properties for laser applications such as strong band gap (Eg) shrinkage (with reduced temperature dependence) and a large increase of the spin-orbit split-off energy (ΔSO). It has been shown that in III-V bismides it is possible to realize a condition when ΔSO>Eg which should lead to the suppression of the dominant hot-hole producing Auger recombination and Inter-valance band absorption (IVBA) processes which limit the performance and energy efficiency of current 1.55um lasers. In this work we present the first temperature dependent measurements of electrically pumped GaAsBi/AlGaAs quantum well (QW) lasers. They have been grown by MOPVE and contain a single or triple 6.5nm QW with 2.2% Bi and AlGaAs barriers. The lasers operate at room temperature at a wavelength of ~950 nm, in a good agreement with theoretical calculations for this bismuth concentration. The room temperature threshold current density, Jth, was measured to be 1.6 and 0.7kA/cm2/QW for the SQW and ~TQW sample, respectively with a To of ~100K around room temperature. Through waveguide optimisation, Jth reduces to ~800/cm2 for the SQW devices. Laser operation for a SQW laser containing 3.9% Bi has also been achieved at low temperature. Spontaneous emission measurements suggest that defect-related recombination and carrier leakage processes influence the thermal properties of the devices and have been investigated further using high pressure and low temperature techniques, as shall be discussed at the conference.

9002-7, Session 2

Red-emitting monolithic dual-wavelength DBR diode lasers for shifted excitation Raman spectroscopy

Bernd Sumpf, Martin Maiwald, André Müller, Frank Bugge, Jörg Fricke, Peter Ressel, Johannes Pohl, Götz Erbert, Günther Tränkle, Ferdinand-Braun-Institut (Germany)

Raman lines are often obscured by background light or fluorescence especially when investigating biological samples or samples containing impurities. Shifted excitation Raman difference spectroscopy is a technique to overcome this. By exciting the sample with two slightly shifted wavelengths, it is possible to separate the Raman lines and distortions.

In this paper, monolithic dual wavelength DBR diode lasers meeting the demands of Raman spectroscopy and SERDS will be presented. The wavelengths are stabilized and selected by using deeply-etched 10th order surface gratings with different periods manufactured using i-line wafer stepper lithography. Two possible resonator concepts, i.e. a mini-array of two parallel DBR RW-lasers and a Y-branch DBR laser, will be compared. Established excitation wavelengths for Raman spectroscopy at 671 nm and 785 nm are chosen. The total laser length is 3 mm, the ridge width is 5 µm. The length of the DBR gratings is 500 µm.

The devices at 671 nm reach output powers up to 100 mW having an emission width smaller than 12 pm (FWHM). The 785 nm lasers show output powers up to 200 mW and a narrow emission below 22 pm. For the dual wavelength lasers the spectral distance between the two excitation lines is about 0.5 nm as targeted. The power consumption at both mid-wavelengths is below 1 W.

These data proof that the devices are well suited for their application in portable Raman measurement systems such as handheld devices using SERDS.

9002-8, Session 2

Bragg-grating-stabilized external cavity lasers for gas sensing using tunable diode laser spectroscopy

Stephen Lynch, Univ. of Southampton (United Kingdom); Fei Chen, Cranfield Univ. (United Kingdom); James C. Gates, Christopher H. Holmes, Univ. of Southampton (United Kingdom); Stephen Staines, Cranfield Univ. (United Kingdom); Stephen W James, Cranfield University (United Kingdom); Jane Hodgkinson, Cranfield Univ. (United Kingdom); Peter G. R. Smith, Univ. of Southampton (United Kingdom); Ralph P. Tatam, Cranfield Univ. (United Kingdom)

Conventional singlemode semiconductor DFB and VCSEL lasers used in high resolution spectroscopy are often required to operate at specific, custom wavelengths, such as those associated with gas absorption lines. The narrow tuning range of such devices imposes a demanding wavelength tolerance in manufacture, especially for certain low volume gas detection applications where the required wavelengths are outside the telecoms bands.

Bragg grating stabilised external cavity lasers have gained much interest in recent years, using the grating as a wavelength-selective element. The different methods of writing Bragg gratings in optical fibre and planar silica-on-silicon allow a high degree of flexibility in the choice of emission wavelength.

We present the latest developments of our work to develop such sources in the 1550nm and 1650nm regions, the latter coinciding with an absorption line of methane. Custom wavelength Bragg gratings have been used to stabilise the laser output of both an optical fibre laser and planar silica-on-silicon integrated circuits, coupled to a commercially available semiconductor gain chip. Thermal expansion or mechanical strain of the Bragg grating offers a suitable wavelength tuning mechanism. We present recent results including the wavelength tuning range, output power, relative intensity noise (RIN), side-mode suppression and linewidth of different device designs for application in high resolution gas spectroscopy.

9002-9, Session 2

Properties of 62x nm red-emitting single-mode diode lasers

Katrin Paschke, Johannes Pohl, David Feise, Gunnar Blume, Götz Erbert, Ferdinand-Braun-Institut (Germany)

Single-mode lasers in the spectral region between 620 nm and 630nm are still realized using complex laser systems, such as ring-dye laser or using non-linear frequency shifted lasers, when used in applications such as laser cooling of beryllium ions or spectroscopy on rare earth elements. Direct emitting AlGaInP based diode lasers offer a much simpler approach to this wavelength range, but so far lack a suitable beam quality and spectral purity.

Recently distributed Bragg reflector (DBR) ridge waveguide lasers (RWL) were developed for the 630nm to 640nm region. Building on this knowledge CAMFR simulations were performed to find suitable grating periods and duty cycles to obtain emission wavelengths below 630nm. The grating itself was then introduced by stepper lithography and reactive ion etching into the laser structure.

The manufactured DBR-RWLs show laser emission at 628.5 nm and 626.5 nm at a temperature of 15°C with threshold currents below 150 mA. The spectral emission shows single-mode operation with side mode suppression ratios > 20 dB. Two DBR-RWLs with the lower wavelength were packaged into sealed TO-3 housings to provide a small-sized non-condensing environment with temperatures down to 30°C. When cooled internally to about 0°C, an emitted power of more than 50 mW was measured at a wavelength of 626.0 nm. At this operation point a diffraction-limited single longitudinal mode was observed that allowed a heterodyne measurement where a spectral width below 1 MHz was obtained.

These new diode lasers have the potential to drastically miniaturize existing set-ups for quantum information processing.

9002-10, Session 2

LED-pumped organic semiconductor lasers *(Invited Paper)*

Yue Wang, Emiliano Rezende Martins, Georgios Tsiminis, Univ. of St. Andrews (United Kingdom); Alexander Kanibolotsky, Peter Skabara, Univ. of Strathclyde (United Kingdom); Ifor D. W. Samuel, Graham A. Turnbull, Univ. of St. Andrews (United Kingdom)

In this talk we will present the design and development of organic semiconductor microlasers pumped by light-emitting diodes. Compact distributed feedback resonators, fabricated by UV nanoimprint lithography, are used in combination with a PPV-derivative polymer to achieve very low threshold nanoimprinted polymer lasers. Using mixed-order and substructured distributed feedback resonators, optically-pumped laser thresholds below 50 W/cm2 are demonstrated. These lasers are combined with nanosecond-pulsed InGaN LEDs to create very compact hybrid polymer laser systems. The LED-pumped lasers are found to exhibit an unusual two-stage turn on of the laser emission, which is related to the dynamics of laser action under pulsed pumping of 30 to 50 ns duration. Finally we will show how these sources can be used as miniature sensors for explosive vapours.

9002-11, Session 3

Mode-locked InAs/InP quantum-dash-based DBR laser with monolithically-integrated SOA *(Invited Paper)*

Siddharth Joshi, Nicolas Chimot, Sophie Barbet, Alain Accard, François Lelarge, III-V Lab. (France)

Mode Locked Lasers based on InAs/InP quantum dash material have been well explored in the recent years in both single section and two section device formats. Monolithic semiconductor passively mode locked lasers (MLL) are indeed very attractive for frequency comb generation and for radio over fibre applications. In order to fully exploit the unique

low phase noise performances of such Qdash lasers, it would be necessary to monolithically integrate such sources in photonic integrated circuits.

In this contribution, we focus on the technical challenge that consists in closing the cavity of a Fabry Pérot (FP) lasers while keeping the intrinsic low phase noise properties of the QDash based active layer. We present an effective Bragg mirror design ensuring a large reflectivity bandwidth without perturbing the mode locking efficiency. These DBR cavities offer a building block for integration to various active devices like a Semiconductor Optical Amplifier (SOA) or a modulator section to achieve an integrated functional device on a single chip. As an illustration, we successfully integrated a SOA in a simple way by using the same active medium as that of the laser, which resulted in an overall gain of about 10dB for an amplifier length of 1mm. The RF linewidth after amplification of the comb is found to be as low as 33 kHz. We also demonstrate that the SOA section can be used to modulate data up to 5Gb/s. These results open the way to the use of such building block for Radio Over Fibre applications.

9002-12, Session 3

Femtosecond semiconductor laser system with arbitrary intracavity phase and amplitude manipulation

Jan C. Balzer, Benjamin Döpke, Ruhr-Univ. Bochum (Germany); Andreas Klehr, Götz Erbert, Günther Tränkle, Ferdinand-Braun-Institut (Germany); Martin R. Hofmann, Ruhr-Univ. Bochum (Germany)

Since the 90's semiconductor lasers are in the focus of researchers as a source for ultrashort laser pulses. They have several unique advantages like direct electric pumping, variable wavelength, compactness and low costs. However, due to the complex carrier dynamics of the semiconductor material pulse durations below 500 fs are difficult to achieve. As a consequence of this no fs semiconductor fs laser system is commercially available despite the high potential of the semiconductor technology. We were able to demonstrate that intracavity dispersion management is a key to generate ultrashort pulses from a mode-locked semiconductor laser. Pulse durations below 200 fs were generated from a dispersion optimized external cavity laser. The drawback of the setup was that it only allows for linear chirp compensation with small amounts of uncontrollable quadratic chirp. In this work we will present a laser cavity with a spatial light modulator, which allows for arbitrary phase and amplitude manipulation. We were able to demonstrate that a combination of linear and quadratic chirp leads to mode-locked spectra with a full width half maximum of 9 nm with a central wavelength of 850 nm. This bandwidth has the potential to generate sub 150 fs pulses. We are planning to expand the setup with an evolutionary algorithm to generate even broader spectra and hence shorter pulses. A further improvement is expected for the implementation of amplitude shaping by the evolutionary algorithm.

9002-13, Session 3

Femtosecond pulse generation from a two-section mode-locked quantum-dot laser using random population

Patrick Finch, Tyndall National Institute (Ireland); Peter Blood, Peter M. Smowton, Angela Sobiesierski, Cardiff Univ. (United Kingdom); Russell M. Gwilliam, Univ. of Surrey (United Kingdom); Ian O'Driscoll, Tyndall National Institute (Ireland)

200 fs optical pulses, the shortest to date, have been demonstrated using a two-section, passively mode-locked InAs quantum-dot (QD) laser with a proton bombarded absorber, at 20 GHz around 1220 nm. By measuring the optical pulsewidths and emission spectra between 300 K and 20 K, the pulsewidth decreases by a factor 25, from 5 ps to 200 fs.

At 300 K the optical bandwidth is 9 nm and there is a thermally induced exchange of carriers between the QDs and wetting layer (WL). When a QD is emptied by stimulated emission, it is refilled from another QD via the WL, so they are not independent of each other and we cannot access to the full available gain bandwidth.

At 20 K, the bandwidth increases to 30 nm, thermal equilibrium breaks down and the ratio of the QD depth compared to kBT is much greater than that at 300 K. The QDs become randomly populated and act as independent oscillators with an increase in the useable bandwidth.

Temperature was used as a tool to access the random population regime. However, a broad gain spectrum due to a random population and an absorber with a fast recovery time are incompatable in the same material. To counteract this, the absorber was bombarded with protons to ensure a fast recovery time.

This work demonstrates that QDs can generate ultrashort pulses by making the energy separation between the QDs and WL very large compared with kBT while ensuring the absorber retains a short recovery time.

9002-14, Session 3

Second harmonic pico-second pulse generation with mode-locked 1064nm DBR laser diodes

Andreas Klehr, Thomas Prziwarka, Daniel Jedrzejczyk, Olaf Brox, Frank Bugge, Hans Wenzel, Götz Erbert, Günther Tränkle, Ferdinand-Braun-Institut (Germany)

Laser systems emitting short green light pulses with high pulse energies are requested for applications in medicine, fluorescence spectroscopy and display technology. With passively mode-locked semiconductor lasers short optical pulses can be generated. Frequency doubling requires a fixed and stable wavelength to match the spectral acceptance the nonlinear crystals (<0.2nm). This can be reached with a grating integrated in the laser cavity.

The aim of this paper is to present detailed experimental investigations for the generation of high energy short infrared and green pulses with mode-locked multi-section DBR lasers in dependence of gain- and saturable absorber (SA) lengths, gain current and reverse absorber voltage.

The laser has a length of 3.5mm with a 500µm DBR section. The remaining cavity was divided into four 50µm, four 100µm, two 200µm and eight 250µm long electrically separated segments so that SA- and gain section length can be simply varied by bonding and the mode-locking behaviour can be investigated on the same device.

Optimal mode locking was obtained for absorber lengths between LAbs=200µm and 300µm and absorber voltages between UAbs=-2V and -3V. Pulse length of $\tau\approx$10ps, repetition frequency of 13GHz and RF linewidth of less than 100kHz were measured. An infrared peak pulse power of 800mW was reached. The FWHM of the optical spectrum was about 150pm.

With a 11.5mm long periodically poled MgO doped LiNbO3 crystal having a ridge geometry of 5µm width and 4mm height green light pulses were generated. With 800mW infrared pump peak power a green peak power of 225mW was reached corresponding to a conversion efficiency of 23%.

9002-15, Session 3

Dynamics in green GaN-based laser diodes

Ulrich T. Schwarz, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany) and Albert-Ludwigs-Univ. Freiburg (Germany); Thomas Weig, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); Thomas Hager, Georg Brüderl, Uwe Strauss, OSRAM Opto Semiconductors GmbH (Germany)

The development of green (Al,In)GaN ridge waveguide laser diodes (LDs) made tremendous progress in the past years and opens up new possibilities in laser projection. We present studies of the dynamics of green LDs grown on free-standing c-plane GaN. The spectral and temporal behavior on a GHz time scale of these devices was investigated with a streak camera.

Dependent on the epitaxial design, unequal pumping of the individual quantum wells (QWs) may occur. In devices, in which the QWs are unequally pumped, a sublinear behavior of the P-I-curve close to threshold and turn-on delays up to 100 ns are observed. In contrast, LDs with symmetrically pumped QWs show a linear P-I dependence and significantly shorter turn-on delays.

Furthermore, we investigated the temporal development of the longitudinal modes in the laser cavity. We observe a periodic hopping between one to two dozen modes from short to long wavelengths. While the spectrally integrated signal shows a continuous wave operation, every single longitudinal mode is modulated in the 10 to 70 MHz range, with a logarithmic dependence of the frequency on driving current. This behavior is explained by mode hopping, caused by asymmetric gain saturation, as previously observed in violet LDs. We simulate the mode hopping with rate equations, including an asymmetric gain saturation coefficient, caused by neighboring modes. By means of Hakki-Paoli gain spectroscopy we extract information on the gain profile needed for accurate simulations. These are in good agreement with the measurements, specifically the logarithmic dependence of the mode hopping frequency on current.

9002-16, Session 4

Optically-pumped deep-ultraviolet AlGaN multi-quantum-well lasers grown by metalorganic chemical vapor deposition *(Invited Paper)*

Yuh-Shiuan Liu, Tsung-Ting Kao, Mahbub Satter, Zachary Lochner, Xiaohang Li, Shyh-Chiang Shen, P. Douglas Yoder, Theeradetch Detchprohm, Russell D. Dupuis, Georgia Institute of Technology (United States); Yong Wei, Hongen Xie, Alec Fischer, Fernando Ponce, Arizona State Univ. (United States)

Ultraviolet (UV) emitters are of interest for a number of applications including water purification, food sanitation, bio-agent detection, optical memory storage, and medical sterilization. Mature UV light sources such as dye lasers, quadrupled Nd:YAG, and excimer lasers suffer from several disadvantages including, containing toxic materials, a large footprint, high power consumption, and extreme fragility. Thus a compact and efficient semiconductor-based alternative is desirable. This work describes AlGaN/AlN multiple-quantum-well structures specifically optimized for optical pumping studies operating at room temperature. A native c-plane (0001) AlN substrate is employed for the metalorganic-chemical-vapor deposition growth of AlGaN/AlN heterostructures at ~ 1130 °C. The layer structure consists of eight 3 nm $Al_{0.6}Ga_{0.4}N$ quantum wells with 6 nm $Al_{0.75}Ga_{0.25}N$ quantum barriers between a 200 nm AlN buffer layer and 8 nm AlN cap layer. The wafer is then cleaved along m-plane to form laser bars with a cavity length of ~1.4 mm. One of the facets is then coated with 6 pairs of SiO_2/HfO_2 forming high reflection coating which has reflectivity of ~ 99.8% at 245 nm. The AlGaN MQWs are photopumped with a 193 nm ArF excimer laser, which operates with a pulse width of 20 ns at a repetition rate of 10 Hz. A 35% reduction in threshold power density is observed when the HR coating is coated on one of the facets. The peak wavelength of the laser emission spectrum was measured as 245.3 nm. The material growth technology and the optical properties of these deep-UV lasers will be further discussed.

9002-17, Session 4

Influence of surface roughness on the optical mode profile in GaN-based violet ridge waveguide laser diodes

Katarzyna Holc, Annik Jakob, Thomas Weig, Klaus Köhler, Joachim Wagner, Oliver Ambacher, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); Ulrich T. Schwarz, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany) and Albert-Ludwigs-Univ. Freiburg (Germany)

To achieve long lifetime performance with good operating parameters, GaN-based ridge waveguide laser diodes require a low defect density substrate. The most common choice is a free-standing GaN, nowadays available through different fabrication technologies, like HVPE (hydride vapor-phase epitaxy) or ammonothermal growth. In the classical approach of c-plane oriented substrates, the optimized epitaxial growth regime promotes the step flow growth mode in order to obtain atomically flat surfaces and sharp interfaces, in particular in the multi quantum well (MQW) active region of the laser structure. However, in the case of laser structures, grown by metal organic chemical vapor deposition (MOCVD), due to the long range growth instabilities, we occasionally observe a periodical modulation in the surface roughness on the order of a few 10 nm and in the length range of 20 µm. Using different characterization techniques, like atomic force microscopy (AFM), white light interferometry (WLI), far-field measurements and Hakki-Paoli gain spectroscopy, we investigate the influence of this surface roughness on the vertical mode profile and internal losses. Here, we concentrate mainly on two aspects, i.e. on the influence of light scattering at the rough waveguide interfaces, as well as on that of substrate modes, on the vertical far-field profile, along the fast axis. In addition, we discuss how the process of ridge formation by reactive ion etching (RIE) and control of the final etch depth contributes to the optical mode guiding and the internal losses.

9002-18, Session 4

Reliability of InGaN laser diodes *(Invited Paper)*

Piotr Perlin, Lucja Marona, Institute of High Pressure Physics (Poland)

Although the nitride laser diodes have been on the market for almost 10 years, the physical mechanism responsible for their reliability never were clearly formulated. In contrast to other classical semiconductor lasers, degradation of nitride devices seems not to be caused by extended defects formation and/or propagation. There are experimental evidences suggesting point defects or impurity atoms diffusion as a degradation mechanism, however no clear model has been so far presented. Hydrogen and magnesium atoms are suspected to be involved together with native defects like gallium and nitrogen vacancies.

Within the present work we will demonstrate the combination of various method like: cathodoluminescence imaging, transmission electron microscopy, capacitance measurements, to quest for degradation mechanism of nitride laser diodes.

In particular, we demonstrate electron beam induced degradation processes and we compare them with current induced degradation. We will also discuss differences between magnesium containing and magnesium free structures.

9002-19, Session 4

Absorption at large reverse bias in monolithic GaN-based multi-section laser diodes

Thomas Weig, Gerrit Lükens, Katarzyna Holc, Klaus Köhler, Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); Ulrich T. Schwarz, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany) and Albert-Ludwigs-Univ. Freiburg (Germany)

GaN-based laser diodes with monolithically integrated saturable absorbers are compact short-pulse, high peak power light sources in the violet and blue spectral range. We demonstrate multi-segment, edge-emitting laser diodes with an absorber section p-contact in the center or at the edge of the cavity. Envisioned applications for these multi-section laser diodes are high-density optical storage systems, high-resolution bioimaging, and nanoprocessing.

We investigate the pulse repetition frequency (PRF) as a function of the gain current and the bias voltage on the absorber section with a streak camera. In the regime of relaxation oscillations (bias from +3 V to -15 V) the PRF stays constant at typically 5 to 8 GHz, dependent on the gain current. At larger reverse bias (-15 to -40 V) self-Q-switching occurs and the PRF decreases linearly until no pulsation is observed due to large absorption. We model the system with the rate equations. Besides gain spectroscopy, the carrier lifetime in the absorber and the modal absorption are measured to obtain a set of parameters.

The modal absorption increases monotonically to values above 500 1/cm at -40 V bias. Our calculations of the absorption show that transitions of bound states in the quantum wells alone cannot lead to such large absorption in our structure. The role of the Franz-Keldysh effect in the strongly tilted band structure at such large bias is taken into account and discussed. Furthermore, we simulate and discuss epitaxial designs and their impacts on the absorption and the flat band position.

9002-20, Session 5

Quantum cascade lasers comb spectrometers *(Keynote Presentation)*

Jérôme Faist, Andreas Hugi, Gustavo F. Villares, Mattias Beck, ETH Zurich (Switzerland); Stéphane Blaser, Alpes Lasers SA (Switzerland); Hui Chun Liu, Shanghai Jiao Tong Univ. (China); Markus Roesch, ETH Zurich (Switzerland); Giacomo Scalari, Alpes Lasers SA (Switzerland) and ETH Zurich (Switzerland)

The quantum cascade laser has demonstrated the ability to provide gain over a very broad wavelength range. Recently, we have shown that such broadband devices, when operated in continuous wave, emit as a coherent optical comb1 in which the phase relation between the comb modes corresponds approximately to a FM modulated laser. These new comb lasers enables the fabrication of a dual comb spectrometer based on a quantum cascade laser that offers a broadband, all solid-state spectrometer with no moving parts and a ultrafast acquisition time. We discuss also the extension of these ideas to the THz.

1. A. Hugi, G. Villares, S. Blaser, H. C. Liu and J. Faist, Nature 492 (7428), 229-233 (2012).

9002-21, Session 5

Noise properties of a mid-infrared quantum cascade laser frequency comb

Gustavo F. Villares, Andreas Hugi, ETH Zurich (Switzerland); Stéphane Blaser, Alpes Lasers SA (Switzerland); Hui Chun Liu, Shanghai Jiao Tong Univ. (China); Jérôme Faist, ETH Zurich (Switzerland)

Recently we demonstrated a mid-IR frequency comb based on a quantum cascade laser (QCL) spanning 60 cm-1 at a centre wavenumber of 1430 cm-1. The phase-locking mechanism of such a free-running, continuous-wave QCL frequency comb was identified to be four-wave mixing, which, combined with the short gain recovery time of a QCL ($\tau \approx 0.3$ ps), leads to a phase signature comparable to a frequency-modulated laser. Due to this new approach of comb generation, its noise properties are not yet fully understood. Furthermore, they are of particular importance for spectroscopic applications as they set the achievable resolution and sensitivity of a spectrometer based on a QCL frequency comb.

In this work, we characterize the noise properties (frequency noise and amplitude noise) of QCL based frequency comb. First, we characterize the low (< 10 Hz) and high phase-noise properties observed in the beatnote at the round-trip frequency (intermode beat) of such a comb. By measuring the beating between two free-running frequency combs with slightly different repetition frequencies (heterodyne beat), we analyze the phase-noise properties of a single comb line, showing a linewidth of 150 kHz with an acquisition time of 170 µs. The impact of the high phase-noise of the intermode beat in the heterodyne beat is also described. We also characterize its amplitude noise by measuring the photocurrent noise at low frequencies, showing different noise regimes in agreement with the intermode beat measurements. Finally, we study the amplitude noise of a single comb line.

9002-22, Session 5

Three-mirror cavity quantum cascade lasers for single-mode operation

Romain Blanchard, Harvard School of Engineering and Applied Sciences (United States); Tobias S. Mansuripur, Harvard Univ. (United States); Pauline Metivier, Harvard School of Engineering and Applied Sciences (United States); Yongrui Wang, Aleksander K. Wojcik, Alexey A. Belyanin, Texas A&M Univ. (United States); Federico Capasso, Harvard School of Engineering and Applied Sciences (United States)

We present experimental and simulation results on a three-mirror cavity mid-infrared quantum cascade laser (QCL) exhibiting single mode operation in the absence of additional frequency selective element. The device consists of an uncoated QCL chip experiencing strong feedback from a long straight external cavity terminated by a flat mirror. Different design parameters such as the cavity length or the amount of feedback are explored to understand the mode-selection process. Additionally, interesting regimes such as self-sustained intensity oscillations at the external cavity round-trip frequency are observed.

9002-23, Session 5

Ring cascade lasers with integrated pi phase shifts *(Invited Paper)*

Rolf Szedlak, Clemens Schwarzer, Tobias Zederbauer, Hermann Detz, Aaron M. Andrews, Werner Schrenk, Gottfried Strasser, Technische Univ. Wien (Austria)

No Abstract Available

9002-24, Session 6

Novel THz quantum cascade laser active materials and designs *(Invited Paper)*

Christoph Deutsch, Martin Brandstetter, Michael Krall, Tobias Zederbauer, Gottfried Strasser, Karl Unterrainer, Technische Univ. Wien (Austria)

Terahertz quantum cascade lasers are amongst the most promising sources for terahertz radiation. However, their operation is still limited in terms of operating temperature and output beam properties. Therefore, we investigate new materials system and active regions designs. We use InGaAs/GaAsSb due to the lower effective mass and lower conduction band offset. We have achieved record operating temperatures despite the large interface roughness asymmetries in this material. We quantify this asymmetry by studying symmetrically designed active regions. This is used to choose the proper operating direction and doping profile. We will also report on the fabrication of laterally structured active regions to reduce intersubband scattering and on vertically stacked active regions to improve beam output properties.

9002-25, Session 6

Broadly-tunable room-temperature THz quantum cascade laser sources *(Invited Paper)*

Mikhail A. Belkin, Yifan Jiang, Karun Vijayraghavan, Seungyong Jung, The Univ. of Texas at Austin (United States); Frederic Demmerle, Gerhard Böhm, Markus-Christian Amann, Walter Schottky Institut (Germany)

I will discuss recent advancements in design and performance of the first mass-manufacturable room-temperature electrically-pumped terahertz laser sources based on efficient intra-cavity frequency mixing in mid-infrared quantum cascade lasers. Our latest devices provide over 0.1 mW of power output and are widely tunable in 1-6 THz range.

9002-26, Session 6

Towards an octave spanning CW THz quantum cascade laser

Markus Roesch, Giacomo Scalari, Mattias Beck, Jérôme Faist, ETH Zurich (Switzerland)

Frequency combs represent one of the most powerful tools in modern spectroscopy. In order to operate a frequency comb in the THz spectral region an active medium with a large gain bandwidth is highly desirable. We report here on a THz quantum cascade laser (QCL) which operates in continuous-wave (CW) with a bandwidth exceeding 1 THz with regular comb teeth and low threshold current density. The laser is based on a heterogeneous cascade design. It contains three different active region designs at central frequencies of 3 THz , 2.7 THz and 2.3 THz for a total active region thickness of 13.25 um. Devices are processed in a 150 ?m wide metal-metal waveguide fully exploiting the resonator characteristics of broadband and high temperature operation.

The measured bandwidth in CW is 1 THz at -20 dB which corresponds to $\Delta f/f$ =36 % for a central frequency of 2.5 THz. At -40 dB we measure a bandwidth of 1.46 THz , corresponding to $\Delta f/f$=58%: the spectrum extends from 1.79 THz to 3.29 THz. For an octave spanning laser we are then missing 300 GHz of spectral bandwidth. The laser operates up to 105 K in pulsed and 50 K in CW. Lasing threshold lies at 210 A/cm2 in pulsed and at 260 A/cm2 in CW operation, and Jmax is 360 A/cm2. The total dissipated power at the maximum current is approximately 13 W in CW, which allows easy operation in a closed cycle mechanical cooler.

9002-27, Session 6

Simulations of laser seeding dynamics with few-cycle pulses

Joshua R. Freeman, Univ. of Leeds (United Kingdom) and Ecole Normale Supérieure (France); Jean Maysonnave, Ecole Normale Supérieure (France); Suraj Khanna, Edmund Linfield, Giles Davies, Univ. of Leeds (United Kingdom); Sukhdeep S. Dhillon, Jérôme Tignon, Ecole Normale Supérieure (France)

Optical injection seeding is widely used to imprint some desirable characteristic of one `seed' laser onto another laser. The desirable characteristic is most often frequency stability, however we have recently made use of optical injection seeding to stabilize the phase of a laser[1]. The stabilized laser was a THz quantum cascade laser (QCL) and the seed was a broadband single-cycle pulse.

Besides the technological interest of this measurement, it also provides a new means to study laser emission in unprecedented detail and gain insights into the operation of QCLs. The type of signals observed from seeded QCLs can vary significantly from quasi-constant to a single pulse per round trip and multiple pulses per round-trip.

To gain a deeper understanding of these signals and the processes involved, we have developed a numerical simulation to describe the seeding of a laser by few-cycle broadband pulses. We use a model based on Maxwell-Bloch equations solved under the FDTD framework. The simulations are in good agreement with the experimental data, reproducing the differing signals observed for different cavity lengths [2]. The least well known parameter in the model is the gain recovery time. However we see good qualitative agreement with the data when using a value of 15ps, which compares favorably with values previously found [3]. We have also used this model to investigate the dependence of the laser emission on the type of seed used to initiate laser action.

1. Oustinov, D., et al., Phase seeding of a terahertz quantum cascade laser. Nat. Commun., 2010. 1(6): p. 69-.

2. Freeman, J.R., et al., Laser-seeding dynamics with few-cycle pulses: Maxwell-Bloch finite-difference time-domain simulations of terahertz quantum cascade lasers. Phys. Rev. A, 2013. 87(6): p. 063817-.

3. Scalari, G., et al., Population inversion by resonant tunneling in quantum wells. Appl. Phys. Lett., 2007. 91(3): p. 032103.

9002-28, Session 6

Surface-emitting THz quantum cascade lasers based on graded photonic heterostructures: towards phased arrays for high-power operation *(Invited Paper)*

Raffaele Colombelli, Institut d'Électronique Fondamentale (France)

THz surface emitting quantum cascade lasers with graded photonic heterostructure (GPH) resonators feature state-of-art performance in pulsed and continuous-wave operation.

We will present recent results, and we will discuss the possibility of developing phased-arrays of GPH lasers to achieve elevated output powers and optimized far fields.

9002-29, Session 7

Heterogeneously-integrated lasers on silicon *(Invited Paper)*

Brian R. Koch, Aurrion, Inc. (United States)

Heterogeneous integration enables all the elements of photonic systems to be fabricated on a single silicon chip. With this approach, photonic integrated circuits can meet the complexity, volume, and cost requirements of next generation communication systems. In our presentation we will discuss results of our lasers and other devices formed on our heterogeneous integration platform.

9002-30, Session 7

Monolithic integration of III-V quantum-dot lasers on silicon substrate

Qi Jiang, Andrew D. Lee, Mingchu Tang, Jiang Wu, Alwyn J. Seeds, Huiyun Liu, Univ. College London (United Kingdom)

Silicon photonics has been desirable for the future development of VLSI to overcome issues such as limitations caused copper interconnects. However the realisation of photonic integrated circuits has been slowed by the lack of light source on Si due to the indirect bandgap nature of Si. On the other hand, III-V quantum-dot laser has demonstrated efficient and robust performance. Growing III-V quantum-dot laser monolithically on Si can potentially pushing the silicon photonics to a whole new level. Both techniques of direct growth III-V material on Si and using Ge buffer layer has been investigated. Different nucleation layers such as AlAs and GaAs have been studied for lower defects/dislocation density, hence better laser performance. TEM and AFM images suggest better defect/dislocation control with AlAs nucleation layer. At room-temperature, laser threshold current density of 650 A/cm2 was demonstrated at ~1290 nm. The Ge-on-Si substrates has also been used for grow high quality lasers since more and more high quality Ge-on-Si substrates are available on the market nowadays. Similar lattice constant between Ge and GaAs reduces the defect/dislocation density in a few orders of magnitude. The Ga-prelayer technique can eliminate the dislocation imitated by anti-phase boundaries. The combination of them lead to the quantum-dot lasers grown on Ge-on-Si substrate have comparable results to lasers grown on GaAs substrate. Room-temperature lasing at ~1280 nm with threshold current density of ~164 A/cm2 was demonstrated.

9002-31, Session 7

Analysis of band structure characteristics of Ga(NAsP)/(BGa)(AsP)-quantum well heterostructures for monolithically-integrated lasers on (001) Si-substrate *(Invited Paper)*

Wolfgang Stolz, Philipps-Univ. Marburg (Germany)

Ga(NAsP)/(BGa)(AsP)-quantum well heterostructures have successfully been monolithically integrated on (001) Si-substrate by using metal organic vapour phase epitaxy. The bandstructure characteristics as a function of composition, strain and quantization have been studied in order to improve optical efficiency and laser performance.

9002-32, Session 7

Hybrid III-V on silicon lasers for photonic integrated circuits on silicon *(Invited Paper)*

Guang-Hua Duan, III-V Lab. (France)

Silicon photonics is attracting large attention due to the promise of fabricating low-cost, compact circuits that integrate photonic and microelectronic elements. It can address a wide range of applications from short distance data communication to long haul optical transmission. Today, practical Si-based light sources are still missing, despite the recent demonstration of an optically pumped germanium laser. This situation has driven research to the heterogeneous integration of III-V semiconductors on silicon though wafer bonding techniques. In this approach, unstructured InP dies are bonded, epitaxial layers down, on a SOI waveguide circuit wafer, after which the InP growth substrate is removed and the III-V epitaxial film is processed.

This talk will report on recent advances on integrated hybrid InP/SOI lasers and transmitters using a wafer bonding technique made in particular at III-V Lab and CEA LETI, France. We demonstrate that thanks to the high quality silicon bend waveguides, hybrid III-V/Si lasers integrating two intra-cavity ring resonators can achieve a wide thermal tuning range exceeding the C band, with side mode suppression ratio higher than 40 dB. Such lasers exhibit excellent performance as local oscillator in a coherent receiver. Moreover a compact array waveguide grating on silicon is integrated with a hybrid III-V/Si gain section, creating a wavelength selectable laser source with 5 wavelength channels spaced by 400 GHz. We demonstrate also an integrated transmitter by incorporating silicon modulators with tunable hybrid III-V/Si lasers. Finally this talk will conclude by giving some future directions on photonic integrated circuits on Silicon

9002-33, Session 8

Self-frequency conversion in photonic crystal nanocavity quantum dot lasers *(Invited Paper)*

Yasutomo Ota, Katsuyuki Watanabe, Satoshi Iwamoto, Yasuhiko Arakawa, The Univ. of Tokyo (Japan)

Self-frequency conversion, in which both lasing action and nonlinear frequency conversion take place using the same laser crystal, is a simple but powerful method for efficiently extending the operational wavelength of lasers. Application of nanocavities with high Q factors and small mode volumes could substantially enhance the conversion processes, as demonstrated in previous studies using 'passive' nonlinear photonic crystals irradiated by external lasers. Here, we discuss self-frequency conversion in high Q photonic crystal nanocavity quantum dot lasers under optical carrier injection. The GaAs-based nanocavities enhanced the self-frequency conversion processes for the internally generated near infrared light and allowed us to observe second harmonic generation even when the average intracavity photon number is only ~ 0.1. Across the fundamental mode lasing threshold, we observed a change of the frequency doubling efficiency due to the change of the photon statistics of the intracavity laser field from thermal to coherent. We compared this result with a newly developed theory and found a good agreement between them. We also show that the combined broadband InAs quantum dot gain, small cavity footprint and the lack of a restrictive phase matching requirement enabled the micro-integration of 26-different-color nanolasers covering almost the entire visible range. Furthermore, by simply changing the cavity design, the nanolasers supported simultaneous multimode lasing so as to exhibit the self-frequency summing in the nanocavities. We believe that these self-frequency conversion nanolasers could be useful for studying few photon nonlinear optics, as well as for on-chip synthesis of arbitrary wavelengths of light.

9002-34, Session 8

Photonic crystal surface-emitting lasers as pumping light source for second harmonic generation

Akiyoshi Watanabe, Kazuyoshi Hirose, Yoshitaka Kurosaka, Takahiro Sugiyama, Hamamatsu Photonics K.K. (Japan); Yong Liang, Susumu Noda, Kyoto Univ. (Japan)

Recently, photonic crystal surface emitting lasers (PCSELs) have been realized with both a single spectrum and narrow spot beam pattern under several hundred mW of output power. Even though the high coherence properties of PCSEL are expected to be used for various applications, we focus on a pumping light source for a wavelength conversion system in this work. To obtain a green light, we fabricate a 1.06um PCSEL with a square lattice 2D photonic crystal in which the lattice period corresponds to the lasing wavelength. The fabricated device has a narrow spot beam pattern of less than 0.5 degrees and a single spectrum at 1068 nm under CW output power of more than 200 mW in spite of a broad emitting area of 200 * 200 um2. The wavelength conversion system used single pass second-harmonic generation (SHG), consisting of only the PCSEL and 50 mm long bulk MgO doped periodically with poled lithium niobate (MgO:PPLN) as a nonlinear medium: a lens-free system. In this system, it is important to maintain the high brightness of the pumping light with single spectrum through the MgO:PPLN. As a result, 534 nm SHG light is obtained with a narrow spot beam pattern of less than 0.5 degrees, which follows the beam quality of the PCSEL under CW operation.

9002-35, Session 8

Room temperature lasing from individual GaAs-AlGaAs core-shell nanowires

Benedikt Mayer, Daniel Rudolph, Joscha Schnell, Julia Winnerl, Stefanie Morkoetter, Julian Treu, Technische Univ. München (Germany); Gerhard Abstreiter, Gregor Koblmueller, Jonathan J. Finley, Walter Schottky Institut (Germany)

We present lasing action from individual GaAs/AlGaAs core-shell nanowires (NWs), subject to pulsed optical excitation, up to room temperature. The active GaAs core of the NWs, grown using solid source MBE, has diameter of 360nm and is surrounded by a 5nm thick AlGaAs surface passivation shell to efficiently suppress non-radiative surface recombination and capped with 5nm of GaAs. Uniaxial elongation of the excitation spot using a cylindrical lens ensures efficient excitation of the entire 11µm long NW and, together with a diffraction limited confocal detection spot facilitates detailed studies of the spatial dependence of their optical emission properties as a function of the pump level.

For low excitation intensities spontaneous emission detected from the NW end facets is clearly modulated by the longitudinal Fabry-Pérot cavity and exhibits distinct peaks separated by 10meV, in excellent agreement with expectations from our finite difference time domain simulations for the guided TE01 and TM01 modes. As the excitation laser power density increases beyond the threshold of ~760 W/cm2 at 10K, the emission intensity from a single Fabry-Pérot mode exhibits a dramatic, and highly non-linear increase and is accompanied by strong linewidth narrowing, reducing from a few millielectronvolts to <0.1meV, limited by the spectral resolution of our detection setup. At higher excitation power densities a transition from amplified spontaneous emission to a linear lasing regime is observed, with single mode lasing from the vast majority of the NWs investigated. Lasing operation is found to persist up to room temperature, exhibiting typical s-like input-output characteristics that allow us to directly monitor the transition from spontaneous emission, over amplified spontaneous emission, into the lasing regime. By monitoring the spontaneous emission spectrum from the midpoint of the NW laser allows us to estimate the effective carrier densities at threshold and the evolution with lattice temperature. A remarkably low temperature coefficient (T0=109±12K) is measured, the temperature stability of the GaAs/AlGaAs NW-lasers being comparable to conventional double heterostructure lasers.

9002-36, Session 8

Directly-modulated photonic crystal lasers for computercom applications *(Invited Paper)*

Shinji Matsuo, NTT Photonics Labs. (Japan)

The introduction of the photonic crystal (PhC) wavelength-scale cavity as a laser cavity enables us to obtain both ultra-low threshold current and operating energy. These parameters are essential when using the transmitters in computercom applications such as chip-to-chip and on-chip interconnects. To improve the device performance, we employ an ultra-compact embedded active region that we call a lambda-scale embedded active-region PhC laser or LEAP laser. We have developed an electrically driven LEAP laser, which operates under room-temperature continuous-wave conditions. The threshold current is 4.8 uA, which is the lowest threshold current reported for any laser. We also describe the dynamic characteristics of the laser. The LEAP laser exhibits a maximum 3-dB bandwidth of 16.2 GHz and the modulation current efficiency factor is 53.8 GHz/mA0.5or 1.7 GHz/uA0.5, which is four times that of a vertical cavity surface emitting laser (VCSEL). The device is directly modulated by a 10-Gbit/s non return to zero (NRZ) signal with an energy cost of 5.5 fJ/bit. This is the smallest operating energy for any laser. These results indicate that the LEAP laser is highly suitable for use as a transmitter in computercom applications.

9002-37, Session 8

Electrically-driven nanobeam photonic crystal laser *(Invited Paper)*

Hong-Gyu Park, Kwang-Yong Jeong, Korea Univ. (Korea, Republic of); Min-Kyo Seo, Yong-Hee Lee, KAIST (Korea, Republic of)

Electrically pumped nanolasers with high quality factors and small mode volumes were demonstrated as practical coherent light sources in an ultracompact photonic integrated circuit. Although single-cell photonic crystal lasers with submicron-sized central posts and band-edge-type photonic crystal lasers fabricated using wafer fusion technique were demonstrated successfully showing good optical properties, the threshold currents of these lasers are still higher than one hundred uA. In order to achieve ultralow lasing threshold at room temperature and high-density integration with other photonic devices such as waveguides, it is necessary to develop new nanolasers with simple geometry and small physical size. In this work, we report the experimental demonstration of the smallest-possible nanolasers in one-dimensional photonic crystal nanobeam structures at room temperature. A submicron-sized central post was formed accurately in a desired position underneath the nanobeam by highly reproducible wet etching, and current was injected efficiently through the post. An ultrasmall zero-cell nanobeam laser with a physical device volume of ~1.2 um3 was demonstrated successfully and also, an ultralow lasing threshold of a few uA was achieved from three-cell nanobeam structure. The improved electrical injection system and small physical size yielded the lasing threshold that is substantially lower than those of previously reported two-dimensional photonic crystal lasers. We believe that our nanolaser will be an essential element as a practical and promising coherent light source in an ultracompact photonic integrated circuit.

9002-38, Session 9

Cascade pumping of GaSb-based type-I quantum well diode lasers *(Invited Paper)*

Leon Shterengas, Rui Liang, Gela Kipshidze, Takashi Hosoda, Sergey Suchalkin, Gregory Belenky, Stony Brook Univ. (United States)

Type-I quantum well (QW) GaSb-based diode lasers operate in continuous wave (CW) regime at room temperature in spectral region from 1.9 to 3.5 µm. Limited power conversion efficiency (below 25% near 2 µm and below 10% near 3µm) leads to thermal rollover of the device CW power-current characteristics. Initial value of the laser efficiency is critical factor that determines its peak CW output power. Cascade pumping recycles injected charge carriers and, hence, makes it possible to achieve the device internal current efficiency values above 100%.

Cascade pumping scheme enabled high power CW room temperature operation of quantum cascade lasers utilizing intersubband gain sections and GaSb-based interband cascade lasers utilizing Type-II QW gain sections. Cascaded injection in GaSb-based bipolar lasers is implemented using broken gap (Type-III) band alignment between InAs and GaSb. The efficient interband tunneling at type-III heterointerface requires neither high doping nor large reverse bias. Application of cascaded injection scheme to type-I QW GaSb-based lasers makes it possible to combine the advantages of the electron recycling and high optical gain of type-I QWs.

This work reports on the experimental demonstration of the efficacy of the cascade pumping of the type-I QW gain sections of the GaSb-based mid-infrared diode lasers. Two-stage cascade 2.4 – 3.3 µm diode lasers were designed, fabricated and characterized. Twofold increase of the internal efficiency was obtained as compared to reference single-stage diode lasers. Two stage cascade diode lasers generated 590 mW of output power near 3 µm.

9002-39, Session 9

Ultra-low input power long-wavelength GaSb type-I laser diodes at 2.7-3.0 µm

Augustinas Vizbaras, Mindaugas Greibus, Edgaras Dvinelis, Augustinas Trinkunas, Deividas Kovalenkovas, Ieva ?imonyte, Kristijonas Vizbaras, Brolis Semiconductors UAB (Lithuania)

Mid-infrared spectral region (2-4 µm) is gaining significant attention recently due to the presence of numerous enabling applications in the field of gas sensing, medical, environmental and defense applications. Major requirement for these applications is the availability of laser sources in this spectral window. Type-I GaSb-based laser diodes are ideal candidates for these applications being compact, electrically pumped, power efficient and able to operate at room temperature in continuous-wave. Moreover, due to the nature of type-I transition, these devices have a characteristic low operation voltage, typically below 1 V, resulting in low power consumption, and high-temperature of operation.

In this work, we present recent progress of 2.7 µm – 3.0 µm wavelength single-spatial mode GaSb type-I laser diode development at Brolis Semiconductors. Experimental device structures were grown by solid-source multi-wafer MBE, consisting of an active region with 2 compressively strained (~1.3 %-1.5 %) GaInAsSb quantum wells with GaSb barriers for 2.7 µm devices and quinternary AlGaInAsSb barriers for 3.0 µm devices. Epi-wafers were processed into a narrow-ridge (2-4 µm) devices and mounted p-side up on CuW heatsink. Devices exhibited very low CW threshold powers of < 100 mW, and single spatial mode (TE00) operation with room-temperature output powers up to 40 mW in CW mode. Operating voltage was as low as 1.2 V at 1.2 A. As-cleaved devices worked CW up to 50 deg C.

9002-40, Session 9

InGaAsSb/AlGaAsSb laterally-coupled index-grating distributed feedback lasers for HF gas sensing at 2475 nm

James A. Gupta, Andrew Bezinger, Pedro J. Barrios, Jean Lapointe, Daniel Poitras, Geof C. Aers, National Research Council Canada (Canada)

Tunable diode laser absorption spectroscopy using GaSb-based lasers has very exciting potential for the development of rapid, highly-selective and highly-sensitive gas analyzer instrumentation. In this work, single-mode distributed feedback laser (DFB) diodes were developed for HF gas detection at 2475nm. The lasers were fabricated using an index-coupled grating process without epitaxial regrowth, making the process significantly less expensive than conventional DFB fabrication.

The devices are based on an InGaAsSb/AlGaAsSb separate confinement heterostructure grown on GaSb by molecular beam epitaxy. DFB lasers were produced using a two step etch process. Narrow ridge waveguides were first defined by optical lithography and etched into the semiconductor. Lateral first-order gratings were then defined on both sides of the ridge using electron-beam lithography and etched to produce the index-grating. Effective index modeling was used to optimize the ridge width, etch depths and the grating pitch to ensure single-lateral-mode operation and adequate coupling strength. The effective index method was further used to simulate the DFB laser emission spectrum, based on a transfer matrix model for light transmission through the periodic structure.

The fabricated lasers exhibit single-mode operation which is tunable through the target HF gas absorption feature by adjustment of the drive current. The measured emission spectra agree very well with simulations, including the anti-reflection and high-reflection facet coatings. The only variable simulation parameters were the random facet phases related to the location of each facet cleave with respect to the grating. The model is thus suitable for further optimization of the DFB design, and for evaluation of alternative approaches, including higher-order gratings.

9002-41, Session 9

2-micron GaSb-based metamorphic laser grown on GaAs *(Invited Paper)*

Paveen Apiratikul, Lei He, Richard P. Leavitt, Nathan P. Siwak, Joseph Duperre, Christopher J. K. Richardson, Univ. of Maryland, College Park (United States)

There is an increasing interest in lasers operating near wavelengths of 2-µm for applications including gas detection and remote sensing. GaSb-based metamorphic lasers grown on GaAs substrates could offer advantages to conventional pseudomorphic lasers resulting from the use of a substrate with a higher thermal conductivity, availability of 6-inch diameter wafers and lower substrate cost. We review our work on the growth, and fabrication of metamorphic lasers operating continuous wave at room temperature.

Our GaSb-based laser was grown on a GaAs substrate using a solid-source molecular beam epitaxy system. A GaSb metamorphic buffer was grown such that the lattice mismatch is abruptly relaxed using a 2-dimensional array of edge dislocations. From this material, we demonstrate broad-area metamorphic lasers operating continuous wave at 15ºC with a total output power of 70 mW, an internal loss of 3 cm-1 and a threshold current density of 1.04 KAcm-2. The thermal resistance of 14 K/W measured from our metamorphic laser is better than that of GaSb-based pseudomorphic lasers of similar size due to a higher thermal conductivity of the GaAs substrate. Fabry-Perot ridge lasers operating continuous wave are demonstrated with a single lateral mode with the total output power up to 20 mW at 20 ºC.

We also demonstrate, for the first time, GaSb-based laterally coupled distributed-feedback (LC-DFB) metamorphic lasers that operate continuous wave at room temperature. The LC-DFB lasers operate in a single longitudinal mode at 20ºC with the total output power up to 40 mW and the slope efficiency of 115 mW/A

9002-42, Session 9

Generation of high-peak power from a 4.55 um optically-pumped semiconductor laser

Andrew P. Ongstad, Air Force Research Lab. (United States); Michael Tilton, Boeing-SVS, Inc. (United States); Ron Kaspi, Air Force Research Lab. (United States)

We report on the generation of high peak power from a broad area, optically pumped, semiconductor laser (OPSL) emitting at 4.56 µm.

The OPSLs contained 14 type-II InGaSb/InAs/InGaSb quantum wells periodically inserted into thick 1000 Å lattice matched quaternary (InGaAsSb) layers. The quaternary layers act as efficient absorbers of the pump radiation with ~ 80-90 % single pass absorbance. The epitaxial material was processed into 5 mm long edge-emitting lasers, which were subsequently pumped by the 2.09 µm output of a passively Q-switched Ho:YAG laser. The high peak power capabilities of the pump laser (90 kW) allow pumping OPSLs at thousands of times above threshold. The maximum double-ended OPSL power obtained was 628 W at an input power of ~29 KW. For low power pumping the OPSL pulse tracks the 16 ns FWHM pump pulse and the OPSL power conversion efficiency is ~16 %. As the pump power is increased, the OPSL pulse-width increases and eventually self-modulates, generating two nearly discrete pulses separated by ~17 ns. In addition, OPSL efficiency drops as pump power increases. We attribute the self-modulation and declining efficiency, in part, to increasing free-carrier absorbance in the thick quaternary regions induced by carriers' reservoiring in these layers. In fact, in some OPSL samples we observe co-lasing from the quaternary region near 2.67 µm; lasing from this region occurs at a much higher threshold than lasing from the QW. A three-rate equation dynamics model gives good agreement with the OPSL power and pulse dependence on pump power data.

9002-43, Session 10

High-power high-brightness single-mode master oscillator power amplifier and tapered QCLs for stand-off detection *(Invited Paper)*

Romain Blanchard, Patrick Rauter, Guy-Mael J. De Naurois, Harvard School of Engineering and Applied Sciences (United States); Tobias S. Mansuripur, Harvard Univ. (United States); Federico Capasso, Harvard School of Engineering and Applied Sciences (United States)

Quantum Cascade Lasers (QCLs) have unprecedented design flexibility and functionality broadly impacting sensing, spectroscopy, atmospheric chemistry and high power applications such as infrared countermeasures. This talk will focus on recent developments on single mode Master Oscillator Power Amplifier (MOPA) QCLs and on MOPA QCL array technology with single mode, high power, broadband tuning capability, as well as on high-brightness tapered QCLs and low-divergence collimated high power QCLs using plasmonics.

9002-44, Session 10

Quantum cascade laser in a master oscillator power amplifier configuration

Borislav Hinkov, Mattias Beck, Emilio Gini, Jérôme Faist, ETH Zurich (Switzerland)

Distributed feedback (DFB) quantum cascade (QC) lasers are very interesting light sources for the spectroscopy of prominent greenhouse-gases in the mid-infrared spectral region (3-12 µm) like CO2 or N2O. Increasing the maximum emitted optical output power is of particular interest for such kind of sources. Two approaches to achieve this are either to increase the length of the waveguide of a DFB QC laser or to combine a short DFB-section with a long Fabry-Pérot cavity which results in a device in a so called master-oscillator power-amplifier (MOPA) configuration.

This work compares both approaches theoretically by applying a transfer-matrix approach to both configurations. It is shown that the long DFB device leads to bad mode discrimination whereas the MOPA results in more than one order of magnitude higher mode discrimination due to the use of a short DFB section and therefore strong grating-coupling. Including small ridge-width fluctuations which can easily occur during device fabrication results in no singlemode emission for the DFB device whereas the singlemode discrimination is barely influenced for the MOPA geometry.

We also show experimental results from buried heterostructure MOPAs in this work. They typically emit Watt-level peak optical output power at 1% duty-cycle for 4 µm x 5.25 mm devices. Since no tapering is included, the devices show a symmetric farfield in TM00-mode with divergences around 25° along and perpendicular to the growth direction. The devices can be tuned singlemode and mode-hope free in a temperature-range of 50°C around room-temperature with a sidemode suppression-ratio of >20 dB.

9002-45, Session 10

AlAs/InAlAs-InGaAs QCLs grown by gas-source molecular-beam epitaxy *(Invited Paper)*

William T. Masselink, Mykhaylo P. Semtsiv, Yuri V. Flores, Mikaela Elagin, Grygorii Monastyrskyi, Jan F. Kischkat, Sergii S. Kurlov, Anna Aleksandrova, Humboldt-Univ. zu Berlin (Germany)

Active region designs of QCLs containing composite barriers based on AlAs allow short wavelength emission, improved injection efficiency, and high values of T0 and T1. On the other hand, AlAs introduces challenges, not only in strain compensation and growth, but also in effects on thermal management, thermal stability, and scattering.

Leakage current, allowing electrons to bypass transitions between upper and lower laser levels occur due to scattering of electrons into higher-lying states via phonons and interface roughness scattering. This interface roughness scattering is exacerbated by large values of ΔEc and by the rms roughness itself, both of which are pronounced at the AlAs/InGaAs interface. The resulting leakage current noticeably reduces the slope efficiency, leading to more heating to achieve a given emission power.

Efficient thermal management requires a buried heterostructure design; the re-growth of InP:Fe, however, needs to be carried out at temperatures consistent with maintaining the highly strained AlAs/InGaAs interfaces.

The talk describes the physics of intersubband electron scattering due to strained interfaces and some partially optimized structures with Jth=1.7 kA/cm2 at 300 K, slope efficiency η = 1.4 W/A, T0 = 175 K, and T1 = 550 K. Re-growth of InP:Fe using gas-source MBE at substrate temperatures below 550°C results in packaged lasers with 7 µm width having thermal conductance of 600 W/(K cm2).

9002-46, Session 11

Interband cascade lasers for the mid-infrared spectral region *(Invited Paper)*

Sven Höfling, Robert Weih, Matthias Dallner, Martin Kamp, Julius-Maximilians-Univ. Würzburg (Germany)

Interband cascade lasers are mid-infrared semiconductor lasers that are very promising for low power consumption applications in the 3-6 µm spectral range. Therefore, they are ideal for gas sensing of hydrocarbons. Combining interband transitions utilized in diode lasers with a cascading scheme widely exploited in intersubband transition based quantum cascade lasers, interband cacscade lasers can operate at threshold current densities around or below 100 Acm-2 at room temperature. Distributed feedback interband cascade lasers emit at room temperature continuous wave output powers in the mW range and above, and their side mode suppression ratio can well exceed 20 dB.

9002-47, Session 11

High-power high-brightness tapered-ridge interband cascade lasers operating in CW mode

William W. Bewley, Chadwick L. Canedy, Chul S. Kim, Charles D. Merritt, Joshua Abell, Igor Vurgaftman, Jerry R. Meyer, U.S. Naval Research Lab. (United States); Mijin Kim, Sotera Defense Solutions (United States)

While tapered lasers and amplifiers are well known in the near-infrared and 2-um spectral regions, there have been no previous reports of cw operation in the mid-infrared (mid-IR, 3-5 um). This is partly because a strong tendency for current spreading in cascade lasers makes it difficult to implement a tapered section with gain-guided geometry. Here we discuss the development of tapered-ridge mid-IR (lambda = 3.75 um) interband cascade lasers (ICLs) emitting up to 403 mW in cw mode at T = 25 deg. C with a near-diffraction-limited beam quality of M2 = 2.3. The highest brightness realized in this device was ≈30% higher than the best result obtained previously for a corrugated ICL ridge, in spite of the slightly poorer baseline performance of the present ICL wafer. The tapered ridge comprised a 4-mm-long single section with width varied linearly from 5 um at the high-reflection-coated back facet to 63 um at the anti-reflection (AR) coated output facet (corresponding to a half-angle of 0.42 deg.). The AR coating was a single dielectric layer with estimated reflectivity of a few percent at the lasing wavelength. The etch proceeded through the ICL active core, to the bottom separate-confinement region, in order to eliminate current spreading. A slightly lower maximum cw brightness was obtained from another device with a 1-mm-long narrow straight section combined with a 3-mm-long section that was tapered at half-angle 0.5 deg. The optimum taper angle remains to be investigated in future work.

9002-48, Session 11

Quantum band engineering of nitride semiconductors for infrared lasers *(Invited Paper)*

Oana Malis, C. Edmunds, D. Li, G. Gardner, J. Shao, Purdue Univ. (United States); W. Li, P. Fey, University of Notre Dame (United States); M. J. Manfra, Purdue Univ. (United States)

No Abstract Available

9002-49, Session 11

High performance InP-based InAs triangular quantum well lasers operating beyond 2 ?m

Yi Gu, Yong-Gang Zhang, Yuanying Cao, Xingyou Chen, Haosibaiyin Li, Li Zhou, Shanghai Institute of Microsystem And Information Technology (China)

Mid-infrared semiconductor lasers in the wavelength range of 2-3 μm have aroused increasing interests as they are highly desired for a wide range of applications from medical diagnostics to environmental sensing. Accessing to this wavelength range was so far mainly achieved by antimony-containing structures on GaSb substrates. Antimony-free laser structures on InP substrates are promising to achieve superior performances than GaSb-based structures owing to the superior quality of InP substrate as well as mature growth and processing technology of InP-based antimony-free materials. InxGa1-xAs (x>0.53) strained quantum well (QW) lasers on InP substrate have been demonstrated with wavelength up to around 2.3 μm.

Through calculation, the strain extent of the QW can be decreased by changing the energy band from conventional rectangular shape to triangular one while with the same lasing wavelength. Therefore, improved device performances are expected by using triangular QW in the active region. We have grown triangular InAs/ In0.53Ga0.47As QW by digital alloy technology using gas source molecular beam epitaxy. The growth temperature and QW structures were optimized by the characterizations of X-ray diffraction and photoluminescence. After that, laser wafers were grown and devices were demonstrated. It was proved that the laser performances were significantly improved by using triangular QW instead of rectangular one. The devices were operated at temperatures higher than 330 K under continuous-wave mode, with the characteristic temperature of T0=82.1 K from 200 K to 280 K and T0=40.5 K from 280 K to 330 K.

9002-50, Session 12

High-power and high-efficiency broad-area diode laser emitting at 1.5 um *(Invited Paper)*

Toby J. Garrod, Don Olson, Michael Klaus, Chris J. Zenner, Christian Galstad, Francois Brunet, Compound Photonics (United States); Luke J. Mawst, Dan Botez, Univ. of Wisconsin-Madison (United States)

High power diode lasers emitting over the 78x – 10xx nm range have made significant progress in terms of reliable power (8 – 12 W), efficiency (60 – 70%) and brightness (horizontal beam divergence ~ 10 - 15°) over the last decade. This level of power and efficiency has not been demonstrated for long wavelength diode pumps emitting around 1.4 – 1.6 um, a range useful for pumping solid-state laser systems as well as direct-diode applications. Diode-pumped laser systems will benefit from pumps that have high efficiency, high brightness and are able to operate at high temperatures (20°C to 80°C). In this work, we have taken a systematic approach in analyzing the power loss mechanisms associated with diode lasers emitting around 1.5x um. We illustrate a step-by-step comparison of experimental results from long wavelength diode lasers emitting around 1.5x um outlining the benefits of low loss materials, carrier leakage suppression and balancing the effects of resistive losses and free-carrier absorption. Through the design optimizations outlined in this work, state-of-the-art long wavelength diode laser performance has been achieved. We report a single quantum well laser (1.5 x 0.1 mm^2) emitting 2 W of reliable power at 1.5x um under continuous wave operation at room temperature with a peak electrical-to-optical conversion efficiency of 50%.

9002-51, Session 12

Very high-power broad area laser diode with internal wavelength stabilization at 975 nm for Yb fibre laser pumping

Michel Krakowski, Patrick Resneau, Michaël Maria, Marco Lamponi, Michel Lecomte, Yannick Robert, Eric Vinet, Michel Garcia, Olivier Parillaud, III-V Lab. (France)

High-power laser diodes at 975 nm are required for pumping fiber lasers and amplifiers. Due to the narrow absorption peak of Yb in glass at 975nm, people use either a very large absorption peak at 915nm or a wavelength stabilisation at 975nm with Volume Bragg Gratings (VBG).

However, at 915nm the absorption of the Yb doped glass is three times lower than at 975nm.

The use of VBG requires specific optics and alignment.

Our approach is to use a built-in stabilisation scheme through an integrated Bragg grating forming a Distributed Feedback (DFB) broad area (BA) structure. This approach is made possible since we use an

Aluminium free active region structure. The target is to obtain both a reduce wavelength evolution with temperature (less than 0.07nm/K) and a low spectral width (less than 1nm).

Our Al-free active region structure contains one GaInAs quantum well embedded in a GaInAsP waveguide, forming a large optical cavity structure with very low internal losses of 1cm-1. The grating is defined in a specific GaInAsP waveguide layer. Then an epitaxial regrowth is performed with GaInP fill in layer, and P type cladding and contact layers.

On a 3mm x 100 µm BA Fabry Perot (FP) laser, we have obtained a high power of 10W, thanks to a high differential efficiency of 1W/A, a very low series resistance of 35mOhm and a wall plug efficiency exceeding 60%

At the conference, we will present the results on DFB BA lasers that will be compared to PF BA ones.

9002-52, Session 12

Defect temperature kinetics during Catastrophic Optical Damage in high power diode lasers

Martin Hempel, Jens W. Tomm, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

The catastrophic optical damage (COD) is one of the limiting factors in reaching higher optical output powers from diode lasers.

Starting from a microscopic ignition site well below 1 µm in size, the COD develops in nanoseconds to a macroscopic defect of several micrometers. The temperature kinetics during this process has been discussed controversial in the past. We employed different methods to uncover it: The motion of the defect front related heat source and the signal amplitude were measured in-situ with micro-thermography. A special kind of accelerated aging based on short single high current pulses was used to control the energy that is incorporated into defect growth. The defect sites were inspected by high-resolution microscopy. The heat spread was modeled based on the experimental data and a comprehensive model for the defect spread establishes the link between the microscopic and macroscopic mechanisms.

The experiments were performed with AlGaAs/GaAs based quantum well diode lasers emitting around 808 nm. All results point to a maximal temperature of ≈1500°C that is present during the entire process at the defect front. Furthermore, a very rapid heating/cooling thermo-cycle can be observed at locations passed by the defect front.

The results allow insights into the kinetics of COD on both the microscopic and macroscopic level.

9002-53, Session 12

Cryogenic ultra-high-power infrared diode laser bars *(Invited Paper)*

Paul Crump, Carlo F. Frevert, H. Hösler, Frank Bugge, Steffen Knigge, Wolfgang Pittroff, Götz Erbert, Günther Tränkle, Ferdinand-Braun-Institut (Germany)

GaAs-based high power diode lasers are the most efficient source of optical energy, and are in wide use in industrial applications, either directly or as pump sources for other laser media. Increased output power per laser is required to enable new applications (increased optical power density) and to reduce cost (more output per component leads to lower cost in $/W). For example, laser bars in the 9xx nm wavelength range with the very highest power and efficiency are needed as pump sources for many high-energy-class solid-state laser systems. We here present latest performance progress using a novel design approach that leverages operation at temperatures below 0°C for increases in bar power and efficiency. We show experimentally that operation at 220K increases conversion efficiency and suppresses thermal rollover, enabling peak quasi-continuous wave bar powers of > 1.6 kW to be achieved (1.2 ms, 10 Hz), limited by the available current. The conversion efficiency at 1.6 kW is 53%. Following on from this demonstration work, the key open challenge is to develop designs that deliver higher efficiencies, targeting > 80% at 1.6 kW. We present an analysis of the limiting factors and show that low electrical resistance is crucial, meaning that long resonators and high fill factor are needed. We review also progress in epitaxial design developments that leverage low temperatures to enable both low resistance and high optical performance. Latest results will be presented, summarising the impact on bar performance and options for further improvements to efficiency will also be reviewed.

9002-54, Session 12

Realization of high-power narrow beam divergence in photonic-crystal surface-emitting laser

Kazuyoshi Hirose, Yoshitaka Kurosaka, Akiyoshi Watanabe, Takahiro Sugiyama, Hamamatsu Photonics K.K. (Japan); Yong Liang, Susumu Noda, Kyoto Univ. (Japan)

The photonic-crystal surface-emitting laser (PCSEL) is an attractive semiconductor laser in which a thin two-dimensional photonic-crystal (2D-PC) layer is incorporated into the ordinary broad area edge-emitting laser structure to control the longitudinal-transverse mode owing to diffraction. In principle, the zero group velocity effect at the band edge of the 2D-PC is utilized as a resonator and can be used for the unique properties including large-area coherent oscillation as well as arbitrary beam controlling, which includes the polarization, beam patterns, directions, and generation of vector beams. We investigated the PCSEL toward realizing a practical device that has high power and high beam quality. Here, we show our recent progress.

The device structure, which consists of an InGaAs/AlGaAs material system on n-GaAs substrates, is based on an ordinary broad area edge-emitting laser structure except it has a thin 2D-PC layer. The 2D-PC layer is placed near the active layer, and both are embedded between the p and n cladding layers. It is fabricated by using EB lithography, dry etching, and regrowth or MOCVD. The square emitting area has side of 200 micrometers, and transverse modes are well controlled in the entire region. The output power is more than 0.75 W with a single wavelength of 966 nm, and the narrow beam divergence is as narrow as 1° under continuous wave (CW) operation at room temperature. The beam quality is superior with an M2 of 1.1, which is almost the same as that of the ideal Gaussian beam.

9002-55, Session 13

Monolithic wavelength tuning of quantum cascade lasers *(Invited Paper)*

Christian J. Pflügl, Mark F. Witinski, Laurent Diehl, EOS Photonics (United States)

We will present our recent developments on widely tunable quantum cascade laser arrays for spectroscopic applications. Our QCL array approach is based on proprietary technology and inventions pioneered by the group of Prof. Federico Capasso at Harvard University and further developed by Eos Photonics. Each element of the array is individually addressable and emits by design at a slightly different wavelength. Our array technology is also a very promising candidate for high power applications. Combining the output power of all array emitters with our beam combining solutions allows for power scaling without degrading beam quality.

9002-56, Session 13

Design optimization of metal-semiconductor grating-coupled substrate-emitting quantum cascade lasers for CW operation in the mid-infrared

Luke J. Mawst, Chris A. Sigler, Jeremy Kirch, Toby J. Garrod, Xiaodong Wang, Colin Boyle, Dan Botez, Univ. of Wisconsin-Madison (United States); Thomas Earles, Intraband , LLC (United States)

Compact laser sources emitting in the mid-infrared (IR) range (i.e., 3-5 micron) are currently of great interest for: standoff spectroscopic sensing of toxic-chemical agents, free-space communications, directed infrared countermeasures (DIRCM) and LIDAR. Monolithic surface-emitting (SE) semiconductor lasers hold promise for significant advantages over edge-emitting lasers in terms of both reliable operation and manufacturing cost. Grating-coupled (GC) episide-down distributed feedback (DFB) surface emitters offer a path to achieving high power, single-spatial-mode, single-frequency CW operation. A second-order, metal-semiconductor grating-based device is desirable as a means to efficiently diffract the laser output through the substrate, as reported in the near-IR spectral region by Macomber et al.[1]. Although such TE-polarized near-IR-emitting devices have produced multi-watt CW powers, in the mid-IR spectral region, where quantum cascade lasers (QCLs) naturally emit TM-polarized light, only low (~10 mW)[2,3] peak pulsed powers have been achieved at room temperature from devices with DFB sections terminated by cleaved facets. We have carried out a comprehensive design study to determine the impact of the placement and tooth depth of the metal-semiconductor grating within QCL structures on the grating coupling coefficients and associated losses. In our study, Distributed Bragg Reflector (DBR) regions are employed on both device ends, in order to avoid reflections from cleaved facets into the DFB section of the device, just as was done in the past for near-IR GC episide-down surface-emitting lasers[4]. We employ an electromagnetics full-wave simulation software package in conjunction with a large-index-step grating-laser model[4] to design QCL devices for high, CW surface-emitted powers.

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9002-57, Session 13

Distributed Bragg reflector THz quantum cascade light sources with tuning range of ~300 GHz

Seungyong Jung, Aiting Jiang, Yifan Jiang, The Univ. of Texas at Austin (United States); Xiaojun Wang, Mariano Troccoli, AdTech Optics, Inc. (United States); Mikhail A. Belkin, The Univ. of Texas at Austin (United States)

We present monolithically integrated room temperature operating tunable distributed Bragg reflector (DBR) terahertz (THz) QCL sources. Room temperature THz lasing was realized using difference frequency generation (DFG) in dual wavelength mid infrared (MIR) active regions integrated with giant nonlinearity. The Cherenkov phase matching condition was used to enhance the out-coupling efficiency. Two design schemes have been investigated for tunable single mode operation. One DBR-QCL consisted of the gain section at the center of the device and two DBR sections for each MIR wavelength at each side of the gain section. The other DBR-QCL consisted of the gain section with a grating of one MIR wavelength and the second grating for the other MIR wavelength written on both sides of the center section. The total cavity length of both DBR-QCLs was about 1.8 mm. Single-mode lasing of MIR and THz was obtained at 940 cm-1, 1060 cm-1 and 120 cm-1, respectively. Wavelength tuning as high as ~300 GHz was achieved by applying continuous wave current into one of the DBR sections while the gain section was biased at a fixed pulse current. Continuous tuning, as much as the mode spacing determined by the coupling strength of the DBRs, and mode hopping was repeated in the range of wavelength tuning. The spectral gap due to mode hopping can be accessed by changing temperature of the laser. Peak THz power of 35 μW was obtained at 3.6 THz with a conversion efficiency of 17 mW/W2.

9002-58, Session 13

Integrated widely-tunable quantum cascade lasers with super-structure gratings

Dingkai Guo, Univ. of Maryland, Baltimore County (United States); Xing Chen, Univ of Maryland Baltimore County (United States); Jiun-Yun Li, National Taiwan Univ. (Taiwan); Liwei Cheng, Intel Corp. (United States); Terrance Worchesky, Fow-Sen Choa, Univ. of Maryland, Baltimore County (United States)

Integrated tunable quantum cascade lasers (ITQCLs) is possible to outperform external cavity tunable QCLs by achieving wider tuning range and higher output power because they can eliminate intra-cavity losses caused by coupling between laser chip and external grating. ITQCLs using binary sampling gratings have recently been reported by Corning and Harvard University. The binary sampling grating is simply a grating with part of the grating being periodically removed. Such a structure has the advantage of easy fabrication. However, its Fourier spectrum is not flat and has a Gaussian profile, which will limit the tuning range. Using super structure grating (SSG) the Fourier spectrum of it reflectivity can achieve a flat and rectangular profile, which can extend the tuning range to it full sampling spectrum. In the design, the sampling grating can be achieved by using either a chirped pitch profile or a chirped phase shift profile in real space. Our first run devices are designed with a chirped pitch profile. Without adding current into either one of the grating sections, the lasing wavelength is at 4.64um. By separately adding current into the front and back gratings, a total tuning range of more than 90cm-1 is achieved, which is currently limited by the gain material and grating etching depth where reflectivities from uncoated facets were coming to play and competing with reflectivity from SSGs. We expect a wide tuning range of 350cm-1 centered at 4.6 um shall be achieved with good broadband gain materials and AR coatings.

9002-59, Session 13

InGaAs/InP-based echelle mirror multiplexer using dual Rowland circle gratings for DFB QCL arrays in the mid-long infrared range

Luis Jorge Orbe Nava, Carlos Gordon, Guillermo Carpintero del Barrio, Univ. Carlos III de Madrid (Spain); Grégory Maisons, Mathieu Carras, III-V Lab. (France)

In this work we introduce the design, optimization, simulation and experimental characterization results of a 30-to-1 wavelength multiplexer for a Distributed Feedback Quantum Cascade Laser (DFB QCL) laser array operating in the 7-8.5 μm (mid-long) infrared (IR) range based on an Echelle mirror using a dual Rowland circle grating scheme. This design is proposed in order to achieve a continuous tuning range overcoming the limited tunability of an individual QCLs. The design is based on a DFB-QCL array with wavelength spacing of 0.05 μm, aiming

to reducing coupling between the slab waveguides to a minimum. We discuss the design parameters such as the order of diffraction, the operation wavelength range in the slab waveguides and the position of both the input and output waveguides, which are optimized for obtaining higher output power in the overall wavelength range of the multiplexer device than in a single Rowland circle grating scheme, providing an improvement in channel transmission. Other design characteristics, such as the structure scalability and reduction in size for these devices are considered and studied, including the input/output waveguide optimization as a function of parameters such as waveguide width, etching depth and wavelength. A systematic process is presented for all steps in the design of these devices, comparing both simulated and experimental results, placing them as suitable options when compared to other IR multiplexer schemes in terms of size and transmission.

9002-60, Session 14

Photonic engineering of quantum cascade lasers *(Invited Paper)*

Qijie Wang, Guozhen Liang, Nanyang Technological Univ. (Singapore); Houkun Liang, Ying Zhang, A*STAR Singapore Institute of Manufacturing Technology (Singapore)

Photonic engineering of semiconductor lasers can enable us to achieve desired laser performance, such as single-mode operation, low beam divergence far-field profile, low laser threshold and high output power. In this presentation, I am going to talk about our recent development on achieving mid-infrared quantum cascade random lasers, mid-infrared photonic crystal lasers with defects, and Terahertz quantum cascade lasers with single-mode operation and low beam divergence.

9002-61, Session 14

Low-power-consumption (P<1W) distributed feedback quantum cascade lasers for portable device applications

Mariano Troccoli, Jenyu Fan, Xiaojun Wang, AdTech Optics, Inc. (United States)

In this paper we present our most recent results on distributed feedback (DFB) quantum cascade (QC) lasers operation. The devices were grown by metalorganic vapor phase epitaxy and fabricated into buried heterostructure lasers with different waveguide designs and geometries. The gratings were dry etched into a sacrificial layer in close proximity to the active region and successively buried by re-growth of the waveguide claddings. The devices have been mounted epi-side down on copper heat spreaders and have shown pulsed and continuous wave operation at room temperature on a single mode with a side mode suppression ratio (SMSR) of 30dB. Several active regions were designed for emission at different wavelengths across the mid-IR range (WL=4-12um).

Devices with cavity sizes as small as 1mm have been shown to demonstrate laser action in continuous wave at room temperature with output powers in excess of 50mW at WL=4.55um, threshold power consumption of 0.9W and maximum power consumption below 3W. The wavelength emission and tuning with grating period is consistent with our modeling of the active region and the expected waveguide coupling. Longer cavity devices emitting in the 7.5-8um range have shown peak powers of 300mW in CW operation. The wavelength sensitivity to temperature changes is in the range of 0.5nm/K.

The devices were packaged in uncollimated TO-3 cans or high-heat load packages which include collimating optics.

9002-62, Session 14

The role of electron temperature in the leakage current in QCLs and its impact on the quantum efficiency

Yuri V. Flores, Sergii S. Kurlov, Mikaela Elagin, Mykhaylo P. Semtsiv, William T. Masselink, Humboldt-Univ. zu Berlin (Germany)

We have recently described a method to analyze the leakage current (Jleak) in quantum-cascade lasers (QCLs) for carriers scattering into higher minibands due to LO-phonon absorption [1,2]. In this presentation we demonstrate that even at low temperature when inelastic scattering is negligible, Jleak due to elastic scattering becomes significant for devices under normal lasing conditions.

A method is presented to determine Jleak above threshold and investigate its effect on the differential quantum efficiency. For a given QCL-structure, this method allows the reconstruction of Jleak using two parameters: the activation energy and the scattering time.

This procedure is supported by a self-consistent calculation of the rate equations based on a phenomenological scattering-rate model [3].

We apply our approach and investigate Jleak above threshold for a QCL emitting near 5.4 ?m operated at a low duty cycle and a heat sink temperature of 80 K. The measured activation energy corresponds to the calculated energy difference between the injector states and an excited miniband. The scattering time determined from the data corresponds to the value calculated for intersubband elastic scattering via interface roughness.

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9002-63, Session 14

Current spreading in shallow-ridge Ion-implanted quantum cascade lasers

Loan T. Le, Princeton Univ. (United States); Vadim Tokranov, Serge Oktyabrsky, Univ. at Albany (United States); Igor E. Trofimov, PTAC, Inc. (United States); Claire F. Gmachl, Princeton Univ. (United States)

Quantum Cascade (QC) lasers are customarily fabricated as deep-etched ridges, exposing the active region sidewalls to increased optical and thermal losses. Shallow-ridge or ridgeless geometries, while solving some of these issues, contend with potentially excessive lateral current spreading. QC lasers with the shallow-ridge ion-implanted (SRII) geometry are attractive because of the minimal current spreading that can be achieved without the optical and thermal losses incurred by deep etching. Here, we conduct experimental and modeling work to quantitatively attribute current spreading to the actual device geometry with the goal of optimizing the device geometry.

In our initial work, we study current spreading in SRII devices with ridge widths ranging from 25-60µm and contact widths from 4-17µm. Ion implantation was performed with 8 doses of protons with ion energies ranging from 80 400 keV to provide uniform implantation well through the active region. We fit our data to a linear model and found a stronger correlation of threshold current with contact width than with ridge width, and thus we were able to extract the value of current spreading of 5µm to either side of the contact. 2D simulations of current spreading further confirm that spreading is much smaller than what had been recorded in the literature for shallow-ridge devices.

Future work will feature a more comprehensive study of current spreading and comparison of performance of deep-ridge, shallow-ridge, and ridgeless geometries.

This work is supported by MIRTHE NSF-ERC and the NSF Graduate Diversity Fellowship.

9002-64, Session 14

Non-resonant optical modulation of quantum cascade laser and its potential in communication and spectroscopy (Invited Paper)

Rainer Martini, Stevens Institute of Technology (United States)

Quantum cascade lasers (QCL) have become one of the standard light sources for the Mid- and Far-Infrared Spectral region based on their excellent reliability, high output-power, and simple and reliable emission frequency tuning via current or temperature variation. Yet the high current required for QCL operation limits the ability for high speed modulation as specifically low-capacity contact design are needed – which typically do not allow for high-temperature operation.

However, non-resonant optical modulation of the QCL is a novel scheme in which the emission power as well as the emission frequency are changed based on carrier optically generated directly in the active medium – hence avoiding any specific design requirements. Furthermore the difference in modulation characteristics allow for simultaneous electrical and optical modulation – whereby either amplitude of wavelength variation can be selectively compensated for – and thus allow independently control of output power and wavelength, something previously not achievable. In addition such a setup could allow also for pure frequency modulation while suppressing the normally associated amplitude modulation, i.e. realizing AM without FM.

Within this talk we present experimental results showcasing bandwidth and dynamical range for such non-resonant optical modulation of QCL and its effect on both intensity and wavelength modulation. We will address the possibility of novel AM and FM modulation schemes as well as present first results on FM-modulation spectroscopy using a non-resonant optical modulated QCL.

Conference 9003: Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting XVIII

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9003-1, Session 1

Quality of light of LED lighting: accurately rendering whites and colors *(Invited Paper)*

Aurelien David, Michael R. Krames, Soraa, Inc. (United States)

The current performance of LEDs makes them suitable for general-illumination applications. However, to ensure consumer adoption, the transition to solid-state lighting should come at no compromise on the quality of light (QOL). So far, QOL is only characterized by a few incomplete metrics such as color temperature and color rendering index (CRI). In this contribution, we present theoretical and experimental results on two important and overlooked aspects of QOL:

- Whiteness rendering: many white objects contain fluorescing whitening agents which strongly improve whiteness perception when excited by the ultra-violet and violet light of natural light sources. To accurately render these objects, an LED source should have a properly designed spectrum.

- Color fidelity of real-world objects: the CRI calculation only considers a small number of color standards which can lead to inaccurate predictions of the color fidelity of a light source – especially for very structured spectra. By evaluating color fidelity over a large set of real-world objects, a better assessment of LED sources can be obtained.

9003-2, Session 1

Merit function for the evaluation of color uniformity in the far field of LED spot lights *(Invited Paper)*

Anne Teupner, Univ. Politécnica de Madrid (Spain); Krister Bergenek, Ralph Wirth, OSRAM Opto Semiconductors GmbH (Germany); Pablo Benítez, Juan Carlos Miñano, Univ. Politécnica de Madrid (Spain)

A metric for the evaluation of spatial color distribution of spot lights is proposed which is related to the visual perception. For high quality lighting and efficiency LEDs illumination systems often multiple colored LED chips are used. In combination with secondary optics like lenses or reflectors colors and patterns arises in the far field of the spot. There are typical appearances of colored rings or dots due to optical imaging of the several separated LEDs. A perfect homogenization of the far field is complex and mostly involves efficacy losses and in addition is not necessary for visual preferences. Current evaluation methods show notable divergences between the visual perception and analysis of optical simulation.

In a human factor experiment several spot lights were compared successive and evaluated by observers. They evaluated the spots according to their impression of evenness of the color. The analysis of the experiment detects main influence factors to vision and find the preferences of the observers. Main visual influence factors are determined as luminance, chroma, hue, form and symmetry. Thereof a merit function is derived which combines these factors to a standardized evaluation method. The merit function enables an objective quantitative judgement of the color uniformity in simulated or experimental LED spotlight farfields.

9003-3, Session 1

Dual phosphors-converted white LEDs modeling by using near-field chromatic luminance data

Bing Q. Chen, Hugo J. Cornelissen, Philips Research Nederland B.V. (Netherlands); Neng-Chung Hu, National Taiwan Univ. of Science and Technology (Taiwan)

An innovative way of dual phosphors-converted white LED modeling is established and demonstrated. We use near-field chromatic luminance measurement data to investigate the effect of modeling parameters in Lighttools and propose some key parameters to predict characteristics of LEDs accurately. Because of dual phosphors LEDs, there are many varied parameters to affect results of simulation. It is not only overloading in Lightools but also inefficient. In order to decrease interaction of each parameter, there is an efficient method to be provided as well. The novel thing is that we use mean free path (MFP) to replace a concentration and particle size of phosphors without scattering and add Mie particle to describe scattering of phosphors specifically. It's an equivalent phosphors model which can predict characteristic of dual phosphors-converted LEDs very well. For example, there is a strong dependence of the luminance and the color as a function of position on the LED surface of a phosphor-converted medium-power LED. Our method can accurately predict this phenomenon. Based on our model, we successfully predict characteristics of embedding LEDs in optical devices and coating LEDs with special materials.

9003-4, Session 1

Advances in optical and thermal management of phosphor-converted LEDs

Madis Raukas, John Kelso, Alan Lenef, OSRAM SYLVANIA Inc. (United States); Alexander Linkov, OSRAM Opto Semiconductors GmbH (Germany); Maxim Tchoul, OSRAM SYLVANIA Inc. (United States)

Phosphor conversion is as important to efficacy, spectral tuning and quality of Solid State Lighting (SSL) devices as is the efficient generation of suitable primary light from the pumping semiconductor chips. In SSL, a large number of applications such as low/mid-power distributed area illumination may not need the highest luminance sources that typically bring along most stringent requirements on materials, for example, as with high-brightness spotlights or automotive headlights. Nevertheless, the actual efficiency of handling generated photons matters everywhere. Basic properties of phosphors like refractive index and temperature-dependent quantum efficiency, in a series of physical processes and according to conditions surrounding the converter (for example optical scattering and reflection off of various interfaces, transmission and heat conductivity through materials), determine the overall amount of light being extracted into application. Modifying the light scattering, reflectance and transmission in different conversion media types and adding to it options for reducing the converter temperature has the cumulative effect that allows for optimizing the light generation process. Crucial to the overall efficiency are losses both from light recycled back into the LED, from various reflective surfaces, and weak volume absorption, including self-absorption of the phosphor emission. The influence of these factors will be demonstrated through examples of thermal-optical modeling and actual measurements on specific packaging configurations for a range of forward currents If. For example, advantages gained through controlling the scattering in ceramics versus powder-in-silicone and using thermally conductive materials will be elaborated. The gains can be realized in either efficacy or luminous flux.

9003-5, Session 2

Phosphor-free InGaN/GaN/AlGaN core-shell dot-in-a-wire white light-emitting diodes *(Invited Paper)*

Zetian Mi, Hieu P. Nguyen, Shaofei Zhang, Ashfiqua Connie, Md Kibria, Qi Wang, Ishiang Shih, McGill Univ. (Canada)

Recently, nanowire LEDs have emerged as a promising candidate for future phosphor-free solid-state lighting. To date, however, such nanowire-based phosphor-free white LEDs generally exhibit extremely low output power. In this context, we have developed phosphor-free InGaN/GaN/AlGaN dot-in-a-wire core-shell white LEDs, which can exhibit significantly improved output power, compared to the nanowire LEDs without the AlGaN shell. Additionally, such phosphor-free nanowire white LEDs can deliver an unprecedentedly high color rendering index (CRI) of ~92-98 in the warm and cool white regions.

InGaN/GaN dot-in-a-wire LED heterostructures were first grown on Si by plasma-assisted MBE. The LED active region consists of ten vertically aligned InGaN/GaN dots. White light emission is achieved by varying indium compositions of the dots in the range of ~ 10 to 50%. Subsequently, an AlGaN shell was grown. An output power of ~ 1.5 mW was measured for a current density of ~70A/cm2, which is nearly a factor of 100 higher than similar nanowire LEDs without the use of AlGaN shell. The significantly improved performance is attributed to the reduced nonradiative surface recombination, due to the effective lateral confinement offered by the AlGaN shell. The spectral power distribution can be further engineered by varying the growth parameters. Consequently, the devices can exhibit extremely high CRI in the range of ~ 92 to 98 in both the warm and cool white regions. Future work includes the exploitation of various schemes to significantly enhance the light extraction efficiency of such core-shell nanowire white LEDs for advanced lighting applications.

9003-6, Session 2

DERI method: Possible approach to green, red, and IR light emitters based on nitride semiconductors *(Invited Paper)*

Yasushi Nanishi, Ritsumeikan Univ. (Japan); Tomohiro Yamaguchi, Kogakuin Univ. (Japan); Tsutomu Araki, Ritsumeikan Univ. (Japan); Euijoon Yoon, Seoul National Univ. (Korea, Republic of)

Developments of Light Emitting Devices based on InN and In-rich InGaN were hampered mainly due to relatively poor quality of these material systems. We have developed a new RF-MBE growth method called DERI (Droplet Elimination by Radical Beam Irradiation) for growth of these materials. This growth method is consisted of the two series of growth steps with In-rich growth step (MRGP: Metal Rich Growth Process) and consecutive nitrogen radical beam irradiation step (DEP: Droplet Elimination Process). We found that this growth process can be considered as atomic layer level Liquid Phase Epitaxy from in-situ observation by RHEED and optical reflection. This enabled us to obtain flat and high quality InN reproducibly without precise control of V/III ratio.

As DERI process is carried out under almost thermal equilibrium condition, as conventional LPE, InGaN tends to make phase separation under highly metal rich growth condition. Using this phenomenon positively, we have successfully obtained InN/InGaN, InGaN/InGaN MQW structures, which emitted strong PL at IR and green wavelength range, respectively.

In order to realize InGaN LED covering full wave length between GaN to InN on one specific substrate, we should suppress electrical or optical adverse effects of generated misfit dislocations due to 11% lattice mismatch. For this purpose, we propose a new way to suppress dislocation effect by using this phase separation phenomenon, growing wider band gap material surrounding dislocation cores.

9003-8, Session 2

Low-cost nanofabrication of nanorod InGaN/GaN multiple-quantum-wells light-emitting diodes

Min-Huan Wang, Han Li, Yi-Kai Huang, Wei-Chi Lai, Jinn-Kong Sheu, Yun-Chorng Chang, National Cheng Kung Univ. (Taiwan)

Modern light-emitting diodes (LEDs) have been improved to a record-high efficiency with a unbelievable pace. However, to further improve the efficiency, newer concepts are very crucial. Nanophotonics provides new and novel ways to manipulate the emitted photonics, which has been proved to be able to improve the device's performance. The expensive fabrication cost to fabricate the necessary nanostructures proved to be the bottleneck for the penetration of these nanostructures into current industrial applications of LEDs.

In this study, we will propose a low-cost nanofabrication method to fabricate nanorod LED. The method is based on top-down approach where GaN layers are etched by combination of dry inductive-coupled plasma (ICP) and wet etches. The etch mask will be patterned by low-cost Nanosphere Lithography (NSL) or Nanospherical-Lens Lithography (NLL) that have been developed in our group for the last few years. The most difficult steps for this research is to fabricate the top contact to the nanorods. We proposed to use either a thin layer of graphene or metal nanohole membranes fabricated by NLL. Optical and electrical characterizations of these LEDs will also be presented. We believe the fabricated nanorod LED will demonstrates new properties that will be trigger new design of LED for the future LED industries.

9003-9, Session 2

Implementation of graphene electrodes in nanoparticle light-emitting devices

Svenja Wolff, Simon Sanders, Gerd Bacher, Ekaterina Nannen, Univ. Duisburg-Essen (Germany)

Graphene is a very attractive candidate for "green" electrodes in future large-area light emitting devices (LED) which are required to be cost-effective and robust. As a standard electrode for large-area LEDs, like O-LEDs or QD-LEDs, mainly ITO (Indium Tin Oxide) is used. However, this approach suffers from the limited resources of indium. A good alternative could be graphene layers. They are conductive, have a high mechanical strength, are chemically stable and they are flexible. In addition the transparency of graphene (97.6%) is obviously higher compared to ITO (85%).

We used commercially available colloidal quantum dots dispersed in toluene which emit at a wavelength of 608 nm. The nanoparticles were spin coated, resulting in a tight homogeneous layer on top of a graphene laminated glass substrate, which acts as a transparent back electrode instead of the conventional ITO.

After evaporation of a top aluminium electrode, a diode-like I-V characteristic was obtained. At room temperature, the device operates at a voltage of 4V and shows large-area electroluminescence in the red spectral range indicating an efficient electrical carrier injection. Thus, our findings open a path towards all-inorganic and large-area particle based luminescent devices with graphene electrodes.

9003-10, Session 3

A critical review of III-Nitride LED efficiency droop models

Joachim Piprek, NUSOD Institute LLC (United States)

III-nitride LEDs based on GaN or AlN deliver high efficiency only at relatively low current and at relatively low brightness. At the elevated injection current required in practical high-brightness applications, the internal quantum efficiency (IQE) is substantially reduced. This efficiency droop phenomenon is observed across a broad wavelength spectrum, with and without self-heating. It is subject to intense research worldwide, as it hampers general lighting applications of GaN-based LEDs. Thus far, it seems clear that the droop originates in carrier loss mechanisms which prevent electron-hole pairs from generating photons inside the active layer. Several and partially contradicting proposals have been developed to explain the microscopic droop process. Among them are density-activated defect recombination (DADR), indirect Auger recombination, and deficient hole injection (electron leakage). However, conclusive experimental evidence is still missing and none of these proposals is generally accepted, including a recent report on Auger electron emission. None of the proposed droop models is able to single-handedly explain all droop observations.

In an effort to bring more clarity to the ongoing and sometimes confusing droop discussion, this presentation reviews the current state of the art of efficiency droop models. Strengths and weaknesses of the existing explanations are analyzed. In particular, the talk demonstrates that a reliable prediction of the LED efficiency droop through numerical simulations is hindered by the insufficient knowledge of key material parameters.

9003-11, Session 3

Modeling the temperature dependence of efficiency versus current density in InGaN light-emitting diodes

Weng W. Chow, Sandia National Labs. (United States)

This paper investigates LED efficiency as functions of current density and lattice temperature. The analysis uses a model that allows direct input of band-structure properties. Band-structure details are important, because underlying emission properties in a wurtzite quantum-well (QW) structure are the excitation dependences of energy dispersions, confinement energies and optical transition matrix elements. These dependences arise from screening of piezoelectric and spontaneous polarization fields. Band-structure properties are computed by solving Poisson and k?p equations in the envelop approximation. The information is used in a dynamical model for populations in momentum-resolved carrier states.

The model is applied to compute the temperature dependence of internal quantum efficiency (IQE) versus current density. Motivations for adding temperature dependence to the droop investigation are the possibility of further physical insight and to provide more stringent testing of the model. To relate to experiment, simulations are performed for two LED configurations. The experimental devices had single-QW active regions, which circumvented complications arising from nonuniform population in multi-QW structures. One device consisted a 2nm In(0.37)Ga(0.63)N QW between GaN barriers, while the other device consisted a 3nm In(0.20) Ga(0.80)N QW between GaN barriers.

9003-12, Session 3

Analyzing the correlation between nanoscale indium fluctuation in multiple quantum wells and efficiency droop behavior for InGaN-based light-emitting diodes grown on GaN substrate and sapphire

Da-Wei Lin, National Chiao Tung Univ. (Taiwan); Yuh-Renn Wu, National Taiwan Univ. (Taiwan); Yu-Ting Kang, National Chiao Tung Univ. (Taiwan); Shu-ting Yeh, National Taiwan Univ. (Taiwan); Yu-Lin Tsai, Gou-Chung Chi, Hao-Chung Kuo, National Chiao Tung Univ. (Taiwan)

Presently, high power LEDs have been used in solid-state lighting and replace most of the traditional lighting sources. However, efficiency droop would be introduced as the LEDs operating at high current density. In this study, we compare the efficiency droop effect of LEDs grown on GaN substrate and sapphire and report the correlation between nanoscale indium fluctuation in multiple quantum wells (MQWs) and efficiency droop behavior. The same LED structure was grown on GaN substrate and sapphire. We attempted to analyze the degree of indium fluctuation in MQWs from macroscopic and microscopic angles, respectively. From macroscopic angle, the temperature dependent and time-resolved PL were employed to investigate the degree of indium localization and its potential fluctuation. On the other hand, the TEM and Energy Dispersive X-Ray Analysis (EDX) were also used to measure the practical nanoscale indium content fluctuation in 2-dimentional cross-section view. The PL and EDX measurements indicated that the MQWs structure grown on less strain homo-epitaxial substrate—GaN substate, showed much uniform indium distribution and less fluctuation, as compared to the MQWs grown on sapphire. As a result, we believe that the LEDs grown on GaN substrate exhibit a better and less efficiency droop behavior is due to more uniform indium distribution in MQWs. To verify our supposition, a two-dimensional Poisson and drift-diffusion solver with very fine mesh was constructed to simulate the electrical properties and droop behavior for MQWs with different degree of nanoscale indium fluctuation and the simulated results have a good agreement with experimental data.

9003-13, Session 3

Comprehensive study of internal quantum efficiency of high-brightness GaN-based light-emitting diodes by temperature-dependent electroluminescence method

Yaqi Wang, Mengshu Pan, Ting Li, Lightera Corp. (United States)

The wall-plug efficiency (WPE) of hight-brightness GaN-based light emitting diode (LED), benefiting from better epitaxy design and chip structure with better light extraction features, has improved dramatically during the past decade. In this study, we carry out systematic temperature-dependent electroluminescence measurements on LED chips from major chip manufacturers including Sanan, Osram, Nichia, Cree, and Lumileds. We will report on the IQE, droop, hot-cold factor, I-V, and current-spreading behavior on these chips. We will also discuss the implications of these findings on epitaxy and chip design for future performance improvement.

9003-14, Session 3

Reduction of efficiency droop in InGaN light-emitting diodes on low dislocation density GaN substrate

Kouhei Yamashita, Nagoya Univ. (Japan); Tomohiko Sugiyama, Makoto Iwai, NGK Insulators, Ltd. (Japan); Yoshio Honda, Nagoya Univ. (Japan); Takashi Yoshino, NGK Insulators, Ltd. (Japan); Hiroshi Amano, Nagoya Univ. (Japan)

It has been expected that light emission efficiency of InGaN-based light-emitting diodes (LEDs) can be improved by using low dislocation density GaN substrates. We have confirmed that LEDs on liquid phase grown GaN substrates showed high internal quantum efficiency (IQE) [1]. However, IQE decreased in high current density region over 200 A/cm^2. In this study, we investigated LED structures for liquid phase grown GaN substrates to use in higher current density region.

Three LED structures were grown by metal organic vapor phase epitaxy on liquid phase grown GaN substrates. The cathod-luminescence dark spot densities of these substrates were approximately 10^7 cm^-2. Sample A as a reference, structure is p-GaN(200 nm) / InGaN/GaN 8QW (2.5 and 11 nm, respectively) / Si-doped n-GaN(3 µm) on the substrate. In addition to the structure, sample B and sample C have a 25-pair InGaN/GaN super-lattice (SL) and Si-spike layer (2-pair 100-nm-thick u-GaN / 20-nm-thick n-GaN), respectively, between their n-GaN and MQW. We fabricated horizontal LEDs by using conventional lithography and dry etching process.

We measured the light output power–current (L-I) characteristics of all samples. The light output of sample B was slightly higher than sample A until 600 A/cm^2. However, the light output of sample A was saturated over 600 A/cm^2, and the light output at 1000 A/cm^2 of sample B was 10 % higher than sample A. On the other hand, the light output of sample C was lower than sample A until 700 A/cm^2. Nevertheless, the light output at 1000 A/cm^2 of sample C was 20 % higher than sample A. These results indicate that LEDs on GaN substrates can be modified for lower efficiency droop after employing a suitable LED structure.

[1] T. Sano, et al., Jpn. J. Appl. Phys. 52, 08JK09 (2013).

9003-15, Session 3

Efficiency droop improvement in InGaN/GaN light-emitting diodes by thinner quantum well with different location

Sheng-Wen Wang, Da-Wei Lin, Chia-Yu Lee, Chien-Chung Lin, Hao-Chung Kuo, National Chiao Tung Univ. (Taiwan)

We use thinner-quantum well to improve the droop behavior of light emitting diode. The thin quantum well will saturate easily, but this structure has more wave-function overlap than the thick well. Furthermore, we can use this characteristic of thin well to improve carrier distribution. This simulation result showed that decreasing the well thickness in specific position will not only improve the holes transport but also increase the quantum efficiency at high current density in the active region, and the efficiency droop behavior can be effectively suppressed. The simulation results show that when we injected current into the device, the electric field of the quantum barrier nearby thin well structure will be decreased.Due to the current density of the thin wells is greater than normal thickness of the quantum well, the carriers can screen the electric field of the quantum barrier. The phenomenon will let the band bending become smooth and it will improve the carriers transport in the active region. In this research, we designed the thin well structure and then put different numbers of the thinner-well on the active region and compared to the conventional LED.Finally, we find the thin well structure can improve the efficiency droop behavior of LED.

9003-16, Session 3

Identifying the cause of the efficiency droop in GaInN light-emitting diodes by correlating the onset of high injection with the onset of the efficiency droop

David S. Meyaard, Guan-Bo Lin, Rensselaer Polytechnic institute (United States); Jaehee Cho, Chonbuk National Univ. (Korea, Republic of) and Rensselaer Polytechnic Institute (United States); E. Fred Schubert, Rensselaer Polytechnic institute (United States); Hyunwook Shim, Sang-Heon Han, Min-Ho Kim, Cheolsoo Sone, Young Sun Kim, Samsung Electro-Mechanics (Korea, Republic of)

Light-emitting diodes (LEDs) in the GaInN/GaN material system suffer from a loss of external quantum efficiency at high current densities, a phenomenon known as efficiency droop. We demonstrate a strong correlation between the onset of the high-injection regime, and the onset of the efficiency droop. Once the LED violates the low-injection condition, an electric field begins to develop in the p-type region, sweeping carriers away from the active region.

Experimentally, an unequivocal correlation between the onset of high injection and the onset of the efficiency droop is demonstrated in GaInN light-emitting diodes over a wide range of temperatures. The diode voltage at the onset of high injection and the voltage at the onset of the efficiency droop are correlated by the equation V_High-injection onset + ΔV ≈ V_Droop onset. The excess voltage, ΔV, determined to be 0.3 V, drops partially over the junction, and partially over the p-type region. It is shown that because the electron sweep-out time (τ_DL << 1 ns) is much shorter than the radiative recombination time in QWs (τ_Radiative >> 1 ns), substantial electron leakage can occur despite the high barriers that confine carriers to the active region.

In addition to experimental correlation between the onset of high injection and the onset of the efficiency droop, an LED is simulated using APSYS. Simulation shows that at increased current densities, the barriers that confine electrons are reduced, leading to high-injection, the buildup of electric fields in the p-type region, and electron leakage out of the active region.

9003-17, Session 4

Long wavelength nanowire light-emitting diodes *(Invited Paper)*

Pallab K. Bhattacharya, Shafat Jahangir, Ethan Stark, Univ. of Michigan (United States); Martin Mandl, Tilman Schimpke, Martin Strassburg, OSRAM Opto Semiconductors GmbH (Germany)

High efficiency visible light emitting diodes (LEDs) are important to many applications including solid-state lighting, display technologies, and medical applications. Long-wavelength (green and red) LEDs are especially necessary to realize red-green-blue (RGB) phosphor-free white light sources which offer an unparalleled level of tunability in color temperature, chromaticity coordinates, and color rendering index.Here we have realized green (? = 540nm) and red (? = 650nm) InGaN/GaN disk-in-nanowire (DNW) LEDs capable of being used for these applications.GaN nanowires with InGaN disks can be grown on inexpensive Silicon substrates, and offer much lower Quantum-Confined Stark Effect (QCSE) blue-shift at high injection currents due to their inherently lower polarization fields compared to bulk quantum wells.

We have grown DNW InGaN/GaN green and red LEDs by RF plasma-assisted molecular beam epitaxy (RF-MBE) on (001) Silicon substrates. Through growth and surface passivation optimization, we have achieved internal quantum efficiencies (IQE) of 55% and 52% in the green and red devices, respectively. We observe Quantum Confined Stark Effect (QCSE) blue-shift of 7nm and 15nm respectively in the green and red

LEDs, from which we calculate the polarization field in the disks to be 605kV/cm for green and 1.26MV/cm for red, much lower than 2MV/cm measured in green quantum wells. Our devices display no external quantum efficiency droop below 385A/cm2pulsed bias current. We will also discuss our ongoing work to improve light extraction efficiency by transfer of nanowire heterostructures to Ag mirrors from the silicon growth substrate.

9003-18, Session 4

Nanorod-structured flip-chip GaN-based white light-emitting diodes *(Invited Paper)*

Ching-Ting Lee, Hsin-Ying Lee, Yu-Ting Su, National Cheng Kung Univ. (Taiwan)

(Invited talk)

By improving light extraction of white LEDs to obtain high light output power and high phosphor conversion efficiency, the omnidirectional diffused ZnO nanorod reflector was applied in conventional flip-chip LEDs. The omnidirectional dif-fused ZnO nanorod reflector was fabricated on the p-GaN side by sequentially depositing the ZnO nanorod arrays and the high reflective Al metal. Moreover, the ZnO nanorod arrays were also grown on the light output side of the flip-chip LEDs as an antireflection layer using hydrothermal method. Eventually, the yellow phosphor layer was coated using a remote phosphor coating technique to form the white LEDs. Comparison with the flip-chip white LEDs with flat reflectors, at the same injection current, the output power and phosphor conversion efficiency of flip-chip white LEDs with diffused ZnO nanorod reflectors and ZnO nanorod arrays were improved from 19.95 mW and 75.8% to 23.91mW and 80.1%, respectively. These results verified that both the omnidirectional diffused ZnO nanorod reflector and the ZnO nanorod array on the output side could improve the light output power of the flip-chip white LEDs. Moreover, the ZnO nanorod arrays on the light output side could effectively guide the blue light to efficiently excite the yellow phosphor layer and could enhance the phosphor conversion efficiency. Therefore, the diffused ZnO nanorod reflectors combined with the ZnO nanorod array antireflection layer and the remote phosphor coating technique can be applied to obtain high performance flip-chip white LEDs.

9003-19, Session 4

Nanoscale characterization of nitride nanostructures using helium temperature scanning electron microscopy cathodoluminescence *(Invited Paper)*

Jürgen Christen, Otto-von-Guericke-Univ. Magdeburg (Germany)

No Abstract Available

9003-20, Session 5

Highly-reliable Ag-based reflector for vertical-geometry GaN-based light-emitting diodes: Electrode design to improve the thermal stability *(Invited Paper)*

Tae-Yeon Seong, Tae-Wook Kang, Korea Univ. (Korea, Republic of)

Vertical-geometry GaN-based light-emitting diodes (VLEDs) are of great importance for solid-state lighting application. To enhance the light extraction, Ga-polar p-type reflectors with high reflectance and low contact resistance must be realized. Owing to its reasonable electrical property, Ag is the most frequently used reflector. However, Ag only reflector undergoes poor thermal property when annealed above 300ºC in air. Thus, various approaches have been introduced to overcome the problem. In this work, we present how to design Ag-based reflectors for the improvement of both the thermal and electrical properties. It is shown that the use of interlayers, middle layers, and capping layers significantly improve the optical reflectance. For example, Ag only reflectors produce a reflectance of ~60% at 460 nm when annealed at 500 ºC, whereas the combined Ag reflectors exhibit a reflectance of 75 – 85%. The combined Ag-based reflectors also give better electrical property than the Ag only sample. For instance, the combined schemes give a specific contact resistance of ~10-5 – ~10-4 ohm-cm2. Blue LEDs fabricated with the 500ºC-annealed combined Ag-based reflectors yield a lower forward voltage at 20 mA than LEDs with the 500 ºC-annealed Ag only contacts. The LEDs with the 500 °C-annealed combined reflectors exhibit 25 – 33% higher output power (at 20 mA) than LEDs with the 500 °C-annealed Ag only contacts. On the basis of scanning electron microscopy and X-ray pole figure and phi scan results, possible mechanisms for the electrical and thermal improvement are described and discussed.

9003-21, Session 5

New developments on high-efficiency infrared and InGaAlP light-emitting diodes at OSRAM OS

Markus Broell, Wolfgang Schmid, Petrus Sundgren, Andreas Rudolph, Anton Vogl, Martin Behringer, OSRAM Opto Semiconductors GmbH (Germany)

Efficacies of light emitting diodes (LEDs) have been raised dramatically during the last decade leading to a broad range of new applications for automotive and consumer technologies. We present our latest results on developments of infrared and red light emitting diodes. Both chip types are based on the socalled Thinfilm technology.

Due to the high refractive indices of the AlGaAs and InGaAlP materials, light outcoupling is difficult especially for these materials. Most of the generated light is reflected on the top surface and passes several times through the semiconductor before it is extracted. For an optimum efficiency internal absorbers have to be reduced to a minimum and light outcoupling of the structure has to be optimized.

For the latter condition, surface roughening structures were investigated which lead furthermore to a shaping of the farfield emission pattern. With these optimizations we could demonstrate new record efficiencies.

For infrared the chip efficiency has been raised by 25% with respect to former products and a record wall plug efficiency of more than 72% at a wavelength of 850nm has been reached. For red InGaAlP LEDs we could demonstrate a light output in excess of 200 lm/W and wall plug efficiencies above 60%.

This outstanding performance enables the use of LEDs in various applications which could not be addressed before.

9003-22, Session 5

Advanced packaging methodes for high-power LED modules

Rafael C. Jordan, Constanze Weber, Christian Ehrhardt, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); Martin Wilke, Fraunhofer IZM (Germany)

LED luminaires are already beyond retrofit, which are limited in heat dissipation due to the old fitting standards. Actual LED luminaries are based on new LED packages and modules with high performance but also high heat generation. Heat dissipation through the first level

interconnect is a key issue for a successful LED package. But most packages still use conductive glue for die attachment.

This article will discuss the limits of gluing as well as the critical aspects for flux less soldering like thermal expansion mismatch, metallurgical rules on substrate and die side, and heat dissipation. Also manufacturing issues like availability and compatibility will be taken into account. Beside those more common methods an introduction in forward looking methods like sintering, transient liquid phase soldering/bonding and thermo compression with nano sponge technology will be given. Finally a method to quantify heat dissipation will be shown and an experimental comparison of glued, soldered and sintered LEDs will be discussed.

9003-23, Session 5

Two-dimensional patterned sapphire substrate for full-wafer photoelectrochemical liftoff

Chieh Hsieh, Chun-Han Lin, National Taiwan Univ. (Taiwan); Zhan Hui Liu, National Taiwan Univ. (Taiwan) and Nanjing Univ. of Information Science & Technology (China); Chih-Chung Yang, National Taiwan Univ. (Taiwan)

Although the laser liftoff technique can produce quite effective sapphire liftoff results for fabricating vertical light-emitting diode (LED), it is basically a series process. In other words, this technique needs to process one substrate after another. Also, its high-power laser may damage the active region of an LED, leading to the low yield in fabricating vertical LED. In this paper, a low-cost sapphire substrate liftoff method based on the photoelectrochemical (PEC) process is demonstrated. This method can be used for parallel multiple-wafer liftoff of sapphire substrate. In other words, in one process run, it can remove the sapphire substrates of multiple full-wafer samples simultaneously if the electrolyte container of PEC and the UV light beam for PEC process are large enough. Also, it can be applied to a sample of any wafer size. By preparing patterned sapphire substrate (PSS) with two-dimensional periodic triangular grooves of several microns in width and height and the nitride epitaxial structure with the grooves preserved to form tunnels, PEC electrolyte can flow along the tunnels to etch the bottom of the GaN layer for separating the PSS from the wafer-bonded epitaxial layer. To monitor the formation of such tunnels under the epitaxial layer noninvasively, we use the technique of optical coherence tomography to scan the MOCVD grown samples. In a scanned image, the triangular tunnels can be clearly seen. Based on such a process, the liftoff of the sapphire substrate of a 2-inch full wafer has been accomplished.

9003-24, Session 5

Performance of vertical GaN light-emitting diodes using an embedded finger-type contact

Ray-Hua Horng, Kun-Ching Shen, National Chung Hsing Univ. (Taiwan); Chao-Yu Pai, National Cheng Kung Univ. (Taiwan); Dong-Sing Wuu, National Chung Hsing Univ. (Taiwan)

High performance of GaN light-emitting diodes with a finger-type embedded contact (F-LEDs) was demonstrated on a Cu substrate for improved thermal management and increased efficiency. In contrast to common sapphire-based LEDs (C-LEDs) and the wing-type embedded LEDs (W-LEDs), the use of the finger-type embedded contact not only reduces the effect of the current crowding of W-LEDs to achieve a uniform current injection but also eliminates the problem of light shading of C-LEDs to obtain more output power. At 150 mA, the output power of the three LEDs was measured to be 105.1, 127.15, and 164.42 mW for the C-LED, W-LED, and F-LED, respectively; representing that the F-LED in output intensity was raised 56.44% and 29.31% higher than that in the C-LED and the W-LED. Similarly, a 63.61% increase of output power of F-LED was obtained as compared to the C-LED case at 500 mA current injection. At this point, the efficiency droop of F-LED is 18.9%, which is lower than that of 36% and 57.8% in W-LED and C-LED, respectively; results are promising for the development of high performance LEDs using the finger-type embedded contact.

9003-25, Session 6

UV-LEDs: the long road towards shorter wavelengths *(Invited Paper)*

Michael Kneissl, Technische Univ. Berlin (Germany) and Ferdinand-Braun-Institut (Germany); Frank Mehnke, Christian Kuhn, Christoph Reich, Martin Guttmann, Tim Kolbe, Jens Rass, Tim Wernicke, Technische Univ. Berlin (Germany); Arne Knauer, Viola Kueller, Carsten Netzel, Ute Zeimer, Mickael Lapeyrade, Sven Einfeldt, Markus Weyers, Ferdinand-Braun-Institut (Germany)

Driven by a wide range of applications, research activities in the area of group III-nitride based ultraviolet (UV) light emitting diodes (LEDs) have notably intensified. Compared to conventional UV sources ultraviolet LEDs are compact, robust, and environmentally friendly; they can be rapidly switched on/off, are operated at moderate dc voltages, and exhibit long lifetimes. Most importantly, their emission can be tuned to cover any wavelength in the UV-A, UV-B and UV-C spectral range, which makes them ideally suited for applications like water purification, UV curing, plant growth lighting, and phototherapy. This presentation will provide an overview of recent advances in metalorganic vapour phase epitaxy (MOVPE) of high quality InAlGaN materials as well as the state-of-the-art in UV LED device technologies. We will discuss novel approaches to improve the internal and external quantum efficiency of UV light emitters, including the reduction of defect densities in AlN layers on sapphire by epitaxial lateral overgrowth (ELO), the growth of low resistance n-AlGaN current spreading layers, and enhanced carrier-injection via electron barrier heterostructures (EBH). In our joint effort we have been able to realize group III-nitride-based LEDs in the wavelength range between 380 nm and 235 nm with EQEs in the percentage range even at emission wavelength as short as 265 nm. We will also present new approaches to increase the light output power of UV LEDs by employing advanced methods for light extraction, e.g. micropixel LED designs, as well as improved thermal management techniques like flip-chip mounting on ceramic submounts.

9003-26, Session 6

p+-InAlN layer and ZnO-related TCOs for UV-LED applications *(Invited Paper)*

Dong-Sing Wuu, National Chung Hsing Univ. (Taiwan) and Da-Yeh Univ. (Taiwan); Kun-Ching Shen, Ching-Ho Tien, Chiung-Yi Huang, Ray-Hua Horng, National Chung Hsing Univ. (Taiwan)

High-doping concentration of p+-InAlN layer with lattice-matched to the AlGaN layer was employed in UV-LEDs as current spreading layer to improve the injected current distribution, and thus increased the electron-hole radiative recombination, raising the UV-LED output power. ZnO-related materials have electrical and optical properties similar to ITO, and smaller lattice mismatch to GaN. Particularly, Ga-doped ZnO (GZO) and Al-doped ZnO (AZO) films prepared using MOCVD and PLD exhibited a high transparency above 90% at wavelength of 360 nm and low contact resistance of 10-3 Ω-cm2. The issues of combining p+-InAlN and ZnO-related TCOs in improving the UV-LED performance will be discussed and systematical investigated in this study.

9003-27, Session 6

Enhanced light extraction and electrical properties of deep-ultraviolet light-emitting diodes by reflective contacts on selective-area-grown GaN *(Invited Paper)*

Dong-Yeong Kim, Jong Won Lee, Sunyong Hwang, Jun Hyuk Park, Jong Kyu Kim, Pohang Univ. of Science and Technology (Korea, Republic of)

Recently, AlGaN-based deep ultraviolet (DUV) light-emitting diodes (LEDs) have drawn great attention due to their potential applications such as purification of air and water, sterilization in food processing, UV curing, medical-, and defense-related light sources. However, widespread adoption of DUV LEDs instead of mercury-vapor lamps is obstructed by low external quantum efficiency (< 5% for 250nm) caused by low hole-injection efficiency and poor light extraction efficiency (LEE). LEE of DUV LEDs has not been enhanced as much as expected by conventional LEE-enhancing approaches used for visible LEDs, which originates from different intrinsic property between GaInN and AlGaN (Al > ~30%). Unlike GaInN visible LEDs, DUV light from a high Al-content AlGaN active region is transverse-magnetic (TM) polarized, that is, the electric field vector is parallel to the (0001) c-axis and shows strong side emission through m- or a-plane due to crystal-field split-off hole band being top most valence band. Therefore, a new LEE-enhancing approach addressing the unique intrinsic property of AlGaN DUV LEDs is strongly desired. In this study, we propose a new type of LEE-enhancing method for AlGaN-based DUV LEDs by utilizing its strong side emission. The Al0.55Ga0.45N/Al0.4Ga0.6N multiple quantum well LED structure with peak wavelength of ~280nm is grown by MOCVD on a c-plane sapphire substrate. The geometry of the DUV LED is designed to maximize the strong side emission from the MQW by fine-stripe mesa patterns and to reflect UV photons up to the free space by Al-coated selective-area-regrown GaN stripes, resulting in much enhanced LEE. In addition, the electrical properties of the DUV LED are improved substantially due to reduced specific contact resistivity as well as increased actual contact area on n-type AlGaN. The simultaneous improvements in optical and electrical properties of DUV LEDs by using the new approach will be discussed in detail with light propagating properties calculated by finite element analysis as well as an electrical conduction model.

9003-28, Session 6

Enhancing carrier injection in the active region of a 280nm emission wavelength LED using graded hole and electron blocking layers

Bilal Janjua, Tien Khee Ng, King Abdullah Univ. of Science and Technology (Saudi Arabia); Ahmed Y Alyamani, Munir M El-Desouki, King Abdulaziz City for Science and Technology (Saudi Arabia); Boon S. Ooi, King Abdullah Univ. of Science and Technology (Saudi Arabia)

A theoretical investigation of AlGaN UV-LED with band engineering of hole and electron blocking layers (HBL and EBL, respectively) was conducted with an aim to improve injection efficiency and reduce efficiency droop in the UV LEDs. The analysis is based on energy band diagrams, carrier distribution and recombination rates (Shockley-Reed-Hall, Auger, and radiative recombination rates) in the quantum well, and carrier leakage under equilibrium and forward bias conditions. Electron blocking layer is based on Al(a)Ga(1-a)N / Al(b -> c)Ga(1-b -> 1-c)N / Al(d)Ga(1-d)N, where a > b > c and a = d. A graded layer sandwiched between large bandgap AlGaN materials was found to be effective in simultaneously blocking electrons and providing polarization field enhanced carrier injection. The graded interlayer reduces polarization induced band bending and mitigates the related drawback of impediment of holes injection. Similarly on the n-side, the Al(x -> y)Ga(1-x -> 1-y)N / Al(z)Ga(1-z)N (x < z < y) based HBL, not just reduces obstruction to electron injection into quantum well but also prevents holes from escaping the active region. The reduced carrier leakage and enhanced carrier density in the active region results in an order of magnitude increase in radiative recombination rate compared to a structure with the conventional rectangular HBL and EBL layers. The improvement in device performance comes from meticulously designing the hole and electron blocking layers to increase carrier injection efficiency. The quantum well based UV-LED was designed to emit at 280nm, which is an effective wavelength for water disinfection application.

9003-29, Session 6

High-power UV LEDs in the 290-nm to 330-nm wavelength range

Tim Wernicke, Frank Mehnke, Technische Univ. Berlin (Germany); Johannes Glaab, Mickael Lapeyrade, Sven Einfeldt, Ferdinand-Braun-Institut (Germany); Christian Kuhn, Christoph Reich, Nikolay Ldentsov Jr., Jens Rass, Technische Univ. Berlin (Germany); Tim Kolbe, Ferdinand-Braun-Institut (Germany); Neysha Lobo, Technische Univ. Berlin (Germany); Christoph Stölmacker, Arne Knauer, Markus Weyers, Ferdinand-Braun-Institut (Germany); Michael Kneissl, Technische Univ. Berlin (Germany) and Ferdinand-Braun-Institut (Germany)

Due to their narrow band emission with customized wavelength, small size, and low operation voltages UV-B LEDs are of great interest for a number of applications like phototherapy, plant growth lighting, and UV curing. In this paper we will discuss some of the key steps towards realizing high efficiency and high power (In)AlGaN multiple-quantum-well (MQW) LEDs . For UV-B emission, growth on relaxed AlGaN:Si is necessary to avoid defect formation within the active region. Thick Al0.5Ga0.5N:Si buffer layers on (0001) AlN/sapphire templates exhibit a defect density of around 3x10^9 cm^-2 allowing the growth of quantum wells with internal quantum efficiencies of 10%-20%. Another key challenge is the injection efficiency. By introducing an AlN/AlGaN electron blocking heterostructure and optimizing aluminum content and doping of these layers the carrier injection efficiency was greatly increased. In order to achieve homogenous carrier injection finger and micro pixel geometries were compared leading also to an improved thermal management. Flip chip mounted LEDs exhibit a thermal resistivity in the order of 10 K/W. Additionally the heat load was reduced by using vanadium based n-contacts with low specific contact resistivity of 10^-6 Ohmcm?. LEDs exhibiting external quantum efficiencies (EQEs) > 1% were realized for a broad wavelength range from 295 nm to 330 nm with maximum output power of 18.7 mW for a 310 nm LEDs. LED life time testing shows a very moderate decrease of output-power of < 10 % after 1000 h of operation at room temperature and constant current of 74 A/cm?.

9003-30, Session 7

Surface plasmon coupled light-emitting diodes *(Invited Paper)*

Horng-Shyang Chen, Chia-Feng Chen, Chung-Hui Chen, Pei-Ying Shih, Chieh Hsieh, Che-Hao Liao, Wang-Hsien Chou, Chih-Yen Chen, Yean-Woei Kiang, Chih-Chung Yang, National Taiwan Univ. (Taiwan)

Surface plasmon (SP) coupling in a light-emitting diode (LED) has been proved to be a useful approach for enhancing the LED emission efficiency. The SP coupling with the radiating dipoles in a quantum

well (QW) relies on several issues, including the matching of the QW emission wavelength with the spectral range of SP resonance, the SP resonance strength and the corresponding metal absorption level, and the overlap between the major SP field distribution and the QW. Two sets of InGaN/GaN QW LED based on two epitaxial structures of different p-GaN layer thicknesses are fabricated for demonstrating the effects of SP coupling with the QWs of the LED. In the first set based on the epitaxial structure of thick p-GaN, to reduce the distance between the Ag nanoparticles (NPs) and the QWs for increasing the coupling strength, Ag NPs are filled into a hole array fabricated on the p-GaN layer. To minimize current leakage, SiO2 NPs are used to cover the Ag NPs in the holes. In the second set based on the epitaxial structure of thin p-GaN, Ag NPs are fabricated on the surface of p-GaN. The SP-coupled LEDs and the control LEDs with flat surface or empty holes are covered with the transparent conductor GaZnO. The SP-coupled LEDs show the significant enhancements of LED output intensity and internal quantum efficiency even though the coverage of GaZnO red-shifts the LSP resonance peak such that the QW emission can only couple with the short-wavelength shoulder feature of LSP resonance.

9003-31, Session 7

Optically functional structures on GaN-based light-emitting diodes for emission pattern control *(Invited Paper)*

Jaehee Cho, Chonbuk National Univ. (Korea, Republic of); Ming Ma, E. Fred Schubert, Rensselaer Polytechnic Institute (United States); Gi Bum Kim, SAMSUNG Electronics Co., Ltd. (Korea, Republic of)

Light-emitting diodes (LEDs) are the next-generation lighting source due to their high efficiency, high reliability, and potential to offer new functionalities. However, the large refractive-index contrast between the LED semiconductor and air (i) limits the light-extraction efficiency (LEE) of LEDs by total internal reflection, and, at the same time, (ii) affects the spatial distribution of intensity of light emitted from the LED, i.e., the emission pattern of the LED. As a result, planar-surface LEDs have a very low LEE and an emission pattern with the peak emission intensity along the LED surface-normal and a decreasing intensity off the surface-normal. Such directed emission pattern is not optimized for uniform illumination of, e.g., a street surface.

Currently these two problems are solved separately: (i) the LEE of GaN-based LEDs is enhanced by surface roughening at the nitrogen-face GaN surface using substrate lift-off followed by crystallographic wet chemical etching; (ii) the emission pattern of LEDs is controlled by secondary optics such as freeform lenses. However, a complete solution for both problems will require advanced and detailed control of refractive index and surface structure at the LED semiconductor surface, which is lacking in the current techniques. Here, we present a technique that provides full control of refractive index and surface structure at the LED surface: LEDs having patterned graded-refractive-index (GRIN) coatings, i.e., GRIN LEDs. We design and demonstrate coatings that are patterned into arrays of GRIN micro-pillars, each composed of five dielectric layers of (TiO2)x(SiO2)1-x with the bottom layer having the highest refractive index and the top layer having the lowest one. The GRIN micro-pillars, including their planar geometric shape and size, are structured for emission pattern control and maximum light-extraction efficiency.

9003-32, Session 7

High efficiency green light-emitting diodes based on InGaN-ZnGeN2 type-II quantum wells

Lu Han, Case Western Reserve University (United States); Kathleen Kash, Hongping Zhao, Case Western Reserve Univ. (United States)

High-efficiency InGaN-based quantum wells(QWs) LEDs play an important role in solid state lighting. Due to the existence of both spontaneous and piezoelectric polarizations in InGaN QWs grown along the c-plane, severe charge separation within the QWs leads to significantly reduced spontaneous emission and device efficiency. Recently, both theoretical and experimental studies found that ZnGeN2 is latticed matched to GaN, and that the band gaps of ZnGeN2 and GaN are very close. Most recently, theoretical studies based on first principle calculation indicate a large band offset between GaN and ZnGeN2 (?Ec=1.4 eV; ?Ev=1.5 eV), which allows the formation of a Type-II structure. In this work, we design a strain-compensated type-II QW by inserting a thin layer of ZnGeN2 in an InGaN QW and use a thin layer of AlGaN with low Al-content as a barrier. This structure has the advantages of 1) enhancing the electron-hole wavefuction overlap significantly due to the confinement of holes in the ZnGeN2 layer; 2) extending the emission wavelength into the longer wavelength using low In-content InGaN; and 3) improving material quality due to the use of the strain compensation design. Note that the insertion of ZnGeN2 into an InGaN QW is experimentally feasible as ZnGeN2 has similar optimal growth conditions as InGaN with low In-content. Simulation studies based on a self-consistent 6-band k?p method of the proposed InGaN-ZnGeN2 type-II QW indicate an enhancement of 5-7 times in the spontaneous emission rate as compared to that of the conventional InGaN QW emitting at the same green wavelength.

9003-33, Session 7

Strain-engineered green-to-orange-emitting (wavelength less than or equal to 600 nm) GaInN quantum wells grown on metamorphic graded GaInN buffer layers with an in-plane lattice parameter larger than that of GaN

Juergen Daeubler, Rolf Aidam, Klaus Köhler, Thorsten Passow, Lutz Kirste, Michael Kunzer, Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

To date GaInN based light emitters are grown pseudomorphicaly strained on GaN, irrespective of the substrate used. The large lattice mismatch between the binaries GaN and InN of about 11% results in highly strained GaInN active layers (AL) especially for devices emitting at longer wavelength, requiring a higher In-content AL. Strain in the AL causes an inferior light emitting efficiency due to enhanced defect generation as well as piezo-field induced quantum confined Stark effect.

We propose the use of GaInN buffer layers with suitable in-plane lattice parameter to reduce the lattice mismatch of, and hence the strain in high In-content GaInN quantum wells (QWs). This way, and through increased flexibility in strain-engineering of the GaInN QW AL by e.g. implementing strain-compensated GaInN/GaN-on-GaInN QWs, an improved performance of green-to-orange emitting GaInN-based LEDs should become possible.

To demonstrate the feasibility of our approach we grew metamorphic GaInN buffer layers by plasma assisted molecular beam epitaxy, which exhibit an in-plane lattice parameter equivalent to relaxed Ga0.9In0.1N and a smooth surface (< 1,2 nm RMS).

Subsequently, the AL with different indium content in the QW as well as in the barrier layers was grown by metal-organic vapor phase epitaxy. These QW structures show bright room temperature QW emission at wavelengths between 440 nm and 600 nm. Temperature and excitation density dependent photoluminescence and IQE data will be presented and discussed in terms of carrier localization in the QWs.

9003-34, Session 7

Effective light extraction in surface-grating vertical light-emitting diodes fabricated with photoelectrochemical etching

Chun-Han Lin, Charng-Gan Tu, Chieh Hsieh, Horng-Shyang Chen, Yean-Woei Chen, Chih-Chung Yang, National Taiwan Univ. (Taiwan)

We demonstrate an inexpensive method for fabricating periodic surface structures, i.e., gratings, on the N-face n-GaN surface of a vertical LED (VLED) based on the photoelectrochemical (PEC) etching technique and show that such a grating VLED can have significantly higher light extraction efficiency than a similar VLED with a rough surface. The surface gratings of different periods are formed by building a Lloyd's interferometer within the electrolyte (low-concentration KOH) of the PEC setup. From the observations of scanning electron microscopy and atomic force microscopy, it is found that the surface grating pattern consists of a distribution of grain domains of different sizes. For comparison, rough surfaces are also fabricated with room-temperature high-concentration KOH etching to form a distribution of pyramidal islands. Among the surface grating VLEDs, light extraction is stronger in a sample of a smaller grating period. Compared with the samples of rough surfaces fabricated with PEC or wet etching, the grating VLEDs of short grating periods have the higher light extraction efficiencies. The more effective light extraction in a grating VLED is attributed to the mixture of the diffraction of the grating pattern and the scattering of the distribution of the grain domains of different sizes. Compared with a reference VLED of flat surface, the output intensity of a grating VLED with ~160 nm in grating period and ~220 nm in grating groove depth can be enhanced by >140 %. By adding epoxy to the grating surface, the output intensity can be further increased by >170 %.

9003-49, Session PWed

High-extraction-efficiency GaInN light-emitting diodes with controllable emission patterns enabled by micro-patterned graded-refractive-index coatings

Ming Ma, Jaehee Cho, E. Fred Schubert, Rensselaer Polytechnic Institute (United States); Gi Bum Kim, SAMSUNG Electronics Co., Ltd. (Korea, Republic of)

The unrestricted control of surface structure and refractive index would allow for new and improved functionalities in optoelectronic devices. Specifically, micro-patterned graded-refractive-index (GRIN) coatings can enable control of emission pattern and promote light extraction in GaInN light-emitting diodes (LEDs). We design and demonstrate coatings that are patterned into arrays of GRIN micro-pillars, each composed of five dielectric layers of $(TiO_2)_x(SiO_2)_{1-x}$ with the bottom layer (adjacent to semiconductor) having the highest refractive index and the top layer (adjacent to air) having the lowest one. By micro-patterning the GRIN coatings into GRIN micro-pillars, light rays that would otherwise undergo total internal reflection will enter the GRIN micro-pillars. The graded-refractive-index profile of the micro-pillars will guide the light rays so that they strike the sidewalls of micro-pillars at near-normal incidence and are thus extracted out through the pillar sidewalls.

The GRIN micro-pillars, including their planar geometric shape and size, are structured for emission pattern control and maximum light-extraction efficiency. It is shown that the peak emission intensity of the GRIN LEDs is controllable from ±20° to ±50° off the surface-normal. In addition, LEDs patterned with an array of four-pointed-star-shaped GRIN micro-pillars show a 155% enhancement in light-output power over an uncoated planar reference LED, showing great promise for GRIN LEDs to have emission-pattern control and high light-extraction efficiency. These two characteristics can be tuned to match specific target applications of the LEDs.

9003-50, Session PWed

Enhancement of light extraction on the vertical light-emitting diodes with SiO2 nano-extractor

Sang-Mook Kim, Korea Photonics Technology Institute (Korea, Republic of); Hyokun Son, Chonnam National Univ. (Korea, Republic of)

In this manuscript, we tried to extract the far field radiation pattern of vertical light-emitting diodes using SiO2 nano-extractor for enhancing the white conversion efficiency. The full-width at half-maximum (FWHM) of the radiation patterns of the VLED having nano-extractor (115 °–117 °) extracted more light than conventional VLEDs (108 °–110 °). Furthermore, the light output power of the VLEDs having nanorods was enhanced by 7.9 % compared to conventional VLEDs.

We believe that VLEDs with nano-extractors are more suitable for applications in solid-state lighting and displays by extracting the radiation profile.

9003-51, Session PWed

Compact remote water disinfection device using solar-powered deep-UV LEDs

Brad Butterfield, Quantel USA (United States)

Potable water that is pure and disinfected is an ongoing need worldwide. And a lightweight, inexpensive product to accomplish this solves many problems related to dysentery, disease and quality of life for humanity. Over 1 billion people worldwide lack access to pure and potable water and e-coli contamination is the leading cause of death under the age of 5 from diarrhea especially in developing and third world countries [1]. Water purification can be accomplished by many methods and combinations including active deep UV HB-LEDs to provide safe, reliable pure drinking water.

Until now, solutions to providing treatment for water purification is through chemical processes or the use of large inefficient Hg-lamp based UV systems with large power supplies that depend on fossil fuels to create the electrical power. The renewable energy of photovoltaic solar cells that drive efficient, rugged and lightweight UV-C band LEDs solves this problem of reliance on fossil fuels for power generation (a carbon neutral option). Current designs with these lamp systems including medium scale applications such as local water systems are costly to construct and maintain due to replacement and hazardous disposal of the lamps, inefficient due to power requirement, and are centralized.

It has long been proven that UV-C bandwidth light will sterilize and purify water, air and surfaces. These 200 - 280 nanometer bands break the covalent protein bond in the DNA strand helix of the micro-organism; bacteria, virus, pathogen, etc. prevent it from multiplying and render it harmless. Novel methods which utilize the efficiency of the UV-C LED based system, coupled with renewable PV power create a real world solution. It can be linearly scalable with increased LED matrices and corresponding solar panel areas.

This modular design consists of a PV panel power source connected via USB to an inline controller/display then directly hardwired to the submersible multifaceted UV LED array device which is hermetically sealed and will provide the purification effect; defined as the required dose to reliably reduce (deactivate) baseline viable E. Coli pathogen colony-forming assay concentrations and meet minimum FDA and EPA standards for safe potable drinking water [2].

9003-52, Session PWed

A NOx and SO2 gas analyzer using deep-UV and violet light-emitting diodes for continuous emissions monitoring systems

Ryoichi Higashi, Yu Taniguchi, Kozo Akao, Kazuhiro Koizumi, Noritomo Hirayama, Fuji Electric Co., Ltd. (Japan); Yoshiaki Nakano, The Univ. of Tokyo (Japan)

Gas sensing is one of the promising applications of deep ultraviolet (DUV) light-emitting diodes (LEDs). For continuous emissions monitoring systems, concentrations of nitrogen oxides (NOx) and sulfur dioxide (SO2) shall be continuously measured. Currently, non-dispersive infrared or ultraviolet gas analyzers are commonly used whose light sources are filaments or lamps. If they are replaced by LEDs, gas analyzers need no mechanical choppers or wavelength filters because the lights are turned on and off by injecting currents and spectral bandwidths are originally narrow. Here, a NOx and SO2 gas analyzer based on non-dispersive absorption spectroscopy using DUV and violet LEDs as light sources is developed. The LEDs with wavelengths of 280 nm and 400 nm were alternately turned on and off. The lights transmitted through a stainless steel gas flow cell were detected by a silicon photodiode in order to measure SO2 and nitrogen dioxide (NO2) absorption in sample gas. Nitric oxide (NO) in sample gas was converted into NO2 using an ozonizer before the gas flow cell. Residual ozone and over-oxidized NO2 were decomposed into oxygen and NO2 by a heated gas flow cell. In order to reduce water interference caused by water adsorption onto an inner surface of the gas flow cell, collimating optics reducing reflected lights were designed. As a result, in 0-50 ppm concentration range, less than 1 % F.S. of fluctuation with a 1 s integration time, 2 % F.S. of drift during 7 days and 0.5 % F.S. of water interference from 2 degrees Celsius saturated water vapor were achieved. Conversion efficiency from NO to NO2 was over 95 %.

9003-53, Session PWed

Novel samarium/erbium and samarium/terbium codoped glass phosphor for application in warm white light-emitting-diode

Cosmo M. Silva Jr., Artur S. Gouveia-Neto, Luciano A. Bueno, Univ. Federal Rural de Pernambuco (Brazil)

Lighting technology based upon light emitting diodes has attracted much attention recently due to their wide variety of advantages over daily used incandescent and conventional fluorescent illuminants. Since the realization of white-light-emitting diodes, they are viewed as the next generation solid-state illumination technology. The advantages range from energy consumption to environmental issues. Essentially, there exist two methods to generate white-light using LEDs. Color addition using LEDs producing the three primary wavelengths, or visible light emission from UV/blue excited rare-earth doped phosphors. White LED light via a blue-LED and a yellow emitting phosphor, has drawn much interest recently. However, this technique suffers from low color rendering index and the generated white-light changes with excitation power and/or temperature. Another deficiency is the absence of red components which prevents the generation of light in the red spectral region and the combination of yellow phosphor and blue-LED produces rather high correlated color temperature (CCT > 4500K). To overcome these deficiencies, a white LED fabricated via UV-blue excited red, green, and blue emitting phosphors is required. Recently, several attempts have been made to mix rare-earth multi-doped phosphors to produce either multicolor or white-light emission. Color tunability incorporates versatility to the multicolor phosphor for application in "smart light" technology. Recently, tunable phosphor emission light was realized via excitation power, temperature, and active ions concentration. Tunable polychromatic light emission in the low color correlated temperature range using Tb^{3+}/Sm^{3+} and Er^{3+}/Sm^{3+} co-doped $PbGeO_3:PbF_2:CdF_2$ glass phosphors is presented. The phosphors were synthesized, and their luminescence characteristics examined under UV-blue light-emitting-diode laser excitation. Luminescence emission around 490, 545, 600, and 645 nm in Tb^{3+}/Sm^{3+} and 525, 545, 600, and 645 nm in Er^{3+}/Sm^{3+} co-doped phosphor was obtained and analyzed as a function of rare-earth concentration, and excitation wavelength. Color tunability in the red-orange-yellow region was achieved combining the ratio of the co-dopants. The color-tunable polychromatic phosphor herein reported is a promising candidate for application in warm white-light LED-based illumination technology

9003-55, Session PWed

Enhancement of light extraction efficiency with triangular-shaped GaN-based light-emitting diodes

Ja-Yeon Kim, Korea Photonics Technology Institute (Korea, Republic of); Yong-Jin Kang, Jong-Hyun Jeon, Chosun Univ. (Korea, Republic of); Jong Hyeob Baek, Korea Photonics Technology Institute (Korea, Republic of); Min-Ki Kwon, Chosun Univ. (Korea, Republic of); Dae Woo Jeon, Korea Photonics Technology Institute (Korea, Republic of)

The low light extraction efficiency of GaN based light emitting diodes (LEDs) is one of the most important issue for solid state lighting due to light loss by the total internal reflection and Fresnel reflection that occur at the LED surface and side-wall. Recently, it is reported that conventional rectangular LED was found to be the most inefficient among the polygons, and the device sidewall was the key factor to increase in light extraction. In this study, we have investigated the quadrangular LED to various polygonal LEDs in an attempt to determine an optimum structure for improving the extraction and current injection efficiencies. To measure their electrical and optical properties, LEDs were packaged onto a TO-can after scribing with a diamond tip; the total radiant flux was then measured using an integrating sphere system. This study revealed similar I-V characteristics, while the polygonal LED showed an increase in the total radiant flux, compared to that of the quadrangular LED. Specially, triangular and hexagonal shape had good properties resulting from an increase in its extraction and injection efficiency. Then, we optimize the optical and electrical properties of triangular LED which is possible to scribe with commercial tools without dead space in LED wafer. We'll present the design of triangular LED with optimized the internal angle to increase the extraction efficiency. These results indicate that the fabrication of LEDs with polygonal shapes is a very promising way to develop high-efficiency LEDs.

9003-56, Session PWed

Analysis on the luminous efficiency of phosphor-conversion white light-emitting diodes

Geun-Hwan Ryu, Hyun-Joong Kim, Sang-Ho Lee, Won-Bo Yang, Han-Youl Ryu, Inha Univ. (Korea, Republic of)

Recently, there has been rapid progress in the efficiency of the phosphor-conversion white light-emitting diode (LED) that consists of a blue LED chip and a yellow phosphor. The luminous efficiency (LE) of commercially available white LEDs can be higher than 120 lm/W, and that of R&D LED samples has been reported to be as high as 180 lm/W. However, there has been lack of study on the theoretical analysis of LE in the phosphor-conversion white LEDs. In this study, we rigorously analyze LE of phosphor-conversion white LEDs based on the photometric study of white light. The analysis model is used to find the theoretical limit of LE

using the measured spectrum of the phosphor-conversion white LED. In addition, the presented model can be used to obtain some information on the efficiency of the measured white LED such as the radiative conversion efficiency of the phosphor and the wall-plug efficiency (WPE) of the blue LED chip used in the white LED. When the efficiency model is applied to a commercial phosphor-conversion white LED, the limit theoretical value of LE is obtained to be 261 lm/W. In addition, for the measured LE of 88 lm/W at 350 mA, the lower bound of WPE in the blue LED chip is found to be ~34%. The phosphor absorption ratio of blue light was found to have an important role in optimizing the luminous efficiency and colorimetric properties of phosphor-conversion white LEDs. The theoretical model developed in this work is expected to be advantageously used for optimizing LE and color properties of phosphor-conversion white LEDs.

9003-57, Session PWed

Study of grating layer location of a GaN nano-grated LED for improvement of transmission efficiency

Ashli Behilla, Gabriela Alemana, Xiaomin Jin, California Polytechnic State Univ., San Luis Obispo (United States); Xiang-Ning Kang, Guo-yi Zhang, Peking Univ. (China)

We study nano-grated surface GaN LED to improve light extraction efficiency by optimizing the device parameters. Our study is based on rigorous coupled wave analysis (RCWA) to obtain total transmission across a device. Our simulation results allow us to optimize the device parameters to maximize light extraction efficiency. We simulate our device using a two-dimensional model with square unit grating cells in a crystal lattice arrangement whose parameters we define as follows: grating cell period (?), grating cell height (h), and grating cell width (w). We also define grating layer location (L) as the distance between the multi-quantum wells (MQW) source and the grating surface layer. Each simulation varies in grating cell period, grating cell width, and grating layer location and provides a result of total transmission across the device. These results are used to calculate improvement over the non-grated surface GaN LED. Our study on 50% fill factor grating case shows that location of the grating as well as the grating period both strongly effect the total transmission across the device. In addition, we noticed that optimizing the surface grating location might affect the total transmission by making it invariant to the effect of grating period. Our study allowed us to improve the light extraction efficiency of nano-grated GaN LED by an average of 133% when fill factor is 50%. We will present our study in further detail at the conference, and which include fill factors ranging between 0 to 100%.

9003-58, Session PWed

High-color rendering indices performance of glass based phosphor-converted white light-emitting diodes for solid state lighting

Chun-Chin Tsai, Far East Univ. (Taiwan); Wei-Chih Cheng, National Sun Yat-Sen Univ. (Taiwan); Yu-Chun Lee, Cheng Ta Kuo, Tech. R&D Div., Lextar Electronics Corp, (Taiwan); Wood-Hi Cheng, National Sun Yat-Sen Univ. (Taiwan)

The color rendering of glass-based phosphor-converted warm-white light-emitting diodes (PC-WWLEDs) was characterized demonstrated for high-temperature operation up to 350°C. For high color rendering indices, the fabrication and characteristics of low-temperature phosphor (Y;Ce:3+:YAG, G;Tb3+:YAG, R;CaAlClSiN3:Eu2+) doped glass upon applied to warm-white-light-emitting diodes was presented followed by illumination characteristics as. In this property is color coordinates (x, y) = (0.37, 0.30), quantum efficacy (Q.E) = 66.48%, color rending index (CRI) =86.8, correlated color temperature (CCT) =4059 K. The results of showed the lumen, chromaticity, transmittance, and angular CCT deviations (ACCTD) of the PC-WLEDs can sustained maintained good thermal stability at the high operation temperature up to 350?. The lumen degradation and chromaticity shift in glass- and silicone-based high-power PC-WLEDs under thermal aging at 150?, 200?, and 250? are also analyzed. presented and compared. These more thermally stable illumination properties of The result indicated that the glass based PC-WLEDs were out-performed over those of exhibited better thermal stability than the silicone based counterparts. The glass phosphor with color rendering indices (CRI) should may have potential usage as a phosphor layer for high-performance and low-cost PCWLEDs used in next-generation indoors solid-state lighting applications.

9003-59, Session PWed

Thermal stability behavior in reduced graphene oxide embedded LEDs by temperature-dependent current-voltage measurement

Nam Han, Chang-Hee Hong, Chonbuk National Univ. (Korea, Republic of)

The efficiency of conversion of electric power to light is the principal problem in the development of high-brightness LEDs. The decrease in efficiency with increasing forward current is a well-known effect for light emitting diodes (LEDs) based on InGaN/GaN material system. Increasing the operation current with the aim of increasing the LED lamp luminosity raises the emission of heat, which in turn increases the temperature of the active region of the LED structure. The overheating of a LED reduces the quantum yield of light and limits the maximum optical power and service life. In our previous study [1], we demonstrated the fabrication of reduced graphene oxide (rGO) embedded LEDs where in the acted as a buffer rGO layer for epitaxial lateral overgrowth of GaN, simultaneously effected excellent heat dissipation. The rGO embedded LED device offered comparatively low thermal resistance (down to 28%) and junction temperature (down to 32%) than that of the conventional device together with improved electrical and optical performances.

In this study, the affects of embedded rGO layer on the high power LED performance are evaluated using temperature dependent current-voltage measurements. The current–voltage (I-V) and light-output-current (L-I) measurements were performed at different temperatures from 300 to 440 K. We observed efficiency droop behaviors for all the samples. However, the external quantum efficiency (EQE) and light output power (LOP) of conventional LED decreased more rapidly with increasing temperature and current than that of the rGO embedded LED. This result further proves our earlier argument that the rGO embedded LEDs is more thermally stable over conventional LEDs.

9003-60, Session PWed

Silver nanowire network for high-performance and transparent conducting electrode of GaN-based light-emitting diodes

Ja-Yeon Kim, Korea Photonics Technology Institute (Korea, Republic of); Pan-Ju Choi, Yong-Jin Kang, Jong-Hyun Jeon, Seung-Jong Oh, Min-Ki Kwon, Chosun Univ. (Korea, Republic of)

GaN-based ultraviolet (UV) LEDs are attracting much attention for applications such as chemical and biological detection, and high density optical data storage. Furthermore, the near UV-LED emitting at 400 nm, which pumps red-green-blue phosphors to generate white light, is one of the most promising candidates for solid-state lighting. Although indium tin oxide (ITO) is widely used as a transparent conducting layer (TCL) in optoelectronic devices, the transmittance of ITO decreases rapidly in

the UV and near UV regions. Therefore, it is necessary to find a suitable material for TCLs that have high transmittance in the UV region as well as high electrical conductivity. Recently, use of silver(Ag) nanowire as TCLs has been extensively investigated because of high transmittance in the UV region as well as high electrical conductivity. However, there is no report on the characteristic of LED with silver nanowire TCL. In this study, we demonstrate the characteristic of LED with Ag nanowire transparent conductive electrode based on spin coating method. With optimization of deposition condition by spin coating, silver nanowire TCL has a sheet resistance of ~43 Ω/sq and an optical transmittance (T) of ~ 90% in the 380 – 440 nm wavelength range, which is superior to those of ITO. The electrical and optical performance of LED with silver nanowire TCL will be compared to those of conventional GaN LED with ITO. Our results present the potential development toward future practical application of Ag nanowire TCLs in optoelectronic devices.

9003-61, Session PWed

Multicolor upconversion luminescence of rare-earth doped Y2CaZnO5 nanophosphors for white light emitting diodes

Ramireddy Rajeswari, Sri Venkateswara Univ. (India); S. Surendra Babu, Research Ctr. Imarat (India); C. K. Jayasankar, Sri Venkateswara Univ. (India)

Recently, investigations on rare earth (RE) based upconversion (UC) luminescent materials are growing exponentially due to their potential applications such as displays, photovoltaics, photonics and biomedicine. Since, photon UC can be used for the generation of visible emission by near infrared (NIR) excitation, phosphor-converted white light-emitting diodes could be a potential area of technological interest in solid state lighting. Present work deals with the UC white light emitting properties of novel RE doped Y2CaZnO5 (YCZ) nanophosphors, synthesized via the citrate-gel combustion method. Transmission electron microscopy measurements revealed that the particles are distributed uniformly with the size of 10-30 nm. Er3+-doped YCZ nanophosphors has shown strong green UC emission, due to the (2H11/2, 4S3/2) ? 4I15/2 transitions, which is visible to the naked eye even at 20 mW excitation power of 980 nm laser diode. When these phosphors are co-doped with Yb3+ ions, UC green emission for less than 15 mW power was observed at low Yb3+ ion concentration and it changed to reddish emission at higher Yb3+ ion concentrations. It is found that Er3+/Yb3+ co-doped phosphors has better reddish green yield at intermediate concentrations. Tunable white light has been achieved by the addition of Tm3+ ion concentration in the triply doped YCZ nanophosphor for which CIE chromaticity coordinates fall well within the white region. The systematic investigation and results obtained indicate that these materials are ideal candidate for the development of white LEDs which were discussed and compared with the earlier reports.

9003-62, Session PWed

Classification evaluation of tobaccos using LED-induced fluorescence spectroscopy

Weijia Zhong, Yongjiag Dong, Hongze Lin, Xuan Liu, Zhejiang Univ. (China); Liang Mei, Lund Univ. (Sweden) and Zhejiang Univ. (China); Chunsheng Yan, Centre for Optical and Electromagnetic Research, Zhejiang University (China)

Tobacco is one of the most important economic crops in the world. Massive efforts have been denoted to assess its quality due to the extremely important business worth. A compact, low-cost, and flexible optical sensor is utilized to evaluate the grade and classification of different tobaccos by analyzing the fluorescence induced by multi-wavelength light emitting diodes (LED). Several LEDs with different wavelengths covering the visible range (400nm-650nm) and UV region (265 nm-400 nm) are mounted on a cylindrical alumina tube. Thus, it is convenient for stimulating the fluorescence of different materials by choosing different LEDs, and making the sensor very useful for a variety of applications. In order to better eliminate the interference of the excited spectrum, several long pass filters is mounted on a chopper which can be controlled by computer to select an appropriate filter. We demonstrate that the sensor can retrieve much more physical and chemical information from tobaccos by using multiple excitation wavelengths than single excitation wavelength. In our study, the fluorescence spectra at several different brands for different grades of tobaccos from the same brand were recorded. Principal components analysis (PCA) is utilized to extract the dominant features of the tobaccos with a large signal -to - noise (SNR) ratio, which can be used to identify and characterize the tobaccos. The agreement between the experimental results and the actual qualities shows the feasibility of this sensor to be used for tobacco identification.

9003-63, Session PWed

Real-time monitoring of sulfur dioxide using ultraviolet light-emitting diode

Weijia Zhong, Hongze Lin, Zhejiang Univ. (China); Xiutao Lou, Zhejiang Univ. (China) and Harbin Institute of Technology (China); Chunsheng Yan, Centre for Optical and Electromagnetic Research, Zhejiang University (China); Liang Mei, Lund Univ. (Sweden) and Zhejiang Univ. (China)

As one of the most common air pollutants in the atmosphere, sulfur dioxide has a strong structured absorption band in the ultraviolet region around 300 nm. In the present work, a compact and low-cost light emitting diode (LED) with center wavelength around 295 nm and 15 nm bandwidth is utilized to measure the concentration of sulfur dioxide. The collimated light beam from the UV LED propagates through a 10-cm-long gas cell filled with sulfur dioxide, and a large core multimode optical fiber is used to collect the light absorbed by the gas into a compact spectrometer. Based on differential optical absorption spectroscopy (DOAS), both the spectra from HITRAN and our measurements are used as references to retrieve the sulfur dioxide concentration. A sensitivity of about 1 ppm was achieved with a 10-cm-long gas cell and 1-s integration time. We demonstrate that the technique can obtain a good signal-to-noise ratio (SNR) because of using a LED with high output intensity in the ultraviolet region. The technique is suitable for real-time measurements based on a straightforward data evaluation method, and a low-cost, low complexity setup compared with other real-time optical detection techniques. The technique is particular useful for industrial sulfur dioxide emission monitoring.

9003-64, Session PWed

Monolithically-integrated full-color nano-LED arrays

Chu-Hsiang Teng, Hui Deng, Pei-Cheng Ku, Univ. of Michigan (United States)

In this presentation, we will demonstrate monolithically integrated full-color nanoscale light emitters. Emitters of different emission colors share the same active region, allowing the realization of an array of sub-micron dimension full-color display elements using a single epitaxial wafer. Potential applications can include microdisplays, full-spectrum light sources for chip-scale sensors, and lens-free high-resolution microscopy. To achieve a wide wavelength tuning range, we exploit the strong piezoelectric field exhibiting in GaN and related semiconductors. Via the controlled and localized relaxation of strain, optical intensity, emission wavelength, and output polarization from the InGaN active region can be precisely tuned. We performed both numerical modeling and experiments. The modeling was done using Nextnano. In the experiment,

the sample was grown by MOCVD, consisting of a single InGaN quantum well although multiple quantum wells are expected to work too. The local strain control was achieved using lithography and a combination of dry and wet etching processes. We have characterized the array using optical excitation and were able to show color control of sub-micron pixels. The results agreed well with numerical modeling.

9003-65, Session PWed

Estimation of carrier overflow in InGaN lighting-emitting diodes from photocurrent measurements

Shopan D. Hafiz, Fan Zhang, Morteza Monavarian, Serdal Okur, Vitaliy Avrutin, Ümit Özgür, Hadis Morkoç, Virginia Commonwealth Univ. (United States)

Carrier transport in double heterostructure (DH) InGaN lighting emitting diodes (LEDs) was investigated using photocurrent measurements performed under CW HeCd laser (325 nm wavelength) excitation. The effects of active region and electron injector thicknesses and electron and hole blocking layers were investigated by monitoring the excitation density and applied bias dependent escape of photogenerated carriers from the active region and through energy band structure and carrier transport simulations using Silvaco Atlas. Single 6-nm In0.15Ga0.85N DH LEDs with 10 nm p- Al0.2Ga0.8N electron blocking layers (EBLs) and no electron injector layers showed 17% carrier leakage at -3 V bias and 300 Wcm-2 optical excitation density. For single and quad 3-nm DH LED structures incorporating staircase electron injectors (SEIs) but no EBLs, photocurrent increased with SEI thickness due to reduced effective barrier opposing carrier escape from the active region as confirmed by simulations. The carrier leakage percentile for quad 3 nm DH LEDs at -3V bias and 300 Wcm-2 optical excitation density increased from 24 % to 55 % when In0.04Ga0.96N + In0.08Ga0.92N SEI thickness was increased from 4 nm + 4 nm to 30 nm + 30 nm. The increased leakage with thicker SEI correlates with decreased carrier overflow under forward bias. In this paper, estimation of carrier overflow under forward bias from the photocurrent measurements on LED structures with varying active regions designs and electron and hole blocking barrier heights will be discussed.

9003-66, Session PWed

Microscope investigation and electrical conductivity of Si-doped n-type Al0.45Ga0.55N layer grown on AlGaN/AlN superlattices

Seong-Ran Jeon, Korea Photonics Technology Institute (Korea, Republic of); Sung Jin Son, LG Innotek (Korea, Republic of); Si-Hyun Park, Yeungnam Univ. (Korea, Republic of)

Ultraviolet (UV) emitters based on wide-bandgap III-nitride compound semiconductors have attracted much attention recently because of their numerous applications in civilian and other environments, including efficient white lighting, high-density optical data storage, non-line-of-sight communication, and chemical/biological agent detection. Ternary AlGaN compounds possess a wide direct bandgap that varies from 3.4 eV for GaN to 6.1 eV for AlN, corresponding to a wavelength range of 200–360 nm, making AlGaN a promising candidate for optoelectronic devices that cover a broad portion of the UV spectrum. High-electron-mobility transistors (HEMT) based on AlGaN have also attracted a lot of attention for applications in high-power microwave devices and high-frequency, low-loss power electronics. In order to achieve short-wavelength emission in optoelectronic devices or high electron mobility in electronic devices, however, a high Al mole fraction is necessary, which makes the growth and doping of the material very difficult. Specifically, high dislocation density, slow growth rates, and insufficient conductivity of doped epilayers raise serious obstacles to obtaining high conductivity and high crystalline quality. Many techniques have been investigated to reduce threading dislocation density (TDD) in nitride semiconductor films, including epitaxial lateral overgrowth (ELO), the use of anti-surfactants, employing an interlayer, Si-doping, and so on.

In this letter, we will show that the insertion AlGaN/GaN superlattices (SLs) not only reduced TDD but also increased the free electron concentration of the n-AlGaN layer with 45% Al composition. We will also present the characterization results of the n-AlGaN layer, including dislocation density, electrical conductivity, and free carrier concentrations.

9003-67, Session PWed

On electrical efficiency and droop in MQW LEDs

Volodymyr K. Malyutenko, V. Lashkaryov Institute of Semiconductor Physics (Ukraine)

Although significant progress has been made in advancing InGaN LEDs, several performance limitations still remain. One of the fundamental challenges to be addressed is the efficiency droop which is a gradual decrease of the internal quantum efficiency with increasing injection level. It was shown that the effect occurs as a result of a current-induced dynamic degradation of radiative efficiency or injection efficiency. Broadly speaking, all the mechanisms mentioned could be referred to as the optical losses. In this paper, we come up with an alternative approach to make high-power LEDs more efficient. We identify current-induced electrical efficiency degradation (EED)-electrical losses as a strong (~20%) power conversion efficiency-limiting factor. We found that EED is caused by an increase in series resistance which follows current crowding. By decreasing current spreading length, EED also causes the optical efficiency to degrade and stands for as important aspect of LED performance. Additionally, we show that the studies connected to the optical loss (efficiency droop) are valid, provided low-current one-dimensional approximation is realized and the ratio between internal and external efficiency is independent of current. It is not the case, however, when it comes to large-area high-power LEDs.

9003-68, Session PWed

Portable fluorescence spectroscopy platform for Huanglongbing (HLB) citrus disease in situ detection

Tiago Ortega, Univ. de São Paulo (Brazil) and AgriOS (Brazil); Alessandro Damiani Mota, Giuliano Rossi, Guilherme Castro, AgriOS (Brazil); Paulino Villas Boas, Debora Milori, Embrapa Instrumentação Agropecuária (Brazil); Jarbas Castro Neto, Univ. de São Paulo (Brazil)

In this work, the development of a portable fluorescence spectroscopy platform for Huanglongbing (HLB) citrus disease in situ detection is presented. The HLB, or greening, is the most destructive disease in citrus orchards nowadays. This single disease has caused more than US$3.5 billion in lost revenues and the loss of more than 8000 job posts since 2006 only in Florida. And there is no effective detection method for large scale available. Citrus greening is vectored by a psyllid, Diaphorina citrithe, and the causative agent is Candidatus Liberibacter spp bacteria. HLB has a long asymptomatic phase, in which the infected - but not detected - tree acts as a source of the bacteria for the vector.

The developed equipment for HLB detection consists of an excitation blue LED light source operating in 405nm, a commercial miniature spectrometer ranging from 350 to 800nm, and a dedicated collection optics. Measurements of healthy, HLB-symptomatic and HLB-

asymptomatic citrus leafs were performed. Leafs were excited with the 405nm LED and their fluorescence spectra collected from 450 to 800nm. Also developed in this work, embedded electronics and software were responsible for the spectrum processing and classification via partial least squares regression. Success rates above 95% were obtained for detection through this photonic technique. This device exhibits portability, low-cost and real time detection possibility, characteristics with great potential for in situ large scale detection.

9003-69, Session PWed

Electrical and photometrical performance of LED lighting for ship accommodation quarters

Hong-Shik Lee, Hui-seok Jeong, Miso Noh, Mee-Ryoung Cho, Korea Institute of Lighting Technology (Korea, Republic of)

We present a standardization proposal for the safety and performance test items derived from the evaluation and analysis of electrical and optical characteristics of LED convergence lightings used in ship accomodation quarters. The optical and electrical characteristics of the LED and fluorescent luminaires like power consumption, luminuos flux, efficiency and light distribution were measured and analyzed using photometric measurement systems for each luminaires. The comparative evaluation of the measurement results show that the power consumption can be reduced up to 82% in case of LED luminaire while improving the total luminous flux up to 39% at the same time. As the optical efficiency of LED luminaire is more than 35%, the average illuminance is about 78.5 lx and the power consumption was 79 W, thus translating into an improvement by 53% and a reduction by 82% compared to conventional luminaires in terms of optical and electrical performances respectively. Moreover, the illumination uniformity of LED luminaire were observed to be the same as that of the fluorescent luminaires. As a result, the fluorescent luminaires in the ship accomodation quarters may be effectively replaced by LED luminaires with same illumination uniformity, lowered power consumption and increased luminuos flux.

9003-70, Session PWed

Preference and brightness differences for LED lighting: Korean and Westerners

Jae-Kyu Ko, Min-Jin Lee, Ju-Hyun Kim, Mee-Ryoung Cho, Korea Institute of Lighting Technology (Korea, Republic of)

Brightness and color properties are controllable in LEDs unlike conventional lamps, so that LED lightings can offer optimized illumination conditions according to user requests. Lighting designers can take advantage of these LED charcteristics to create the customized environment to fulfill not only visual but also emotional needs. Furthermore, lighting researchers are studying to find out the best surround conditions where students can be immersed in their studies and fruits in the market look fresher. An LED system lighting with a dimmable function has recently been commercialized (in Korea) for a parking lot aiming at significant energy and maintenance savings. Various types of intelligent network based LED system lighting are being developed for a multiple house or an office building. We therefore attempt to learn differences in perceived brightness and preference between Koreans and Westerners for an office application of LED system lighting. Observers are asked to estimate preference and brightness using a seven-point Likert scale in varied luminous environments in which illumination levels and CCT (Correlated Color Temperatures) are changed. Koreans and Westerners show different preference conditions in both illumination level and color; 800lx and 6000K for Koreans vs. 500lx and 3000K for Westerners. The common results regardless of ethnic groups are that observers view brighter surround as illumination level and CCT are increased. The CCT factor is found to be more influencing in the perception of brightness than the illumination intensity, suggesting the optimization of CCT can provide brighter atmosphere without raising the illumination intensity. This experimental result will be useful in the design of office LED system lighting.

9003-35, Session 8

Measurement of Auger effect and droop in LEDs by energy analysis of electron emission in vacuum *(Invited Paper)*

Claude Weisbuch, Jim Speck, Justin Iveland, J. Perretti, L. Martinelli, Marco Piccardo, Univ. of California, Santa Barbara (United States)

We perfom the energy analysis of electrons emitted in vacuum from commercial LEDs under forward bias. The appearance of hot electrons peaks linearly correlated with the droop current is a signature of Auger dominated droop. We discuss various control experiments and evaluate competing mechanisms for hot electrons generation and droop.

9003-36, Session 8

Microscopic models of non-radiative and high-current effects in LEDs: state of the art and future developments *(Invited Paper)*

Enrico Bellotti, Boston Univ. (United States); Francesco Bertazzi, Marco Calciati, Xiangyu Zhou, Giovanni Ghione, Michele Goano, Politecnico di Torino (Italy)

We present an analysis of non-radiative and high current effects that are relevant to understand the performance of III-nitride based LEDs. We discuss and compare models of radiative recombination processes, free carrier absorption, and non-radiative phenomena including direct (phonon-less) and indirect (phonon-assisted) Auger mechanisms, applicable to the InGaN/GaN quantum wells of a realistic LED active region. We employ these models to assess the relative importance of the corresponding processes on the calculated internal quantum efficiency of LED structures intended to operate in the green and blue spectral regions. Finally, we discuss the need for a fully microscopic, particle-based transport simulation model (such as full-band Monte Carlo), since only an approach able to capture the correct dynamics and energy distribution of carriers can help elucidate which processes are responsible for the efficiency droop.

9003-37, Session 9

Microscopic many-body investigation of the efficiency droop in GaN-based light-emitting devices *(Invited Paper)*

Jorg Hader, Jerome V. Moloney, Nonlinear Control Strategies, Inc. (United States) and The Univ. of Arizona (United States); Stephan W. Koch, Philipps-Univ. Marburg (Germany)

Many models have been suggested as possible explanation for the efficiency droop in GaN-based devices. Generally, these models are based on rate equations in which the underlying microscopic properties are described using macroscopic parameters that are used as adjustable parameters like radiative and Auger constants. The resulting high number of fit parameters allows obtaining good fits of experimental data. However, it is questionable whether they represent the underlying physics correctly.

Fully microscopic many-body models eliminate such adjustable parameters. The reduced fit-parameter space limits the uncertainty of the remaining parameters which, in turn, narrows the range of potentially applicable models.

In addition, the microscopic models can resolve the energy and momentum dependent carrier distributions, which is essential for studying deviations from the thermal equilibrium situation.

Here, we use fully microscopic models for the calculation of the carrier dynamics and resulting optical response in GaN-based devices. The models are used to investigate the validity of various models that have been suggested as the cause for the efficiency droop. In particular, we will use the models to simulate aspects of a recent experiment in which green emitting quantum wells were pumped resonantly and emission from adjacent ultra-violet emitting wells was attributed to carrier redistributions due to Auger processes (M. Binder, Appl. Phys. Lett 103, 071108 (2013)). We will investigate whether carrier localization at the used cryogenic temperatures and/or carrier heating can be responsible for aspects of the observations.

9003-38, Session 9

The efficiency droop in III-V semiconductor light-emitting diodes *(Invited Paper)*

E. Fred Schubert, Rensselaer Polytechnic Institute (United States)

Asymmetry of carrier-transport characteristics is an inherent property of III-V nitride semiconductor materials. Light-emitting diodes made of such materials have a propensity to easily enter the high-injection regime. In the high-injection regime, an electric field develops in the p-type region that extracts electrons from the active region (drift-leakage). It is shown that the onset of high injection precedes and is correlated to the onset of the efficiency droop, consistent with drift leakage being the cause of the efficiency droop.

9003-39, Session 10

Ammonothermal bulk GaN substrates for LEDs *(Invited Paper)*

Mark P. D'Evelyn, Dirk Ehrentraut, Wenkan Jiang, Derrick S. Kamber, Bradley C. Downey, Rajeev T. Pakalapati, Hakdo Yoo, Soraa, Inc. (United States)

GaN-on-GaN LEDs have demonstrated superior performance over GaN-on-sapphire and GaN-on-SiC LEDs at very high current density. Bulk GaN substrates grown by vapor-phase techniques have been in routine commercial use for GaN-based laser diodes since 2006 but have limited availability above 2 inch diameter and are expensive. Soraa has developed a novel ammonothermal approach for growth of high quality, true bulk GaN crystals at a greatly reduced cost. Soraa's patented approach, known as SCoRA (Scalable Compact Rapid Ammonothermal) utilizes internal heating to circumvent the material-property limitations of conventional ammonothermal reactors. The SCoRA reactor has capability for temperatures and pressures greater than 650 °C and 5000 atm, respectively, enabling higher growth rates than conventional ammonothermal techniques, yet is less expensive and more scalable than conventional autoclaves fabricated from nickel-based superalloys.

SCoRA GaN growth has been performed on c-plane and m-plane seed crystals with diameters between 5 mm and 2" to thicknesses of 0.5-4 mm. The highest growth rates are greater than 40 um/h and rates in the 10-30 um/h range are routinely observed. These values are significantly larger than those achieved by conventional ammonothermal GaN growth and are sufficient for a cost-effective manufacturing process.

Two-inch diameter, crack-free, free-standing, n-type bulk GaN crystals have been grown. The crystals have been characterized by a range of techniques, including x-ray diffraction rocking-curve (XRC) analysis, optical microscopy, cathodoluminescence (CL), optical spectroscopy, and capacitance-voltage measurements. The crystallinity of the grown crystals is very good, with FWHM values of 15-80 arc-sec and average dislocation densities below 1E5 cm-2.

9003-40, Session 10

GaN substrates grown by HVPE for LED applications *(Invited Paper)*

Ke Xu, Suzhou Institute of Nano-tech and Nano-bionics (China)

No Abstract Available

9003-41, Session 10

Ultra-high-efficiency GaN-on-GaN violet and white LED sources *(Invited Paper)*

Rafael I. Aldaz, Michael J. Cich, Christophe A. Hurni, Aurelien David, Arpan Chakraborty, Michael J. Grundmann, Troy A. Trottier, Bryan Ellis, Frank M. Steranka, Michael R. Krames, Soraa, Inc. (United States)

Homoepitaxial growth of GaN LEDs on native GaN substrates (GaN-on-GaN) provides many advantages for the design and manufacturing of high efficiency and reliable LEDs. In this work we demonstrate the capability of the technology with results on very high external quantum efficiency LEDs and low forward voltage at high current density, resulting in record wall-plug efficiencies at extreme operating conditions. This technology has allowed for the latest design of high brightness, high efficiency and high color quality white sources for lighting applications.

9003-42, Session 10

Extremely-high current density over 1000 A/cm2 operation in M-GaN LEDs on bulk GaN substrates with low-efficiency droop *(Invited Paper)*

Toshiya Yokogawa, Panasonic Corp. (Japan)

Non-polar InGaN-LEDs have the unique characteristics of a low efficiency droop and a polarized light emission. In this paper, we report a high power m-plane InGaN-LED with a small chip size (450 x 450 μm2) under extremely high current density condition, over 1000 A/cm2. The LED showed a high output power of 1353 mW and a high external quantum efficiency of 39.2% at 1000 A/cm2 (1134 mA). We also explain the effects of polarized light from active layer on radiation pattern. We successfully demonstrate the control technique for both radiation pattern and the polarization using stripe patterned texture.

9003-43, Session 11

Adjustable spectrum LED solar simulator

Kurt J. Linden, William R. Neal, Harvey B. Serreze, Spire Corp. (United States)

Recent progress in the availability of high power LEDs extending across most of the solar spectrum has made it possible to produce solar simulators whose spectral characteristics can be electronically controlled. Such all-solid-state simulators have advantages over currently-used xenon gas lamp simulators in that they operate at relatively low voltages free from deleterious electromagnetic interference difficulties,

with high reliability and without the strong UV and blue spectral lines emitted by xenon and other inert gas light sources. Spectrally tunable solar simulators find application for use in testing and characterizing a variety of solar cells such as crystalline silicon, thin film CdTe, CIGS, amorphous silicon, GaAs, III-V tandem cells, organic and dye-sensitized solar cells and others, each of which have different spectral response characteristics. The spectral tunability of these LED simulators makes it possible to evaluate the specific performance of the individual layers comprising tandem cells. The results obtained from a prototype LED simulator comprised of 23 different LED wavelengths providing complete UV to near-IR spectral coverage with better than 1% intensity uniformity at 1-sun over an area large enough to cover standard 156 mm x 156 mm solar cells are presented. The modular design of this simulator, including compact, low-cost electronic driver circuitry operated via a graphical user interface facilitates simulator size scaling for testing solar modules of arbitrarily large size.

9003-45, Session 11

Spectral behavior and coherence length of GaN- and AlGaInP-based light-emitting diodes

Reinhold Hetzel, Günther Leising, Technische Univ. Graz (Austria)

The coherence length of electromagnetic waves created by different light sources is a largely overlooked parameter. Since the coherence length and its spectral distribution are essential for the entire field of interference, ranging from unintended destructive and constructive pattern to intended interference determining the nature of structural colors. We studied the spectral emission behavior of GaN- and AlGaInP-based Light-Emitting-Diodes (LEDs) under thermodynamic equilibrium conditions driven by direct current as well as by short current pulses (500 ns) in the temperature range from 4.2 to 390 Kelvin. The coherence length under the different driving conditions was measured via a Fabry-Perot interference setup. We discuss the validity and limitations of the conventional determination method from the emission linewidth and lineshape. Besides the distinct shifts of the emission wavelength accompanied by significant changes of the full width at half maximum, we found quite high values for the coherence length exceeding 0.15 millimeters for the blue emission and 0.4 millimeters for the red emission at room temperature, respectively. Furthermore this contribution will also discuss the nature and interrelationships of coherence length, emission peak wavelength and the spectral distribution (lineshape and linewidth) of the investigated LEDs.

9003-46, Session 11

Permanent transparent color glazes for dimmable and non-dimmable LED bulbs

Jan-Marie Spanard, Albany Mural Ltd. (United States)

Drawing on techniques developed for the architectural restoration of stained glass, pigmented coatings have been developed that contribute more of the missing red tones to LED produced light. When these transparent, heat-resistant, and permanent pigmented coatings are applied to any glass surface of an LED bulb, including the phosphor plate, dome or envelope, warmer visible light is emitted.

These glazes can be applied in combination with existing technologies to better tune the LED emitted light or they may be used alone. All spectral colors can be efficiently and economically blended using the LED Light Warming Glazes. Those of the most potential in mass manufacturing of LED light bulbs are glazes containing yellow, orange and red pigments.

The glazes can be applied either during the manufacturing phase or as an after-market consumer product. The glazes may be produced in any variety of colors or tints for decorative purposes. The glazes may be suspended in a clear gloss vehicle or an iridescent shimmering base.

Further, a graduated application of the tinted glazes on dimmable bulbs allow the light to change color as wattage is diminished. They can be economically applied to any shape or size bulb because it is in liquid form. The glazes can be used on current bulb forms and shapes as well as any introduced in the future. They may also be marketed to current bulb owners as an after-market product to better tune the thousands of LED light bulbs currently in use.

9003-47, Session 11

Interplay between multiple scattering, emission, and absorption of light in the phosphor of a white light-emitting diode

Vanessa Y. Leung, Ad Lagendijk, Allard P. Mosk, Univ. Twente (Netherlands); Teus W. Tukker, Wilbert L. IJzerman, Philips Lighting B.V. (Netherlands); Willem L. Vos, Univ. Twente (Netherlands)

There is a major drive to efficiently generate light with white light-emitting diodes (LEDs) consisting of a blue LED combined with luminescent phosphors [1, 2]. In the phosphor blue light is converted and all light is intentionally scattered to become diffuse for a desired even lighting. It is a central challenge to predict the scattering and color conversion from first principles [3]. Unfortunately widely used numerical methods such as ray-tracing lack predictive power which hampers the development of efficient white LEDs.

Here we report new measurements of broadband diffuse transmission through phosphor plates of white LEDs with varying YAG:Ce3+ density. We derive both the transport and absorption mean free paths using the theory of light diffusion adapted to include absorption. We distinguish the spectral ranges where absorption, scattering, and re-emission dominate. We find that phosphors in commercial LEDs operate well within an intriguing albedo range. We will discuss how salient parameters that can be derived from first principles control the optical properties of a white LED.

[1] E.F. Schubert, Light-Emitting Diodes, (Cambridge University, 2006).

[2] M.R. Krames, O. B. Shchekin, R. Mueller-Mach, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford, J. Display Technology 3, 160 (2007).

[3] W.L. Vos, T.W. Tukker, A.P. Mosk, A. Lagendijk, and W.L. IJzerman, Appl. Opt. 52, 2602 (2013); K. Tsakmakidis, Nature Materials 12, 472 (2013).

9003-48, Session 11

Thermal, optical, and electrical engineering of an innovative tunable white LED light engine

Nicola Trivellin, LightCube (Italy) and Univ. degli Studi di Padova (Italy); Matteo Meneghini, Marco Ferretti, Diego Barbisan, Matteo Dal Lago, Gaudenzio Meneghesso, Enrico Zanoni, Univ. degli Studi di Padova (Italy)

The human circadian rhythm regulates our life through the day, from sunrise to sunset light plays a fundamental role in affecting human biology. Color temperature, intensity and blue spectrum of the light affects the melanopsin placed in ganglion receptors stimulating human nervous system. With this work we review different methods for obtaining tunable light emission spectra and propose an innovative white LED lighting system. By an in depth study of the thermal, electrical and optical characteristics of GaN and GaP based compound semiconductors for optoelectronics a specific tunable spectra has been designed. With this method the LED light source is able to smoothly change CCT while sensibly changing the spectral power density in the blue region (450-480nm). The proposed tunable white LED system is able to achieve high

CRI (above 93) in a large CCT range (2800 - 5500K), thus allowing a high comfort light in different conditions. The light engine is engineered to be efficient (above 85 lm/W) and cost effective while working with a standard commercially available constant current LED driver. The specific control gear can be programmed to control the intensity and CCT of several lamps connected together. The work has been completed by means of an extensive reliability study on several commercial LEDs characterized by different emission wavelengths. Results from this study indicate different degradation rates and accelerating factors. Complete results will be presented at the conference and different degradation control techniques will be discussed based on thermal, optical or mixed feedback.

Wednesday 5 –5 February 2014

Part of Proceedings of SPIE Vol. 9004 Emerging Liquid Crystal Technologies IX

9004-1, Session 1

The past, present, and future of hockey-stick-shaped liquid crystals *(Invited Paper)*

E-Joon Choi, Kumoh National Institute of Technology (Korea, Republic of)

Recently, the liquid crystalline materials with a bent-core mesogen have attracted attentions because their interesting properties such as polarity and biaxiality of the mesophase. There are several types of bent-core mesogenic structures have been reported, for instance, banana-shaped, V-shaped, boomerang-shaped, hockey stick-shaped, and Y-shaped molecules etc.. In this presentation, the past, present and future the hockey-stick shaped LC materials will be described concerning with the synthesis and structure-property relationship. In 2001, first hockey stick-shaped liquid crystals were synthesized by structural variations on p-quinquephenyl: thiophene isomers showing variable dipole direction and exocyclic bond angles were synthesized. Recently, we have reported that the hockey stick-shaped molecules can form the polar mesophase when the fluorine atoms are substituted into the one of the terminal groups. Furthermore, hockey stick-shaped reactive mesogens could be used for the confirmation of tilt angle in the VA-mode.

9004-2, Session 1

Electro-optic response of the homeotropic SmC* attached on the slippy interfaces: drastic reduction of threshold for the in-plane electric field *(Invited Paper)*

Jun Yamamoto, Kyoto Univ. (Japan); Isa Nishiyama, Dainippon Ink and Chemicals, Inc. (Japan)

Homeotropic SmC* phase shows the fast electro-optic response against the in-plane electric field, because the molecular tilt direction is inclined keeping the helix due to coupling between the spontaneous polarization and the electric field. Perfect orientation and smooth fast switching can be achieved in this configuration, but it is problem that the threshold voltage of the switching is extremely high compare to the surface stabilized SmC* (SSFLC).

Here, we have investigated the electro-optic response of the homeotropic SmC* under in-plane electric field attached on the slippy interfaces which are artificially introduced by the macroscopic phase separation due to the solvent effects. We have found the clear change of the mechanism of the electro-optic response of SmC* and drastic reduction of the threshold of the switching voltage. We have demonstrated two types of procedures to introduce the slippy interfaces, UV excitation for the azo-dye doped SmC* and the expansion of two-phase coexistence region near Ch-SmC* phase transition induced by the solvent effect. In case of Azo-dye doped SmC*, the difference between with and without slippy interfaces can be confirmed directly using the same LC cell by irradiation of the UV light. Switching dynamics still keeps fast speed as original SmC* (< few msec ~50°C), nevertheless the driving voltage is 1 order smaller than that without slippy interfaces. Unwinding motion of the helix induced by applying the slow AC voltage produces the large transmission of light, but simultaneously induces the slow dynamics. We demonstrate optimization using the AM modulation of applied electric field.

9004-3, Session 1

Grayscale memory effect and flexoelectric property of highly-kinked bent-core liquid crystals *(Invited Paper)*

Ji-Hoon Lee, Chonbuk National Univ. (Korea, Republic of); Tae-Hoon Yoon, Pusan National Univ. (Korea, Republic of); E-Joon Choi, Kumoh National Institute of Technology (Korea, Republic of)

We investigated the electro-optical properties of highly kinked bent-core liquid crystals. First, we observed a grayscale memory effect of bent-core liquid crystal in smectic A phase. The grayscale memory effect was obtained by the spatial distribution of bistable planar and homeotropic domains with different threshold voltage. Planar aligned bent-core molecules were switched to the homeotropic state and remained stable after removing the electric field. The homeotropic domain could be reversible switched to planar state by applying an in-plane electric field. Second, we measured the flexoelectric anisotropy of mixtures of 5CB nematic liquid crystal and bent-core liquid crystals. 7.5 wt% bent-core liquid crystal dopant with a fluorine lateral group and benzene core showed greater flexoelectric anisotropy 37.2 pC/m than the pure liquid crystal showed 10.3 pC/m. On the other hand, another mixture with different bent-core liquid crystal with a naphthalne core showed negligible change of flexoelectric anisotropy in spite of the similar kink angle and molecular length.

9004-4, Session 1

Electro-optic color tuning in cholesteric liquid crystals *(Invited Paper)*

Timothy J. White, Kyung Min Lee, Vincent P. Tondiglia, Michael E. McConney, Timothy J. Bunning, Air Force Research Lab. (United States)

Manipulating the reflection color of cholesteric liquid crystals has potential utility in optics, photonics, and displays. We report on a series of related results in which we have observed symmetric bandwidth broadening, red-shifting tuning, and blue-shifting tuning of the reflection notch of a polymer stabilized cholesteric liquid crystal upon application of a DC field. In all cases, the electro-optic response is only observed in the presence of polymer stabilization, in formulations based on negative dielectric liquid crystals hosts, and when subjected to DC field.

9004-5, Session 2

Twisting and tweezing liquid crystals with lasers *(Invited Paper)*

Helen F. Gleeson, Mark R. Dickinson, The Univ. of Manchester (United Kingdom); Jennifer E Sanders, Yiming Yang, University of Manchester (United Kingdom)

Exciting new directions for liquid crystals (LCs) are emerging on the length scale of the wavelength of light. Two complementary micron-sized systems are formed by LC droplets and by dispersions of colloidal particles in LCs. The dimensions of each of these systems are ideal for laser tweezer manipulation, allowing a new range of photon-addressed LC systems to be envisaged.

Trapping and moving micron-sized particles in LCs is a beautiful approach that can build novel colloidal photonic materials. However, it

is also a unique way of studying fundamental LC properties, particularly anisotropic viscosity coefficients in the low Ericksen regime, which can be accessed by laser trapping. Rather few nematic materials have been studied using laser traps; we describe two different approaches to deduce viscosity coefficients in three different materials.

Micron-sized LC droplets are emerging as intriguing photonic systems in their own right. Angular momentum can be transferred from laser traps to droplets, specific polarization properties and droplet geometries resulting in a variety of novel photon-driven effects. Fast optical switches, rotating at speeds >1kHz, can be produced from nematic droplets in circularly polarized beams. Both droplet geometry and beam polarization influence the droplet rotation, allowing control of the phenomenon. Surprisingly, a chiral nematic droplet can sometimes undergo continuous rotation in a linearly polarized trap, a phenomenon caused by optically-induced changes in chirality. We describe this remarkable effect which demonstrates how the control of chirality through polarization can result in an optically driven transducer.

9004-6, Session 2

Modeling optical modes of in-plane liquid crystal lasers *(Invited Paper)*

Jeroen Beeckman, Inge Nys, Kristiaan Neyts, Univ. Gent (Belgium)

Lasing in liquid crystals has been demonstrated in numerous configurations and material systems. In most systems the laser light is emitted perpendicular to the liquid crystal layer, but in the last few years also in-plane lasers have been demonstrated. The accurate modeling of the light generation in such systems is complex because the materials are optically anisotropic. Accurate optical modeling of perpendicularly emitting LC lasers was carried out with a plane wave expansion method, which is a one-dimensional model. Such a method was previously applied for the analysis of light emission from OLEDs. The extension to anisotropic materials and to simulation of lasing threshold makes it suitable for the simulation of LC lasing characteristics. Good agreement between simulations and experiments was found. For in-plane lasing configurations more advanced optical methods are necessary because the geometry becomes two dimensional. For these simulations we rely on finite-element calculations of the optical modes in periodic two-dimensional structures. The optical modes in a lying helix configuration are calculated as a proof-of-principle for this simulation method. Next to simulation work, we also report on tunable optical amplification in nematic LC cells. An optical signal beam is sent through a liquid crystal cell with laser dye which is pumped optically. The signal beam can be amplified with a factor 4 and the amplification can be voltage tuned close to a factor of one, thanks to the guest-host effect of the laser dye.

9004-7, Session 2

Miscibility and phase separation in LC semiconductor blends *(Invited Paper)*

Yo Shimizu, Yukimasa Matsuda, National Institute of Advanced Industrial Science and Technology (Japan); Takaya Nakao, National Institute of Advanced Industrial Science and Technology (Japan) and Ryukoku Univ. (Japan); Lydia Sosa-Vargas, Minokazu Takahashi, National Institute of Advanced Industrial Science and Technology (Japan); Hiroyuki Yoshida, Akihiko Fujii, Masanori Ozaki, Osaka Univ. (Japan)

We studied some binary blends of phthalocyanine (Pc) LCs which have the identical Colh mesophase and the same order of carrier mobility (~ 10-1 cm2 V-1 s-1). The binary phase diagram showed a complete miscibility. However, the repetitive heating and cooling cycles of these binary systems lead to the recovering of carrier mobility which was down to 10-2 cm2 V-1 s-1 from the original level for the single compounds, though their HOMO and LUMO levels are different. Microscopic observations of optical textures indicated that micro phase separation takes place and thus, this means two types of single component column form a hexagonal array in mesophase. The bundle of single component columns may be controlled for its domain size. Also the blends with benzoporphyrin mesogens were studied to give an interesting properties as LC semiconductors. Furthermore, the solubility of PCBM, a fullurene derivative as n-type of semiconductor, into Pc LCs also were investigated for a possible bulk heterojunction layer in organic photovoltaics.

9004-33, Session 2

Liquid crystal polymer colloids as confined self-organised systems with responsive optical properties *(Invited Paper)*

Verena Görtz, Lancaster Univ. (United Kingdom); Kirsty L. Holdsworth, The Univ. of York (United Kingdom)

The director configurations observed in confined liquid crystal systems, such as micron-sized nematic droplets or colloidal polymer particles, result from a delicate balance between bulk and surface interactions and, therefore, they respond to parameters such as particle size, surface anchoring and temperature. In our studies we use dispersion polymerization to create monodisperse polymer particles in the micrometer range from various liquid-crystalline monomers. Our research reveals that the observed confinement structure in nematic polymer particles is influenced by subtle changes in the chemical makeup and that reversible ordering transitions are triggered by changes in the host environment. Clear changes in the optical appearance of the particles are observed, which provide a mechanism for sensor applications.

9004-8, Session 3

Liquid crystal devices based on photoalignment and photopatterning materials *(Invited Paper)*

Vladimir G. Chigrinov, Hong Kong Univ. of Science and Technology (Hong Kong, China)

The advantages of liquid crystal (LC) photoalignment and photopatterning technology in comparison with common “rubbing” alignment methods tend to the continuation of the research in this field.

Fast switching photo-aligned ferroelectric LC cells with microsecond and sub-microsecond switching time should replace the current micro-electro-mechanical (MEM) switching devices with millisecond switching time.

Recently the new application of photoaligned technology for the tunable LC lenses with a variable focal distance was proposed. A tunable-focus liquid crystal (LC) lens will be achieved using variable pretilt angle in LC layer obtained by exposing the photoalignment layer by UV light.

Thin photopatterned micropolarizer array for CMOS image sensors for in-situ analysis of the four Stokes parameters of the output optical signal are also envisaged. The cheap, high resolution photo-patterned LC matrix sensor to be developed will be able successfully compete with the expensive and low reliable wire grid polarizer patterned arrays currently used for the purpose.

New E-paper displays, based on photo-aligning optically rewritable (ORW) technology are developed. The advantages of ORW E-paper: no drivers, no current conducting layer, high thickness tolerance, the technology is very cheap (the price of ORW E-paper is almost equal to the price of the two polarizers). The ORW technology is highly compatible with flexible substrates. The ORW technology is highly compatible with flexible substrates. New optically rewritable (ORW) LC Photonics devices

with a light controllable structure may include LC plane waveguides, Fresnel lenses and wave plates, etc.

9004-9, Session 3

Surface-induced bistable switching liquid crystal mode and its electro-optic applications *(Invited Paper)*

Hak-Rin Kim, Min-Kyu Park, Kyung-Woo Park, Seong-Woo Oh, Ho Jun Lee, Ji-Sub Park, Cheolho Lee, Mu-Geon Kim, Kyungpook National Univ. (Korea, Republic of)

We present a bistable LC (liquid crystal) switching mode by using topologically patterned LC alignment surface. For the bistable LC anchoring surface, a self-structured dual groove pattern is demonstrated by utilizing the micro-buckling phenomena on the oxidized PDMS (polydimethylsiloxane) surface due to the anisotropic surface stress induced by the macro-pattern. On the dual-groove structure, the surface LCs have two degenerate easy axes induced by the LC anchoring competition of two grooves. Theoretically, when the LC anchoring energies of two grooves are the same each other, the surface LCs have the degenerated ±45° easy axes with respect to the groove directions. However, considering the elastic energy of the LC bulk and the LC anchoring by the opposite LC alignment layer, the degenerated easy axes on the dual-groove surface are not orthogonal each other. In addition, the bulk elastic energy causes the asymmetric energy barrier between two bistable LC anchoring conditions. To control the bulk elastic energy, we introduce chirality in the LC layer. When the LC chiral pitch condition is 8 times larger than the cell gap, the energy barrier asymmetry can be solved and the bistable switching between twisted and homogeneously planar LC geometries can be obtained with low level of in-plane-switching field. With the surface topological pattern and the optimized LC bulk elastic deformation, we can also present the memory/dynamic dual switching LC mode. As for useful applications, we will present the parallax barrier and the LC lens for 3D displays which can be operated with low power consumption.

9004-10, Session 3

Nematic colloidal tilings as photonic materials *(Invited Paper)*

Miha Ravnik, Univ. of Ljubljana (Slovenia); Jayasri Dontabhaktuni, Univ. of Hyderabad (India); Miha Cancula, Slobodan ?umer, Univ. of Ljubljana (Slovenia)

Colloidal platelets are explored as elementary building blocks for the shape-controlled assembly of crystalline and quasicrystalline tilings. Using three-dimensional (3D) numerical modelling based on Landau-de Gennes free energy minimisation for modelling the colloids combined with Finite Difference Time Domain calculations for optics, we demonstrate the self-assembly and optical (transmission) properties of triangular, square and pentagonal sub-micrometer sized platelets in a thin layer of nematic liquid crystal, interestingly finding tilings with crystalline and quasicrystalline (five-fold Penrose) symmetry. Torques acting on individual platelets are calculated, showing that platelets with quadrupolar symmetry (squares, hexagons, etc) are orientationally more strongly bound than platelets with dipolar symmetry (triangles, pentagons) which is important for switching applications. For quasicrystalline tilings, we show that individual tiles can be replaced with smaller-scale tiles forming an interesting hierarchical optical material of various scales.

9004-11, Session 3

In-situ calibration of spatial light modulators in femtosecond pulse shapers

Benjamin Döpke, Jan C. Balzer, Martin R. Hofmann, Ruhr-Univ. Bochum (Germany)

Pulse shapers utilizing twin LC-panel SLM's are a popular tool for the control of ultrashort pulses. Two LC-panels with orthogonal extraordinary axes between linear polarizers form masks in the Fourier plane of a 4f pulse-shaper setup. Combinations of extraordinary phase retardances allow independent control of phase and amplitude of spectral components. For precise operation, a calibration of the relationship between drive voltage of the electrodes and extraordinary phase retardance is mandatory for both panels. Published methods of SLM calibration either evaluate the phase retardance of a mask directly by interferometric means or retrieve them from measurements of the intensity attenuation. The latter method is preferable for pulse shapers, as it allows calibration in the same pulse shaper setup in which it is intended to be used. However, non-idealities in the polarizers and LC's make manual recovery of the phase retardance error-prone. We present a calibration method for twin LC SLM's less susceptible to non-ideal behavior. Intensity attenuation is measured for a wide variety of combinations of phase retardance of both panels. Phase-voltage-relationships are then optimized with an evolutionary algorithm towards minimal error between calculated and measured behaviour of the intensity attenuation characteristics. This yields automatically aquired phase-voltage relationships that are comparable in quality to interferometrically measured phase relationships, but directly measured in the final setup of the SLM and robust towards the non-ideality of the components used.

9004-24, Session 3

Microcharacterization of cholesteric liquid crystals in interdigitated electrode-based cells *(Invited Paper)*

Mariacristina Rumi, Vincent P. Tondiglia, Lalgudi V. Natarajan, Timothy J. White, Timothy J. Bunning, Air Force Research Lab. (United States)

The response of a cholesteric liquid crystal (CLC) material to applied electric fields depends on the direction and strength of the field and the sign of the material dielectric anisotropy. Changes in the optical properties of CLCs in an electric field have been exploited to obtain tunable and switchable devices. We will discuss how, in CLCs with positive dielectric anisotropy in cells with interdigitated electrodes, complex variations in transmission and reflection spectra can be observed even in gap regions between electrodes, as a result of electric field gradients. The changes in optical spectra have been monitored using a microspectrophotometer, to probe selectively different positions in the cell. Variations in field direction give also rise to local changes in texture and spectra above the electrodes and transition regions between electrodes and gaps. We will also show that, when the electric field is directed perpendicular to the substrates in a cell with uniform electrodes, the materials spectra can depend on the configuration of the optical setup used for the measurements. These observations underline the importance of distinguishing between intrinsic material optical properties and manifestations of those properties in a given device and measurement configuration.

9004-12, Session 4

Long-pitch cholesteric liquid crystals for display applications *(Invited Paper)*

Tae-Hoon Yoon, Jae-Won Huh, Byeong-Hun Yu, Pusan National Univ. (Korea, Republic of)

Cholesteric liquid crystals (CLCs) have been applied to reflective displays because of their reflective nature in the planar state. In order to realize a reflective display, the planar state and the focal conic textures are used for the bright state and the dark state, respectively. In this paper we introduce a CLC device, in which a selective wavelength of the reflected light is shifted to infrared wavelengths by controlling the pitch. The planar texture of a long-pitch CLC device is transparent over the entire visible wavelengths in the field-off state. Omni-directional achromatic reflection through light scattering at the focal conic texture can be achieved without a polarizer. Compared to conventional CLC cells that reflect the visible light in the planar state, a long-pitch CLC device has a longer pitch, of which the operating voltage for switching between the two textures is much lower so that achromatic reflective displays and light shutters with low power consumption can be realized using a long-pitch CLC device. By coupling with a reflector, the light efficiency of a long-pitch CLC cell at the focal conic texture can be enhanced, by which higher brightness can be obtained for application to reflective displays. A dye-doped long-pitch CLC device can be placed behind a transparent organic light-emitting diode display to use a light shutter to block the ambient light.

9004-13, Session 4

The novel method of designing zero-birefringence pressure sensitive adhesives for liquid-crystal displays

Wataru Fujimori, Akihiro Tagaya, Keio Univ. (Japan); Sumihisa Oda, Saiden Chemical Industry Co. (Japan); Yasuhiro Koike, Keio Univ. (Japan)

A polarizer is attached to glass substrate of a liquid crystal display (LCD) panel by a pressure sensitive adhesive (PSA). Light leakage tends to be caused by birefringence of the PSA because the PSA is stressed by shrinkage of the polarizer. We proposed the novel method of designing zero-birefringence PSAs for reduction of the light leakage. Here, PSAs that exhibit no birefringence though the PSA molecules are oriented are defined as zero-birefringence PSAs. In this method, PSA samples for the birefringence measurement are prepared, in which a PSA layer is sandwiched by supporting films. Zero-zero-birefringence polymer films that exhibit no orientational birefringence and no photoelastic birefringence are used as the supporting films. Birefringence of the samples is measured after uniaxially heat-drawing. We assumed that birefringence of a PSA was the sum of birefringence of polymer chains and cross-linking structures, and the degree of orientation of polymer chains was proportional to that of cross-linker. Under these assumptions, relation between relative birefringence values (RBVs) of two constituents from composition of zero-birefringence PSA comprising two constituents can be obtained. Here, one of the constituent is chosen as a standard constituent for relative birefringence. Then, relation between RBVs of a constituent and the standard constituent can be obtained from composition of zero-birefringence PSA comprising these three constituents. RBVs of butyl acrylate and phenoxyethyl acrylate to an isocyanate-type cross-linker as standard constituent were obtained. Based on RBVs, we designed and synthesized zero-birefringence PSAs of these constituents. Furthermore, we reduced light leakage by the zero-birefringence PSAs.

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9004-14, Session 4

Switchable liquid crystal contact lenses: dynamic vision for the ageing eye

Harry E. Milton, Sarabjot Kaur, Philip B. Morgan, The Univ. of Manchester (United Kingdom); John Clamp, UltraVision (United Kingdom); Helen F. Gleeson, The Univ. of Manchester (United Kingdom); John Goodby, Stephen Cowling, University of York (United Kingdom)

Imagine a world where people no longer need reading glasses! The inability of the eye to focus on nearby objects, presbyopia, is suffered by ~100% of people over the age of 50. Liquid crystal (LC) spectacle lenses have shown great potential for correcting presbyopia. However, correcting presbyopia in contact lens users has proven elusive and existing commercial options include significant compromises.

We describe a novel contact lens that includes an LC element that offers to correct presbyopia without the compromises associated with other technologies. We fabricated variable focus lenses using a balanced optical system, providing the additional optical power presbyopes require for near vision (typically +2.00 D). The system uses positive optical power from the two substrates and variable negative optical power from the LC layer to form a balanced optical system which, when unpowered, corrects distance vision. Upon voltage application the LC layer decreases in refractive index, resulting in additional optical power in the system, offering correction equivalent to reading glasses.

Our new technology is based on a traditional contact lens material which could be placed directly on the eye. We show that the LC lens employed is well suited to the small optical areas associated with contact lenses. We compare several different LC materials and geometries which are suitable for our application, and discuss the influence of material and geometry on switching times, optical quality and operating voltage. Our contact lenses typically switch ±2.00 D in response to < 10 V with response times of around a second.

9004-15, Session 4

High-definition and high-contrast liquid crystal display with surface diffusing system using scattering film and directional backlight

Yusuke Fujii, Daisuke Sekine, Akihiro Tagaya, Yasuhiro Koike, Keio Univ. (Japan)

As a wide-viewing-angle LCD with small color shift, we have proposed surface diffusing system (SDS) using a directional backlight and a scattering film. As lights from the directional backlight pass the liquid-crystal layer almost perpendicularly, the SDS-LCD has small color shift without retardation films. For realizing the SDS-LCD, optimizing the scattering film considering luminance angular distributions of backlights is necessary. The scattering film is made of polymer containing specific concentration of particles. The image blurring is caused by the multiple light scattering. Therefore, we fabricated a particle-precipitated film, which was expected to have the lower number of light scattering than particle-dispersed film. With this film and backlights with different luminance angular distribution, we investigated relationships between the directionality of the backlight and properties of the SDS-LCD, such as the image sharpness and the contrast. The image blurring and the debasement of the normal direction contrast ratio of the SDS-LCD were suppressed with increasing the directionality of the backlight. The each pixel of the SDS-LCD using the backlight with the highest directionality was discriminable, which meant the image blurring was sufficiently suppressed. The normal-direction?contrast ratio of the SDS-LCD using backlight with the highest directionality was almost equal to that of the LCD without scattering film, which meant the debasement of the normal-direction?contrast ratio was sufficiently suppressed. Moreover, the SDS-LCD using the backlight with the highest directionality showed smaller

color shift and wider viewing-angle than commercial LCD suppressing the image blurring and the debasement of the normal-direction contrast ratio.

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9004-16, Session 4

Voltage controlled adaptive holographic interferometer using liquid crystals

Arnaud Peigné, Thales Underwater Systems (France); Umberto Bortolozzo, Stefania Residori, Institut Non Linéaire de Nice Sophia Antipolis (France); Stéphanie Molin, Daniel Dolfi, Thales Research & Technology (France); Jean-Pierre Huignard, Jphopto (France)

Adaptive interferometers based on dynamic holography within a nonlinear medium allow to measure small phase shifts in noisy environments.

Due to its finite bandwidth, the hologram follows slow external perturbations cancelling the low frequency phase mismatch between the two arms of the interferometer while it appears static at high frequencies. In this case, diffraction converts the phase into intensity modulation. The holographic medium used is a liquid crystal light valve (LCLV) combining a photoconductor (BSO) and a liquid crystal layer (LC).

Here, we take advantage of the LC high birefringence, their voltage sensitivity and their response time to attain cutoff frequencies from a few Hz to several kHz. This offers the possibility to select and tune the cutoff frequency of the interferometer very finely.

Due to the large induced Kerr nonlinearity of the LCLV, the effective refractive index and thus the phase shift depend both on the incident optical intensity and bias voltage. To characterize the bias voltage dependency of the LCLV bandwidth, we modulated the input intensity at 532 nm in order to simulate low frequency fluctuations. As a result, we tuned the cutoff frequency between a few Hz and a few hundreds Hz. Therefore, the low frequency noise can be filtered out with a bandwidth that is voltage controlled. This can be useful for applications where the signal of interest is limited by external temperature fluctuations and/or vibrations.

9004-17, Session 4

Polarization-selective Bragg diffractive wavelengths in holographic structures composed of liquid crystal and polymer phases

Hiroshi Kakiuchida, Kazuki Yoshimura, Masato Tazawa, National Institute of Advanced Industrial Science and Technology (Japan); Akifumi Ogiwara, Kobe City College of Technology (Japan)

Optical components for light switching, wavelength selection, beam steering and so on are fundamentally indispensable for various optical and photonic systems, and are desired to be compact and easy-manufacturable for the reduction in size and cost of optical equipments. We have developed diffraction type of optical wavelength selector composed of meso-scale periodic phase-separation structure of liquid crystal (LC) droplets in polymer matrix, called holographic polymer dispersed liquid crystal (HPDLC). This is a Bragg diffractive device switchable in Bragg wavelength due to polarization states of incident light. This polarization-responsive switchability is produced by advanced optical anisotropy in periodic structure, that is, different grating pitches of refractive-index modulations between orthogonal polarization states. Such anisotropic structure was not elaborated, but was self-organized by interferometric exposure through self-ordering toward uniaxial orientation of LC molecules during periodic phase separation process. We have experimentally realized several types of polarization-switchable optical wavelength selectors by adjusting fabrication conditions such as LC/monomer ratio, monomer functionality, exposure temperature, etc. Furthermore, the anisotropic structures were microscopically analyzed based on optical diffractometry.

9004-18, Session PWed

Design of a cholesteric liquid crystal cell for a high-transmittance light shutter

Byeong-Hun Yu, Jae-Won Huh, Tae-Hoon Yoon, Pusan National Univ. (Korea, Republic of)

Recently, active studies on a transparent organic light-emitting diode (OLED) are in progress as a next generation display. However, since it is not possible to obtain a dark state using a transparent OLED, it exhibits poor visibility. This inevitable problem can be solved by placing a light shutter behind a transparent OLED display.

In this paper, we propose a light shutter using dye-doped liquid crystals whose Bragg reflection wavelength is chosen to be infrared by controlling the pitch of cholesteric liquid crystals. The proposed light shutter is switchable between the dark planar state and the transparent homeotropic state.

The proposed light shutter has the advantages of the high transmittance, low operation voltage, and easy fabrication process compared with previous light shutter devices using liquid crystals. It is expected that the proposed light shutter can be applied to realize high visibility transparent OLEDs and emerging smart windows.

9004-19, Session PWed

Formation of holographic memory for optically-reconfigurable gate array by angle-multiplexing recording of multi-circuit information in liquid-crystal composites

Akifumi Ogiwara, Hikaru Maekawa, Kobe City College of Technology (Japan); Minoru Watanabe, Retsu Moriwaki, Shizuoka Univ. (Japan)

Optically reconfigurable gate arrays (ORGAs) comprising a gate-array VLSI, a holographic memory, and a laser diode array have been developed as a multi-context field programmable gate array to realize fast and numerous reconfiguration contexts. In the ORGAs, holographic memory to store numerous contexts and to reconstruct them with high quality is needed for the parallel optical reconfiguration system. A useful approach for the holographic memory to obtain high resolution and efficiency with volume grating structure is to employ the liquid-crystal (LC) and polymer phase in organic materials. A holographic polymer-dispersed liquid crystal (HPDLC) memory formed by volume gratings has an advantageous optical property to implement the anisotropic reconfigurations for a multi-context recording of various circuit information such as majority, half-adder, and so on.

We report the angle-multiplexing recording of multi-context for optically reconfigurable gate array at a separated small region in holographic memory by using a successive laser illumination in LC composites. The HPDLC memory is fabricated by the angle-multiplexing recording of multi-context for optically reconfigurable gate array. The fabrication setup is constructed by using the optical system consisting of a movable pinhole at X-Y axis and a half mirror on the motorized stages located in laser interferometer under the control of a personal computer. The multi-context information is recorded by changing the incident angle of reference beam at the specific photo area in LC composite. The circuit contexts such as majority and half-adder are clearly reconstructed by the laser illumination at different incident angle in the HPDLC memory.

9004-20, Session PWed

Design of a zero-zero-birefringence polymer in a system containing N-substituted maleimide for liquid-crystal displays

Shotaro Beppu, Shuhei Iwasaki, Houran Shafiee, Akihiro Tagaya, Yasuhiro Koike, Keio Univ. (Japan)

Polymer materials are used for polarizer protecting films of liquid crystal displays (LCDs). However, birefringence of the films changes the polarization state of the incident light and consequently degrades the contrast of images of LCDs. Therefore, birefringence needs to be eliminated. In previous researches of our group, zero–zero-birefringence polymers (ZZBPs) which exhibits no orientational birefringence and no photoelastic birefringence were demonstrated in systems consisting of methacrylate monomers by solving three equations which describe the relationship between birefringence properties (intrinsic birefringence and photoelastic coefficient) and weight fraction of monomers. The ZZBPs have the advantage that it can maintain the polarization state of the incident light. On the other hand, improving glass transition temperature (Tg) of ZZBPs is required for practical use. Therefore, we propose N-substituted maleimides as constituents of novel ZZBPs. The purpose of this article is to design a ZZBP using N-substituted maleimides based on the results of clarifying those birefringence properties. We prepared poly(methyl methacrylate (MMA) /N-methyl maleimide (MeMI)) and poly(MMA/N-ethyl maleimide (EMI)) in various composition ratios and measured birefringence of the copolymer films. Then, we calculated birefringence properties of poly(MeMI) and poly(EMI) from those of the copolymer films. Based on the results, we synthesized and evaluated poly(MMA/benzyl methacrylate/MeMI) with the optimal composition ratio which eliminates birefringence. The results show that synthesized polymer is free of two types of birefringence at the wavelength of 633nm and free of orientational birefringence regardless of wavelengths. Also, the polymer has relatively high Tg (Tg = 120 degree centigrade) and high transparency.

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9004-21, Session PWed

Fabrication of photo responsive multi-bilayered film consisting of

azobenzene containing copolymers and polyvinyl alcohol

Ryohei Yagi, Yutaka Kuwahara, Hiroyuki Iwamoto, Sun-Nam Kim, Tomonari Ogata, Kumamoto Univ. (Japan); Seiji Kurihara, Kumamoto Univ. (Japan) and Japan Science and Technology Agency (Japan)

Multi-bilayered films reflects a specific wavelength of light, the reflection peak wavelength can be calculated according to Bragg diffraction equation. The reflection intensity depends on the difference between refractive indices of stacked materials. Namely, to make difference in the refractive indices is to turn ON the reflection. In contrast, the reflection intensity becomes extremely low, the reflection turns OFF, when the refractive indices of stacked materials are nearly equal. In our previous study, we fabricated the multi-bilayered film containing photo-responsive azobenzene polymer liquid crystals and polyvinyl alcohol (PVA). The multi-bilayered films were showed the reversible change in the reflection intensity by irradiation with visible and UV light. In this study, we synthesized azobenzene copolymer with mesogen groups to achieve faster response speed of ON/OFF switching, as mesogen groups is having no absorbance at UV and visible region. Change in reflection intensity of the multi-bilayered films by light irradiation was investigated. We synthesized polyacrylates copolymers with side chains of azobenzene and biphenyl groups, and multi-bilayered films were fabricated by spin-coating method. We investigated the switching time of reflection, comparing with the multi-bilayered film containing azobenzene homopolymer needing 900 s to ON switching of the reflection. On the other hand, the ON switching times of reflection for the copolymers are faster than homopolymer. It is attributed to the easily transmitted UV light (? = 365 nm) into the film by introducing of biphenyl groups having no absorbance around 360 nm.

9004-22, Session PWed

Manipulation of small objects in liquid crystals by dynamical disorganizing effect of push-pull-azobenzene-dye

Yutaka Kuwahara, Takahiro Oda, Ryo Izumi, Tomonari Ogata, Sun-Nam Kim, Kumamoto Univ. (Japan); Seiji Kurihara, Kumamoto Univ. (Japan) and Japan Science and Technology Agency (Japan)

There are a few reports on the formation of ordered structures of colloidal particles due to topological defects in a nematic liquid crystal. In some reports, laser tweezers were used to position the colloidal particles in a liquid crystal. However, much higher optical intensities are generally required for the manipulation of particles with laser tweezers. In addition, the optical setup is complex. In contrast to the manipulation with laser tweezers, the motion of small objects in a liquid crystal that we would like to present in this presentation is based on a photochemically controlled defect in the liquid crystal, and consequently, neither a complex optical setup nor higher optical laser intensities are required. The combination of the photo-controlled formation of the defect and the intrinsic self-assembling property of a liquid crystal is a promising technology not only for organization of small objects, but also for photo-driving nano- and micro-sized mechanical materials.

9004-23, Session PWed

Thermo-driven light controller by using thermal modulation of diffraction wavelength in holographic polymer dispersed liquid crystal grating

Akifumi Ogiwara, Kobe City College of Technology (Japan); Hiroshi Kakiuchida, National Institute of Advanced Industrial Science and Technology (Japan)

Holographic polymer dispersed liquid crystal (HPDLC) grating comprised of organic materials such as liquid crystal (LC) and polymer has been applied for grating formation to obtain both high diffraction efficiency and polarization dependence. Recently, the optical characteristics achieved in HPDLC gratings are expected to provide novel optical devices for application in a diffractive type of thermo-driven light controller. It possesses a one-dimensional periodic structure consisting of LC and polymer phases with microperiodic structure, and can produce large diffraction intensity at the designed region of diffraction wavelength.

The diffraction state of HPDLC changes dominantly due to an N–I transition in the LC phase because nematic LC is known to be reversibly transformed from a nematic phase to an isotropic one depending on the N–I transition temperature (TNI). We investigate the potential for practical thermo-driven light controllers depending on the HPDLC grating structure based on the thermal modulation on the diffraction wavelength.

The wavelength dependence induced by the N-I transition of LC is analyzed in different grating structures by spectroscopic measurements as a function of temperature at around 35 °C. The diffraction efficiencies in wavelength regions corresponding to infrared lights decrease with a

rise of temperature, while the efficiencies in visible lights approximately maintain the constant values. The controllability of thermal modulation on diffraction wavelength is realized in the HPDLC volume grating formed by the different film thickness. The optical characteristics achieved in HPDLC gratings are recognized to be applicable for the diffractive type of thermo-driven light controller.

9004-25, Session PWed

Anisotropic surface plasmon shift at the interface of gold nanoparticle and nematic liquid crystal

Amit Choudhary, Univ. of Missouri-St. Louis (United States); Guoqiang Li, The Ohio State Univ. (United States) and Univ. of Missouri-St. Louis (United States)

Study of the effect of nanoparticles on liquid crystal (LC) director has been an important topic of research very recently. For the first time to our knowledge, alkanethiol-capped gold nanoparticles (GNPs) were dispersed in nematic LC and analysis of LC director around GNPs was experimentally performed by investigating the behavior of surface plasmon polariton (SPP) absorption peaks of the GNPs using photospectrometry technique. It is found that the incident light polarized at 0 degree, 45 degree, and 90 degree angles with respect to the rubbing direction experiences varying interaction with the medium and the corresponding transmission of light reveals the anisotropic shift in wavelength of SPP peak.The variation in the dielectric constant around GNPs that govern the behavior of SPP has shown blue shift in SPP peak with the change in the alignment and associated dielectric properties of LC molecules. But there has not been found any shift in the SPP when the plane of polarized light is incident at 90 degree angle to the rubbing direction of LC sample cell. This confirms that the dielectric properties of LC have not been changed much on the application of DC bias at 90 degree in comparison to other angles (0 degree and 45 degree). This is the clear visualization of anisotropic dynamics of LC molecules around GNPs. The anisotropic behavior of SPPs of the GNPs is in excellent agreement with theoretical calculations.

9004-28, Session PWed

Light scattering from liquid crystal director fluctuations in steady magnetic fields up to 25 tesla

Pavan Kumar Challa, Kent State Univ. (United States)

We report on homodyne dynamic light scattering measurements of orientational fluctuation modes in both calamitic and bent-core nematic liquid crystals, carried out in the new split-helix resistive magnet at the National High Magnetic Field Laboratory. The relaxation rate and inverse scattered intensity of director fluctuations exhibit a linear dependence on field-squared up to 25 tesla, which is consistent with strictly lowest order coupling of the tensor order parameter Q to field ($Q(\alpha\beta)B(\alpha)B(\beta)$) in the nematic free energy. However, we also observe evidence of field dependence of certain nematic material parameters, an effect which may be expected from the mean field scaling of these quantities with the magnitude of Q and the predicted variation of Q with field.

9004-29, Session PWed

Focused ion beam for studying cholesteric liquid crystal under submicrometer confinement

Giusy Scalia, Seoul National University (Korea, Republic of); Eva Enz, Martin-Luther-Univ. Halle-Wittenberg (Germany); Vera La Ferrara, ENEA (Italy)

Soft self-assembling photonic materials like cholesteric liquid crystals (LCs) are attractive due to their multiple unique and useful properties, like an optical bandgap that can be continuously and dynamically tuned in response to weak external influences.

We induce strong confinement on a short-pitch cholesteric LCs by encapsulating it into coaxially electrospun polymer fibers with sub-micrometer dimension of the internal core. The fibers display highly interesting optical response, with strong variation of the selectively reflected wavelength as effect of very small variations of the cavity dimension. This behaviour is distinctly different from that of the bulk LC. By visualizing the internal structure of the core-sheath fibers using Focused Ion Beam (FIB) milling, we can associate the optical texture with the shape and size of the cavity hosting the LC.

Reference:

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9004-30, Session PWed

Molecular wires from discotic liquid crystals

Ji Hyun Park, Seoul National Univ. (Korea, Republic of); Massimiliano Labardi, Univ. di Pisa (Italy); Giusy Scalia, Seoul National Univ. (Korea, Republic of)

Discotic liquid (LC) can arrange in columnar structures along which electrical conduction occurs via π-π interaction between adjacent molecular cores. The efficiency of the conductivity is strongly dependent on the overlap of the orbitals of neighbour molecules and, in general, on the structural arrangements.

In this paper we present our study on the self-organization of a discotic LC into molecular wires in order to evaluate the factors controlling the wire formation, crucial for the optimization of the resulting conductive properties. In particular, we focus on the effect of the solvent used for preparing the LC solution, of the substrate employed for the deposition and on the effect of the evaporation speed. The resulting morphologies of the fibre assembly were investigated by atomic force microscopy (AFM) and polarized optical microscopy, depending on the LC film thickness. With suitable conditions, combined with a very slow evaporation step, we were able to induce very long fibers, several tents of micrometer long that, in turn, self-organize assuming a common orientation on a macroscopic scale. Conductivity of these long fibers was an order of magnitude higher than the one measured in misaligned, short fibers.

9004-31, Session PWed

Effects of carbon nanotubes on a very low surfactant concentration lyotropic liquid crystal host

Hye Ran Jo, Seoul National Univ. (Korea, Republic of); Jun Yamamoto, Kyoto Univ. (Japan); Jan P. Lagerwall, Giusy Scalia, Seoul National Univ. (Korea, Republic of)

Lyotropic Liquid Crystals (LCs) are attractive materials as host system for nanoparticles, in particular for carbon nanotubes (CNTs), thanks to the LC templating action. In fact, CNTs can be dispersed efficiently in lyotropics and, at the same time, aligned via transfer of order from the host. Although surfactants are useful for preventing CNT aggregation, they can alter the nanotube pristine properties, becoming detrimental for applications, thus it is important to find ways to reduce the amount of surfactant employed in all stages of CNT processes.

In the present work we aim at realizing a lyotropic LC host for CNTs at very low surfactant concentration order of magnitude lower than previously reported [1]. We use a combination of cationic and anionic surfactants SDS (sodium dodecyl 1sulfate) and 12TAB (dodecyl trimethylammonium bromide) for forming the lyotropic LC phase. In addition, CNTs are dispersed using octadecyltrimethylammonium (OTAB), using the sub Krafft method [2] for minimizing the excess of surfactant in the suspension.

Our approach was successful in obtaining a total concentration of surfactant for the LC host as low as 8wt%, Finally, we experimentally verified the alignment of CNTs in fibers drawn from the lyotropic LC-CNT composite, by several methods such as polarizing optical microscopy and polarized Raman spectroscopy.

References

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9004-32, Session PWed

Size distribution and liquid crystal phase behavior of graphene oxide flakes in aqueous environment

Kieup Lee, Ji Hyun Park, Hye Ran Jo, Seoul National Univ. (Korea, Republic of); Vincent Derycke, Arianna Filoramo, Stéphane Campidelli, CEA-IRAMIS (France); Giusy Scalia, Seoul National Univ. (Korea, Republic of)

Graphene, a monolayer of graphite, can be realized by exfoliation of graphite with different methods. Particularly attractive is the method that, as intermediate step, goes through the production of graphene oxide flakes, dispersible in water, unlike graphene. Intriguingly, graphene oxide can form liquid crystal phases, above certain threshold concentration. The details of the chemical steps for the production of graphene oxide appear important not only for the appearance of a liquid crystal phase but also for its phase behavior. The value of the threshold and the width of the region of coexistence of the isotropic and liquid crystal phase can strongly vary from sample to sample. Important factors are the dimensions and the size dispersion of the graphene oxide flakes, as result of the detailed chemical process. We report the study of the size distribution of the flakes of our graphene oxide samples in relation to their phase behavior, exhibiting a nematic liquid crystalline phase at a concentration as low as 0.1mg/ml, start of the co-existence region, and a complete nematic phase at 1.0mg/ml.

9005-18, Session PWed

New red phosphorescent iridium(III) complex with various main ligand

Bona Yang, Dongmyung Shin, Hongik Univ. (Korea, Republic of)

In this study, A new phosphorescent iridium complexs has been synthesized for organic light-emitting diodes(OLEDs)-Ir(TMP-TT)2(acac), Ir(CYP-TT). To analyze color tuning effected by changing the main ligands, we have measured UV-absorption and photoluminescence (PL) spectra and have theoretically calculated the iridium complexes with different main ligands using computational methods(Gaussian modeling program). The ligands, TMP-TT, CYP-TT, have sites of both the electron donor and acceptor in structure. So, It showed Intramolecular Charge Transter(ICT) property. acetyl acetone(acac) as Ancillary ligand was designed to Solution process.

The Iridium complexs were synthesized by Suzuki coupling reaction and Nonoyama reaction .

The UV-vieible absorption peak of Ir(TMP-TT)2(acac), Ir(CYP-TT) was measured to be at 490nm, 513nm in chloroform solvent. The devices fabricated by Ir(TMP-TT)2(acac), Ir(CYP-TT) as emitting layer dopant.

The device structures were ITO / NPB / CBP: Ir(TMP-TT)2(acac), Ir(CYP-TT) / Bphen / Liq / Al.

9005-19, Session PWed

Optical modeling of OLED with random nanostructure using finite difference time domain (FDTD) simulation

Jun-Whee Kim, Ji-Hyang Jang, Min-Cheol Oh, Pusan National Univ. (Korea, Republic of)

Optical modeling for organic light emitting diodes (OLEDs) with a random nanostructure inserted between ITO anode and glass substrate was demonstrated using finite difference time domain (FDTD) simulation. Unlike OLEDs with a periodic structure causing the diffraction, OLEDs with the random nanostructure provides enhanced light extraction without wavelength dependence according to viewing angle. For simulating the light generated in OLEDs, a planar dipole array source without spatial coherence was introduced for x-, y- and z-polarizations and the temporal coherence of optical source was considered by using a Gaussian pulse on the basis of the spectral bandwidth measured from actually fabricated OLEDs. Because out-coupling enhancement of OLEDs was largely affected by the absorption coefficient of material consisting OLEDs, both the surface Plasmon absorption by metal cathode and absorption of ITO anode and organic material having complex refractive index was set to FDTD simulation for OLEDs. In order to form random nanostructure at FDTD simulation, random pattern was generated by using random function of C programming and inserted between ITO anode and glass substrate. The improvement of light extraction efficiency due to the random nanostructure was obtained through the FDTD calculation, and the results were compared to that of the experimental results. FDTD calculation results and experimental results appeared almost similarly. Through this simulation, we found the optimized OLED structure to provide the maximum external quantum efficiency.

9005-1, Session 1

Brightness increase using dual parabolic recycling collar and RGBW LEDs for pico-projector applications *(Invited Paper)*

Kenneth K. Li, Wavien, Inc. (United States)

No Abstract Available

9005-2, Session 1

Fast-response liquid-crystal lens for 3D displays *(Invited Paper)*

Yifan Liu, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Hongwen Ren, Chonbuk National University (Korea, Republic of); Su Xu, Yan Li, Shin-Tson Wu, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Three-dimensional (3D) display has become an increasingly important technology trend for information display applications. Dozens of different 3D display solutions have been proposed. The autostereoscopic 3D display based on lenticular microlens array is one of the promising 3D display methods, and fast-switching microlens array enables this 3D display system to display both 3D and conventional 2D images. Here we report two different fast-switching microlens array designs. The first one is a blue phase liquid crystal lens driven by the Pedot:PSS resistive film electrodes. This BPLC lens exhibits several attractive features, such as polarization insensitivity, fast response time, simple driving scheme, and relatively low driving voltage, as compared to other BPLC lens designs. The second lens design has a double-layer structure. The first layer is a polarization dependent polymer microlens array, and the second layer is a thin twist nematic (TN) liquid crystal cell. When the TN cell is switched on/off, the traversing light through polymer lens array is focused/unfocused, so that 2D/3D images are displayed correspondingly. This lens design has low driving voltage, fast response speed, and simple driving scheme. Simulation and experiment demonstrate that the performance of both switchable lenses meet the requirement of 3D display system design.

9005-3, Session 1

Optical characterization of auto-stereoscopic 3D displays: interest of the resolution and comparison to human eye properties

Pierre M. Boher, Thierry Leroux, Thibault Bignon, Véronique Collomb-Patton, ELDIM (France)

Many papers have been devoted to the optical characterization of 3D displays these last years. Each class of 3D display provides stereoscopy in the eyes of observer with different means and so the requirements in terms of characterization are different. ELDIM has proposed in 2009 a new Fourier optics viewing angle measurement system for the characterization of auto-stereoscopic 3D displays. Spectral polarization analysis with viewing angle instrument and temporal analysis were proposed for passive glass 3D displays in 2010, and active glass 3D displays in 2011 respectively. We are interested in auto-stereoscopic 3D displays that are certainly the more demanding for precise optical characterization. Different recently published papers present results obtained with standard instruments (like imaging luminance meters) that

cannot be representative of what will be seen by the observer simply because these instruments are far to be optically equivalent to the human eye. In the present paper, we are interested by the resolution of optical measurement instruments and the comparison to the human eye properties. Using viewing angle and imaging measurements made on different auto-stereoscopic displays in different conditions we emphasize the resolution effect and show that results can be strongly influenced by this parameters. It is true for angular angle measurements at one location on the display if the angular resolution does not match the resolution of the observer eye at the working distance. It is also true for imaging measurements made from one observer location for the entire display surface if the entrance iris of the instrument is larger than the human eye iris. Specific requirements for the optical measurement instruments are derived

9005-4, Session 1

Pixel-level tunable liquid crystal lenses for auto-stereoscopic display

Kun Li, Brian Robertson, Univ. of Cambridge (United Kingdom); Mike Pivnenko, University of Cambridge (United Kingdom); Daping Chu, Univ. of Cambridge (United Kingdom); Jiong Zhou, Huawei Technologies Co., Ltd. (China); Jun Yao, Huawei Technologies Co., Ltd (China)

Mobile video and gaming is now widely used, and delivery of a glass-free 3D experience is of both research and development interest. The key drawbacks of the conventional 3D display based on a static lenticular lenslet array and parallax barriers are low resolution, limited viewing angle and reduced brightness, mainly because of the need of multiple-pixels for each object point.

This study describes pixel-level cylindrical liquid crystal (LC) lenses, which is designed to steer light to the left and right eye sequentially to form stereo parallax. The width of the LC lenses can be as small as 20-30 um, so that the associated auto-stereoscopic display will have the same resolution as the 2D display panel in use. Such a thin sheet of tunable LC lens array can be applied directly on existing mobile displays. It can deliver 3D viewing experience while maintain 2D viewing capability.

A ZEMAX simulation was used to model the intensity profile at the image plane and design the lens array based on the measured LC phase profile. The transparent electrodes were laser patterned to achieve the single pixel lens resolution, and together with a high birefringent LC material a large diffraction angle was realised for a wide field of view. The measured viewing angle and intensity profile were compared with the ZEMAX simulation. A method to characterise the performance of LC materials in such a scale and fabricate these lenses with the aid of laser patterning is described.

9005-5, Session 1

All-CMOS night vision viewer with integrated microdisplay

Marius E. Goosen, INSiAVA (Pty) Ltd. (South Africa) and Univ. of Pretoria (South Africa); Petrus J. Venter, Monuko du Plessis, Univ. of Pretoria (South Africa) and INSiAVA (Pty) Ltd. (South Africa); Nicolaas M. Faure, Christo Janse van Rensburg, INSiAVA (Pty) Ltd. (South Africa) and Univ. of Pretoria (South Africa); Pieter Rademeyer, INSiAVA (Pty) Ltd. (South Africa)

The unrivalled integration potential of CMOS has made it the dominant technology for digital integrated circuits. With the advent of visible light emission from silicon through hot carrier electroluminescence, several applications arose, all of which depend upon the features of mature CMOS technologies for a competitive edge in a very active and attractive market.

In this paper we present a low-cost night vision viewer which employs only standard CMOS technologies. The consumer night vision system comprises a commercially available VGA resolution CMOS image sensor in combination with a near-infrared illuminator for capturing a reflected image under low ambient light conditions. The captured image is conveyed to the user via a 128x96 pixel CMOS microdisplay with a pixel pitch of 25 µm. The monochrome image produced by the microdisplay is magnified to allow for easier viewing, resulting in a virtual image presented to the user equivalent to a 19-inch display viewed at 3 meters. The fully characterised display incorporates driver and interface electronics on the same CMOS die as the display – further lowering total system cost. The presented microdisplay, implemented in a standard 0.35 µm CMOS technology, exhibits excellent reliability while conserving the unrivalled cost framework of the mature technology which is CMOS.

The night vision viewer has a range of 15-20 meters, dependant solely on the near-infrared illuminator optical output power. The complete system also incorporates a flashlight for illumination in the visible range. This work presents the first attempt towards a reliable low-cost consumer night vision system for application in personal security and toy markets.

9005-6, Session 2

High-power laser phosphor light source with liquid cooling for digital cinema applications *(Invited Paper)*

Kenneth K. Li, Wavien, Inc. (United States)

No Abstract Available

9005-7, Session 2

The outlook for blue-phase LCDs *(Invited Paper)*

Yuan Chen, Shin-Tson Wu, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Polymer-stabilized blue-phase liquid crystal (BPLC) has become an increasingly important technology trend for information display and photonic applications. BPLC exhibits several attractive features, such as reasonably wide temperature range, submillisecond gray-to-gray response time, no need for alignment layer, optically isotropic voltage-off state, and large cell gap tolerance when an in-plane switching (IPS) cell is employed. Fast response time not only suppresses image blurs, improves the overall transmittance but also enables color sequential display without noticeable color breakup. With time sequential RGB LED colors, the spatial color filters can be eliminated so that both optical efficiency and resolution density are tripled. High optical efficiency helps to reduce power consumption while high resolution density is particularly desirable for the future Ultra High Definition Television. However, some bottlenecks such as high operation voltage, hysteresis, residual birefringence, image sticking, charging issue due to the large capacitance, and relatively low transmittance for in-plane switching (IPS) mode, remain to be overcome before widespread application of BPLC can be realized. To reduce operation voltage, both new BPLC materials and new device structures have been investigated. In this paper, we will highlight some recent advances in large Kerr constant, fast response time BPLC material development, and new device structures. Especially, we will focus on new BP LCDs with low operation voltage, submillisecond response time, high transmittance, and negligible hysteresis and residual birefringence. The sunrise for BP LCD is near.

9005-8, Session 2

Full-color reflective display based on high-contrast dielectric grating

He Liu, Wei Wu, Yuhan Yao, Shujin Huang, The Univ. of Southern California (United States)

Reflective display, which is mainly known as e-paper, is getting more and more popular. It is mainly used in e-book readers, such as Kindle and Nook. Comparing with transmissive display, reflective displays consume less energy, display well under bright light and are more comfortable to human eyes. However, commercial reflective displays are dominantly black-and-white. One of the major challenges is that using parallel RGB sub-pixels cannot produce color with good saturation. That is mainly due to the sub-pixels of each color only cover a portion of the reflection surface. This issue can be solved by stacking three tunable band reflection mirrors (RGB). We proposed to build the band reflection mirrors using 2-D sub-wavelength high contrast dielectric gratings (HCG) and tune the reflection by electro-wetting. One advantage of HCG based color mirror is that the reflection spectra (colors) were highly designable, compared with traditional ink. Three different kinds of gratings were designed and fabricated to reflect blue, green and red light respectively, in order to operate in a trichromatic additive display mode. The reflection intensity and spectrum are highly sensitive to the refractive index contrast between the grating material and its surrounding. Our theoretical studies showed that the ON state reflection of more than 80% and the OFF state reflection of less than 10% can be achieved by driving a liquid out and in the grating region. Those band reflective mirrors were fabricated using low-cost nanoimprint lithography with master mold fabricated by interference lithography. More details in design, fabrication and characterization will be presented.

9005-9, Session 2

Emerging applications of ferroelectric nanoparticles in display technologies

Anatoliy V. Glushchenko, Yuriy Garbovskiy, Olena Zribi, Univ. of Colorado at Colorado Springs (United States)

We present the most recent astonishing results on the interaction of ferroelectric nanoparticles and liquid crystals. Ferroelectric nanoparticles embedded into a liquid crystal host strongly interact with the surrounding mesogenic molecules, due to the strong permanent electric field of this particle. There were great debates whether these interactions can affect the basic physical parameters of liquid crystals: birefringence, dielectric permittivity, elastic constants, viscosity, electrical and thermal conductivity, temperatures of phase transitions, etc. There are two basic mechanisms responsible for the observed effects: (1) the increase of the orientation coupling between mesogenic molecules; and (2) the direct contribution of the permanent polarization of the particle. Experimental data suggests that the first scenario is more likely to happen in the case of single component liquid crystals. The second mechanism is the primary factor in the case of multi-component liquid crystal mixtures.

We provide a great number of results which show that ferroelectric nanoparticles modify the intrinsic properties of liquid crystal materials without time-consuming and expensive chemical synthesis, especially for those materials where the method of chemical synthesis has reached its limit. Such modified materials are very attractive and suitable for use in switchable lenses, displays, and beam steering devices, as well as other light-controlling devices (spatial light modulators, tunable filters etc.)

9005-20, Session 2

Biocomposite polymer embedded with light-sensitive molecules for plastic displays

Gurumurthy Hegde, A. R Yuvaraj, Gan Siew Mei, Siti Aisyah Mustapha, Mashitah M. Yusoff, Univ. Malaysia Pahang (Malaysia); Vladimir G. Chigrinov, Hong Kong Univ. of Science and Technology (Hong Kong, China)

Photoalignment is non-contact way of aligning the nanosurface which can have obvious advantages over traditional rubbing method worth to mention, dust free, high resolution, non-mechanical damage. Lot of efforts was put forward to study photoaligning materials and also lot of efforts was done on their fabrication side as well. On the other hand, flexible devices attracted attention enormously due to their light weight, easy to operate and also attractive design. Due to their complexity in designing plastic displays, costs remain the concern. Here we mixed biocomposite materials (mainly the biomaterial polymer used for medical applications) with light sensitive shape anisotropic molecules to get high quality photoalignment on plastics. Due to their compatible nature and water soluble nature, proposed mixture is highly attractive for the industry. Adding to that one can control the film thickness by changing the viscosity of the mixture and can cure at 100oC which fits well with plastic films. This method is highly cost effective since solvent used is water, and also it is environmental friendly.

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9005-11, Session 3

Robust coatable chromonic liquid crystalline polarizer *(Invited Paper)*

Kwang-Un Jeong, Chonbuk National Univ. (Korea, Republic of)

Robust coatable polarizer was successfully fabricated by the self-assembly of lyotropic chromonic liquid crystals and the subsequent photo-polymerization. Their molecular packing structures and optical behaviors were also investigated by the combined techniques of microscopy, scattering and spectroscopy. To stabilize the oriented lyotropic chromonic liquid crystal films and to minimize the possible defects generated during and after the coating, the photo-polymerization of acrylic acid (AA) monomers added to the solution was carried out. The polymer-stabilized lyotropic chromonic liquid crystal films showed good mechanical and chemical stabilities with maintaining a high polarizability. Additionally, patterned polarizers were fabricated by applying a photo-mask during the photo-polymerization of AA, which may open new doors for the practical applications in electro-optic devices.

This work was mainly supported by the Human Resource Training Project for Regional Innovation and the Converging Research Center Program (2012K001428) of Korean government.

9005-12, Session 3

Investigation of the effects of deposition parameters on indium-free transparent amorphous oxide semiconductor thin-film transistors fabricated at low temperatures for flexible electronic applications

Robert Alston, North Carolina A&T State Univ. (United States); Jay S. Lewis, Garry B. Cunningham, RTI International (United States)

Indium gallium zinc oxide thin-film transistors (IGZO TFTs) have been extensively studied however very little has been published on TFTs fabricated at low temperatures without the rare and expensive element indium. In this work we report on the processing effects on the performance of bottom gate RF-sputtered gallium tin zinc oxide (GSZO) TFTs with the entire fabrication process below 150° C. Deposition temperature, annealing duration, channel thickness and deposition pressure were varied to optimize electrical characteristics of the bottom-gate TFT to be compatible with fabrication on polyethylene naphthalate (PEN) substrates. Despite low-temperature processing, an on/off current ratio (Ion/off) of 106, subthreshold swing (SS) of 1 V/dec, and field-effect mobility (μFE) of 0.4 cm2/V•s were achieved. The stability of these TFTs under electrical stress was also examined. Other characterizations such as capacitance-voltage (C-V), x-ray reflectivity (XRR), x-ray photoelectron spectroscopy (XPS) and Rutherford back scattering (RBS) were carried out to better understand the salient features of the channel, surface and interface that affects the performance of the TFT. Finally the above optimized process was implemented on PEN with plasma-enhanced chemical vapor deposition (PECVD) deposited gate dielectrics SiO2 and Si3N4. The device characteristics of the above TFTs on PEN will also be presented. Support by the ARO (Grant# W911NF-10-1-0316 –Mike Gerhold technical monitor) is acknowledged.

9005-13, Session 3

Viewing-angle-enhanced integral imaging system using multi-directional projections and elemental image resizing method

Md. Ashraful Alam, Chungbuk National Univ. (Korea, Republic of); Ki-Chul Kwon, Munkh-Uchral Erdenebata, Chungbuk National University (Korea, Republic of); Jin-A Byeon, Imaging Media Research Center, Korea Institute of Science and Technology (Korea, Republic of); Nam Kim, Chungbuk National Univ. (Korea, Republic of)

Viewing angle enhanced integral imaging (II) system using multi-directional projections and elemental image (EI) resizing method is proposed. In this method, multiple sets of EIs are projected on the micro lens array from different directions. The EIs are generated computationally using 3D object information captured by depth cameras. Each elemental lens of micro lens array collects multi-directional illuminations of multiple EI sets and produces multiple point light sources (PLSs) at the different positions in the focal plane; and the positions of the PLSs can be controlled by the projection angles. The viewing zone is made consisting of multiple diverging ray bundles, wider than the conventional method, due to multi-directional projections of multiple EI sets; whereas a conventional system produces the viewing zone using only a single set of EI projection. Hence the viewing angle of the reconstructed image is enhanced. Directional projection of EIs with the same size of micro lens pitch causes an EI mismatch at the EI plane. To prevent the EI mismatch, EI resizing method is applied; EIs are generated considering the directional projection geometry of each pixel as well as EIs are resized in terms of the projection angle to match them with the micro lens pitch. The proposed II system allows reconstruction of a three dimensional image with wider viewing angle than a conventional II system depending on the angles of directional projections and the number of EI sets used.

To implement the proposed integral imaging system, multiple depth cameras and projectors are used for capturing 3D object information with different directional perspectives and projecting the multiple sets of elemental images with different projection angles respectively.

9005-14, Session 3

Compact multiple laser beam scanning module for high-resolution pico-projector applications using a fiber bundle combiner

Masafumi Ide, Shinpei Fukaya, Kaoru Yoda, Masaya Suzuki, Citizen Holdings Co., Ltd. (Japan)

A novel multiple laser beam scanning projection module using compact red-green-blue (RGB) fiber pigtailed laser modules are proposed and examined.

Our module uses fused-type fiber combiners for mixing the RGB colors. Each single-mode fiber output of the fused-type fiber combiner is connected to a fiber bundle combiner with graded index lenses to generate multiple laser beams. The multiple RGB beams from the fiber bundle combiner are then collimated using a projection lens. The projection lens also acts as a space-to-angle converter, changing the directions of the individual RGB beams to direct them towards the single MEMS mirror. Then, the scanning MEMS mirror changes the angles of the individual RGB beams simultaneously. Each scanned RGB beam is projected onto a screen and creates an image in a different location on the screen without creating any overlaps or spaces among the projection images.

Compared to a conventional single-beam scanned system, our multiple-beam scanned system has a wider projection angle and/or a higher resolution because it uses a single common MEMS mirror system. The projection architecture is also useful for maximizing Class 2 luminous flux output to ensure eye safety.

This novel module with RGB laser light sources and a fiber bundle combiner is an obvious choice for high resolution display applications; the optical system of the module has a simple structure and a small form factor, and is suitable for use in multiple projection systems, particularly in light field display systems. Light field display applications of this system will also be discussed.

9005-15, Session 4

Prospects of quantum-dots-based liquid-crystal displays *(Invited Paper)*

Zhenyue Luo, Su Xu, Yuan Chen, Yifan Liu, Shin-Tson Wu, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Liquid crystal display (LCD) has become the dominant flat panel display technology. However, conventional LCD faces a ceiling in color performance, at best reaching the sRGB color gamut. This limitation originates from the insufficient quality of backlight technology. Quantum dot (QD) has demonstrated several attractive features, including high quantum efficiency, broad absorption band, narrow emission bandwidth, and controllable emission wavelength. It can be a competitive backlight solution for next-generation LCDs. In particular, their narrow emission spectra lead to vivid colors. More amazingly, the individual emission spectrum can be tuned via optimizing QD size/composition to match the transmission peak of a color filter and to reduce the crosstalk between colors. We report a systematic photometric study of LCD based on QD backlight, and find the optimal emission spectrum combination in terms of system efficiency and wide color gamut. Quantum dot LCD has potential to achieve 115% color gamut in CIE 1931 and 140% in CIE 1976 color space, while keeping the same energy efficiency as conventional backlights. Moreover, we will present a transmissive color display based on voltage-stretchable liquid crystal (LC) droplet and quantum dot backlight. This polarization-insensitive display shows richly-saturated color, wide viewing angle and good contrast ratio. QD backlight allows LCD to display original colors with high fidelity and make LCD more competitive as compared to the OLED technology. The prime time for quantum dot LCD is near.

9005-17, Session 4

Development of flying spot illumination system for stage lighting

Hisashi Asakawa, Katsunori Ishii, Hikari Koshiro, Junko Baba, Marumo Electric Co., Ltd. (Japan); Moriaki Wakaki, Tokai Univ. (Japan)

The system to control the area of illumination is important for the luminaires used for stages and TV studios. Presently the methods to change the distance between a lamp and lenses, or to use a zooming projection of the aperture illuminated by the lamp are used to control the area. However, these methods require many optical components or mechanical components. Moreover, the energy of the light source is partially consumed by the absorption of the shutter on adjusting the illumination area. On the other hand, the control of the intensity over the illuminated field is not possible by the methods.

In this study, we developed the lighting system which enables to control both the illumination area and the intensity distribution within the area by scanning the beam of LEDs using a rotating polygon mirror. The area of illumination was expanded along one dimension by scanning the LEDs beam using a rotating polygon mirror. The selection of the illuminated width and the control of the intensity distribution were achieved by synchronizing the rotation of the mirror to the PWM control of the LED. To obtain the enough illumination intensity, a LED array was used. The emission of each LED was collimated using a lens array and focused by a condenser lens to form a point source. The light from the point source was expanded by using an appropriate collimator lens and scanned to form 1D illumination field with some width.

The developed system has the merits of compact and high efficiency.

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9006-1, Session 1

Bayfol(R) HX photopolymer for full-color transmission volume Bragg gratings *(Invited Paper)*

Thomas Fäcke, Friedrich-Karl Bruder, Horst Berneth, Bayer MaterialScience AG (Germany); David Jurbergs, Bayer MaterialScience LLC (United States); Rainer Hagen, Dennis Hoenel, Thomas Rölle, Günther Walze, Bayer MaterialScience AG (Germany)

New optical and optoelectronic applications are emerging from the constant change in miniaturization of electronics, improvements of spatial light modulators and new solid state light sources like LED and laser diodes. Manipulating light with optical gratings based on volume Holographic Optical Elements (vHOEs) also known as volume Bragg gratings have the advantage over surface gratings since those reconstruct only the -1st diffraction order and hence provide high diffraction efficiencies and angular selectivity. In addition further benefits are their ability to be fully transparent in off Bragg condition.

We present in this paper the latest status of our instant developing photopolymer film technology (called Bayfol® HX) and we will discuss beneficial recording parameters like beam ratio, power density and recording time. Also further improvements on full color recordings will be discussed. Foremost also of crucial importance are optical contact copies, enabling to manufacture industrial quantities of volume Bragg gratings for the above mentioned applications.

9006-2, Session 1

Ultra-realistic imaging: a new beginning for display holography

Hans I. Bjelkhagen, Hansholo Consulting Ltd. (United Kingdom); David Brotherton-Ratcliffe, Geola Technologies Ltd. (United Kingdom)

Recent improvements in key foundation technologies are set to potentially transform the field of Display Holography. In particular new recording systems, based on recent DPSS and semiconductor lasers combined with novel recording materials and processing, have now demonstrated full-colour analogue holograms of both lower noise and higher spectral accuracy. Progress in illumination technology 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. So too, recent progress in 1-step Direct-Write Digital Holography (DWDH) now opens the way to the creation of High Virtual Volume Displays (HVV) - large format full-parallax DWDH reflection holograms having fundamentally larger clear image depths. In a certain fashion HVV displays can be thought of as providing a high quality full-colour digital equivalent to the large-format laser-illuminated transmission holograms of the sixties and seventies. Back then, the advent of such holograms led to much optimism for display holography in the market. However, problems with laser illumination, their monochromatic analogue nature and image noise are well cited as being responsible for their failure in reality. Is there reason for believing that the latest technology improvements will make the mark this time around? This paper argues that indeed there is.

9006-3, Session 1

Evaluation of Slavich PFG-03C plates in recording and reconstructing color Denisyuk holograms using the ZZZyclopsTM transportable color holography camera and the HoLoFosTM LED hologram reconstruction lighting devices

Andreas Sarakinos, Alkiviadis Lembessis, Nikos Zevos, The Hellenic Institute of Holography (Greece)

Since its inception, display holography offered the highest hopes for recording objects of cultural interest and using the resulting holograms as optical clones of the originals. In our approach within a more extended framework, full-color holograms could serve as a means of visually documenting cultural artifacts in the form of OptoClonesTM, in addition to the latest tendencies in museology such as digital 3D-modeling, multi-perspective imaging, digital virtual databasing etc.

One of the key factors affecting the feasibility of expanding the use of color Denisyuk holograms as a means of optically documenting cultural artifacts is the availability of emulsions with consistent and predictable results.

We experimented in recording color holograms on the Slavich PFG-03C plates. These commercially available plates are manufactured by a well established factory and exhibit a mean silver grain diameter of 10nm, resolution of 10000 lines/mm and sensitivity about 2mJ/cm2 in the blue and 3mJ/cm2 in the red and green. The emulsion is soft and requires special care in the development and drying stages in order to avoid random distortions of the Bragg's planes.

We recorded test holograms in single red, green and blue as well as in combined RGB laser illumination using our ZZZyclopsTM transportable color holography system. The plates were processed using 3 different developing and bleaching schemes while we tested two different drying methods in order to identify the best practices for results with high diffraction efficiency, low noise and minimal color distortion.

The results of our investigation and experimentation along with spectro-radiometric measurements on achieved diffraction efficiency and color reproduction under our HoLoFosTM LED lighting devices and common halogen spotlight illumination are presented in this paper.

9006-4, Session 1

Master-holograms recorded with pulsed laser on photoresist

Stanislovas J. Zacharovas, Geola Digital uab (Lithuania) and Kaunas Univ. of Technology (Lithuania); Diana Adliene, Kaunas Univ. of Technology (Lithuania); Ramunas J. Bakanas, Geola Digital uab (Lithuania) and Kaunas Univ. of Technology (Lithuania); Pranas Narmontas, Rimas ?eperys, Kaunas Univ. of Technology (Lithuania)

Recently pulsed-laser DWDH systems are used commercially by several companies to produce large format full color digital image reflection holograms. The quality of DWDH, as well as of other types of holograms depends on the availability of Silver Halide or photopolymer photosensitive materials that are in permanent development. However for the origination of transmission holograms for security applications usually are used commercially available photoresists. It was assumed that

photoresists require CW radiation for the proper exposure and production of good quality master original holograms. However the sensitivity of popular photoresists to CW irradiation is rather low as it is to recall from materials data sheets provided by manufacturers – that requires rather powerful CW lasers for master-originals origination. There have been no reports found concerning pulsed laser irradiation of commercial photoresists except of our previous work, where it was firstly reported on the recording of holograms on a S813 photoresist layer of ~10 μm with only 8mJ/cm2 pulsed laser beam energy density at 440 nm, when laser pulse duration was 50ns.

In current work we report that using 440 nm pulsed laser, good quality DWDH holograms on commercially available photoresists (ma-1200 and S1800 series) thinner layers (~0.7μm) might be recorded applying low energy exposures from the range 10 mJ/cm2÷13 mJ/cm2, that are at least 5 times lower as compared to those applied in CW laser beam applications. This indicates relative high sensitivity of commercially available photoresist to pulsed beam exposure which is comparable with the sensitivity of advanced silver halide materials used in holography.

9006-5, Session 1

Diffracting holographic lenses created on azo-polymer films

Ribal G. Sabat, Royal Military College of Canada (Canada)

Surface-relief diffraction gratings can be inscribed onto cast azopolymer films by exposure to an interfering laser pattern at an absorbing wavelength. These diffraction gratings can be used to project other optical element holograms by recording and then later retrieving the phase and amplitude of light. Since the resulting undulations on the azo surface are the recording light's intensity and phase, a probing laser would reproduce the same light profile at the same geometry. In this project, various superimposed chirped relief gratings, acting as diffracting holographic lenses, were photo-inscribed on azo-polymer films upon exposure to the interference pattern of a plane and a curved laser light wavefronts. Depending on the configuration used, this resulted in incident light being focused independently of polarization along the 0th or 1st diffracted order of the grating. A high dynamic range CCD camera was positioned on a linear track and pictures of a focalized laser beam passing through the azo films were taken as a function of distance travelled along the diffracted orders for a number of different holographic lenses configurations. A theoretical treatment was done on the resulting nanostructures from inscribing a diffracting cylindrical holographic lens, and the focusing mechanism for the azo-films was explained.

9006-6, Session 1

An effective phase modulation in the collinear holographic storage

Xiao Lin, Ke Jun, An'an Wu, Xue Xiao, Xiaodi Tan, Beijing Institute of Technology (China)

An effective phase modulation is studied and the results prove that the permitted range of phase coding exists in the condition of keeping high signal-noise-rate (SNR) and low bit-error-rate (BER). We simplified multiple phase-scale (like gray-scale) modulation model to 0 and π phase modulation model because controlling the proportion of 0 and π (0/π) and utilizing multiple phase-scale modulation in the process of phase coding can get same reconstruction effect. In theory, only when 0/π is 50%, the reconstruction effect is best. But in fact the proportion of different phase-scale depends on the input data. This means that 0/π is almost impossible 50%. . Therefore enough free degree for code is needed. We added constraints to dynamic range of the medium in the simulation and got the result. In the condition of no constraints, reconstruction is good in the range of 0/π from 20% to 80% and at this moment BER is less than 0.001. The permitted range of 0/π is changing with the limit of dynamic range of the medium changing. We obtained a series of curves describing permitted range of 0/π according to the different constraints. The maximum permitted range of 0/π is from 5% to 95%. At this moment SNR can increase by about 1.25 times and BER is less than 0.0005. So once material characteristic of recording medium is determined, we can find effective phase code curve and provide the maximum free degree of phase coding.

9006-7, Session 2

Carbon allotropes as photosensitizers in photorefractive organic materials

Prathan Buranasiri, Thanawat Bamrungthai, Suwan Plaipichit, King Mongkut's Institute of Technology Ladkrabang (Thailand)

In this paper, the photorefractive efficiency in carbon allotropes, i.e. fullerene, carbon nanotube, graphene, as photosensitizers of photorefractive organic materials has been explored using a radiation wavelength of 632.8 nm. Using p-polarized beam and s-polarized, the two beam coupling and four-wave mixing gain coefficients have been measured with different carbon allotrope composites. The application example setups for real time edge enhancement and edge correlation have been investigated and the results have been shown also. The purpose of this study is to improve the comprehensive of the mechanisms of photorefractive effect in composited polymer, which can lead to development of more efficient holographic materials for dynamic data processing applications.

9006-8, Session 2

Photosensitive polymers undergoing photo-Fries reaction for volume holography: understanding the mechanism of refractive index modulation

Andrea Bianco, Alessio Zanutta, INAF - Osservatorio Astronomico di Brera (Italy); Letizia Colella, Istituto Italiano di Tecnologia (Italy); Chiara Bertarelli, Politecnico di Milano (Italy)

Materials that show a modulation of the refractive index are suitable for making volume phase holographic elements. Here we consider polymers that can undergo to photo-Fries rearrangement. An important class of these polymers are the ester derivatives of polystyrene such as poly(4-acetoxystyrene). Upon illumination with UV light, the photo-Fries reaction takes place converting the ester to the ketone/alcohol derivative and an increase of the refractive index of the material occurs. Such increase is really large, of the order of 0.01 – 0.08 depending on the chemical structure, that allows in principle to obtain efficient holograms.

What is not fully clear is the reason why upon photo-Fries reaction a so large modulation of the refractive index occurs.

We tackled the problem by performing a theoretical work on the monomers to calculated the refractive index. Moreover, we performed some experimental works to support the theoretical results.

It has been shown that a simple change in the polarizability of the polymer upon photo-reaction cannot explain the large change in refractive index, but it is necessary a non-negligible change in the material density. This change it is actually measured by fitting the spectral reflectance data that provide the refractive index and the film thickness. By studying different polymers, the refractive index modulation it has been correlated with the chemical structure of the polymers.

9006-9, Session 2

Mechanism of the photoanisotropy induction in polarization-sensitive materials based on azo dyes

Barbara N. Kilosanidze, George Kakauridze, Irakli Chaganava, Institute of Cybernetics (Georgia)

A new mechanism is proposed explaining the macroscopically observed anisotropy of optical parameters induced by actinic polarized light in the polarization-sensitive materials based on azo dyes and polymers. The proposed mechanism proves a two-stage process of photoanisotropy induction in such materials. In the first stage, under the action of polarized light the orientation of molecules of the chromophore components occurs at the expense of conformational-orientational processes. In this case under the action of linearly polarized actinic radiation the reorientation of molecule takes place until the direction of the absorbent oscillator of the molecule does not become orthogonal to the plane of polarization of the inducing light. However, this is not enough for the macroscopically observed anisotropy that is confirmed by the special experiments to be carried out. At the second stage the reorientation of the molecules of chromophore causes microstresses in the material in the presence of the intermolecular bonds between the molecules of the chromophore and macromolecules of the polymer

that results in a change in the permittivity tensor of the material and macroscopically observed anisotropy. Moreover, the bonding force between the molecules of the chromophore and the polymer macromolecules significantly affects the value of photoanisotropy. This explains the high values of photoanisotropy in said-chain and main-chain azopolymers with a stable covalent bond between the molecules of the chromophore and the macromolecules of the polymer. The proposed approach (mechanism) has been confirmed by a series of special experiments. This mechanism is also valid for the materials, in which azomethines and stilbenes are used as chromophores. Taken into account such a mechanism more efficient polarization-sensitive materials could be created for polarization holography and polarization optics.

9006-10, Session 2

High-speed reconfigurable holography in InGaAs/InGaAsP quantum-well microcavities

Hao Sun, David Nolte, Purdue Univ. (United States); James Hyland, Eric Harmon, LightSpin Technologies, Inc. (United States)

Real-time holography is a fast and powerful tool for image processing, beam steering and adaptive interferometry. High diffraction efficiencies can be obtained with large refractive index modulation in thick samples or can be enhanced by a resonator. Here, we introduce a multiple quantum well asymmetric Fabry-Perot as a high-speed and high-efficiency dynamic holographic device that displays a significant increase of diffraction efficiencies in four-wave mixing experiment due to matched amplitude and phase gratings within the cavity. The device combines the advantages of excitonic absorption with large carrier density and cavity resonances in a multiple quantum well (MQW) cavity. Strong writing pulses with a wavelength of 1060 nm pass through the transparent back mirror and are absorbed by the quantum wells. A tunable laser around 1550 nm probes the gratings and is diffracted. The absorption and gain in the quantum wells balance the ratio of the mirror reflectivity to allow the device operate at low Q factor ($Q \approx 200$) near the lasing threshold. In this paper, we present significant diffraction efficiencies of the asymmetric Fabry-Perot multiple quantum well device. The input diffraction efficiencies reach 35% in the experiment for each first-order diffracted beam (70% total efficiency), which is significantly larger than previous performance by dynamic holography in broad-area GaAs microcavities [1,2,3]. Fast response is achieved in the device with rise times less than 5 nsec. This holographic device has potential applications for high-speed reconfigurable beam-steering systems.

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9006-11, Session 3

Holographic data storage: rebirthing a commercialization effort *(Invited Paper)*

Ken Anderson, Akonia Holographics (United States)

Several technology innovations have led to a breakthrough in the storage densities of holographic data storage (HDS) including Dynamic Aperture mutiplexing, homodyne detection, and phase quadrature multiplexing. These technologies are explained in detail and analyzed showing achievable capacities of 2TB, 4TB and 8TB respectively on a single disk. We present the details of Dynamic Aperture multiplexing and show why this technique enables ultra-high optical bit densities.

Dynamic Aperture multiplexing is a technology innovation that can be combined with the monocular storage architecture to increase raw bit densities to 2.5Tb/in2. This is a record breaking storage density that cannot be achieved with any other technology: magnetic or optical. The monocular architecture utilizes angle multiplexing within a single objective lens to be used for the data and reference beam. Since the data and reference beams can coexist within the same lens aperture, this enables a dynamically changing data page to be used. In a standard monocular system, the reference beam changes its angle and the data beam is static. This results in broader Bragg peaks when the reference beam is closer in angle to the nearest data pixel and narrower Bragg peaks when the reference beam is at the highest angles. However, the achievable bit density is much lower when the data page is static compared to the dynamic data page based simply on how the grating manifolds are filled.

Homodyne detection can then be used along with Phase Quadrature multiplexing to achieve even higher bit densities. A new holographic storage technology roadmap is presented that shows that holographic data storage can stay highly competitive for many generations to come. In addition to capacity, cost and transfer rate, holographic data storage also offers greater than 30 year archive life along with random access. HDS also has a huge advantage over tape technology in that it has latency times of 10 seconds compared to 90 seconds for tape (in a 1PB system). There is a large "opportunity gap" that exists between the 100ms latencies of hard drives and the minutes of latencies for tape, and HDS is in a unique position to fill this market gap and provide a robust and cost effective solution for Big Data storage needs of the future.

9006-12, Session 3

Optical testing of a membrane diffractive optic for space-based solar imaging

Olga Asmolova, Geoff P. Andersen, Hua, Inc. (United States)

We describe imaging capabilities of a 0.2 m membrane diffractive primary (DOE) used as a key element in FalconSat-7, a space-based solar telescope. Its mission is to take an image of the Sun at the H-alpha wavelength (656nm) over a narrow bandwidth while in orbit. In this case the DOE is a photon sieve which consists of billions of tiny holes, with the focusing ability dependent on an underlying Fresnel zone geometry. We have experimentally studied how environmental conditions such as temperature, humidity as well as mechanical stress, would affect polyimide material chosen for DOE in particular and imaging performance of the optical system in general. Uniform radial expansion/contraction of the substrate due to temperature or relative humidity change will result in a shift in focal length without introducing errors in phase of the transmitted wavefront and without a decrease in efficiency. We will also show that while ideally the DOE surface should be held flat to within 5.25 microns, an opto-mechanical analysis showed that local deformations up to 32 microns are possible without significantly degrading the image quality.

9006-13, Session 3

High-speed deformation measurement using spatially phase-shifted speckle interferometry

Tobias Beckmann, Markus Fratz, Alexander Bertz, Daniel Carl, Fraunhofer-Institut für Physikalische Messtechnik (Germany)

Electronic speckle pattern interferometry (ESPI) is a powerful technique for differential shape measurement with sub-micron resolution. Using spatial phase-shifting (SPS), no moving parts are required, allowing frame acquisition rates limited by camera hardware. We present ESPI images of 1 megapixel resolution at 260 fps. Using light of 532 nm wavelength, deformations of less than 20 nm are easily resolved.

Analysis of SPS data involves at least two Fourier transforms per image, making it a time-consuming endeavor. The graphics processing units found in state-of-the-art personal computers have exceptional parallel processing capabilities: taking advantage of these allows us to perform real-time SPS measurements at 30 fps. Deformation analysis at this frame rate can be used to analyze transient phenomena such as deformation occurring during material processing, were such measurements allow better control of production quality. Our measurement and data evaluation rates are fast enough to enable feedback into the production process.

In addition to materials processing data, we present deformation measurements during small temperature changes of integrated circuit chips on boards; a system in which differential expansion of components can lead to failure. Here, our setup can show deformations which are not accessible with commonly used deformation measurement systems. These transient effects can be fundamentally different from the steady-state temperature-induced deformations, and their understanding will improve packaging and assembly technologies.

9006-14, Session 3

Color optical biopsy

Ardeshir Osanlou, Glyndwr Innovation Ltd. (United Kingdom); Hans I. Bjelkhagen, Glyndwr Univ. (United Kingdom); Emma Snashall, Whiston Hospital (United Kingdom); Orod Osanlou, Univ. Hospital Aintree (United Kingdom); Rostam Osanlou, Univ. of Liverpool Medical School (United Kingdom)

Holographic microscopy in cellular imaging has emerged in recent years as a new tool for medical imaging application. Current techniques allow imaging of very thin layers of scattering media. Stepping up these techniques to apply them for medical research is technologically challenging. The current generation of digital image sensors and spatial light modulators are limited in dealing with light diffraction.

This work reports on the development of 'True color optical biopsy'. Rather than using digital imaging devices, a thin layer of ultrafine grain of silver halide crystals of 10-20nm average diameter, dispersed in a colloid and coated on a substrate is used as the recording media. The significance of this method so far, is in its ability to produce three-dimensional true images of specimen. They have an appreciable depth, permitting the observer to scan through the microscopic image, as one may with a real sample of cells, e.g. from biopsy. Current methods could 'True color optical biopsy' the skin, the gastrointestinal tract and anywhere accessible with a direct scope imaging. This has the potential for deeper tissue 'True color optical biopsy' using appropriate laser wavelengths. 'True color optical biopsy' using novel nanosize panchromatic recording media consisting of dispersed fine nano grain crystals, could potentially revolutionize surgical techniques. Future development of digital recording media will allow it to be utilized in this manner.

9006-15, Session 3

Use of GPU and FPGA in reproduced signal processing in holographic data storage

Nobuhiro Kinoshita, Tetsuhiko Muroi, Norihiko Ishii, Koji Kamijo, Hiroshi Kikuchi, NHK Science & Technical Research Labs. (Japan)

Holographic data storage (HDS) is a technology that optically records and reproduces information data. One of the differences between HDS and the conventional optical disks is the data structure recorded in a medium. The data structure of HDS is two-dimensional array, which is called a data page. During the reproduction, the diffracted beam from the recording medium goes through an optical system and is received by an image sensor. Thus, a signal processing method specialized for the reproduced and captured data page is required. We have developed reproduced signal processing algorithms, which were implemented in graphics processing units (GPUs) as well as optical system for HDS. The GPU can conduct parallel processing due to its multi-core architecture and processes two-dimensional arrays and data pages. The reproduced signal processing for HDS includes data region detection in the captured image, symbol pixel extraction, deinterleave based on transposition, and error correction. We implemented these algorithms in GPUs and found that they were effective by validating with actual reproduced data page. The data processing rate in the GPU system was over 100 Mbps. While the GPU enables us to develop the algorithms quickly because it is more easily reconfigurable, a field programmable gate array processes very quickly. We implemented all their algorithms in an FPGA for much higher data processing rate, and found that the rate was 500 Mbps.

9006-16, Session 4

Addressing the inverse problem of imaging: A noniterative exact solution for phase in imaging based on microHolography

Aaron Lewis, The Hebrew Univ. of Jerusalem (Israel); Danielle Honigstein, Jacques Weinroth, Nanonics Imaging Ltd. (Israel); Michael Werman, The Hebrew Univ. of Jerusalem (Israel)

This talk describes an approach to a solution of inverse problems in imaging with application to optical, electron/ion beam, x-ray and other imaging modalities. The approach is based on a controllable nanoscopic near-field optical or electron optical point source integrated into one of these imaging approaches. We focus on the inverse problem of the phase of an image which has never been solved exactly and can only be approached through iterative methods with all their problems of nonconvergence, slow convergence, convergence to local minima, and stagnation. We now show that it is possible to obtain an exact solution to the inverse problem of phase both experimentally and theoretically. Our method is based on the breakthrough that crystallography experienced in phase retrieval for large molecular entities by Max Perutz's introduction of "heavy atoms" using the method of isomorphous replacement. The availability of scanning probe microscopy and its full integration with optical microscopy allows us to apply these X-ray concepts to implement "heavy atom" restoration of phase in optical phase retrieval. In analogy to the heavy atom method, we acquire Fourier intensities in place of an X-ray diffraction pattern, and in place of the heavy atom, we utilize a nanometrically translatable point source of light, coherently related to the far-field illumination, that is based on atomic force microscopy and near-field scanning optical microscopy. This unifying integration of NSOM/

AFM technology with far-field imaging and interferometry achieves robust phase retrieval independent of external parameters without iteration, leading to 3D optical imaging.

9006-17, Session 4

Defects detection in pipes and laminated structures by means of holographically recorded strain solitons

Irina V. Semenova, Galina V. Dreiden, Alexander M. Samsonov, Ioffe Physico-Technical Institute (Russian Federation)

Laminated structures are widely used nowadays in a wide variety of constructions. The proper functioning of such structures has vital importance especially in automotive and aerospace industries. The major problem in their behaviour is a possibility of a sudden and irreversible delamination caused by various factors. Defects in pipes used for transportation of gas or oil may be a source of tremendous accidents. We propose and study a NDT approach aimed to detect delamination areas in adhesively bonded layered structural elements and prolonged defects in pipes. The proposed approach is based on the holographic detection of the evolution of bulk strain solitons generated in such structures.

Being formed, the soliton propagates along the homogeneous wave guide with almost no change of amplitude, shape and velocity. In inhomogeneous wave guides the soliton parameters vary, depending upon parameters of inhomogeneities. Soliton evolution in long delaminated waveguides and shells was recorded using the technique of holographic interferometry. Delamination areas of different length were introduced to study variations in soliton parameters. Variations of soliton amplitude were shown to demonstrate the existence of delamination areas. The formation of complex wave patterns – soliton trains or radiating solitons became an additional evidence of defects in layered waveguides. Bulk nonlinear solitary elastic strain waves may provide an opportunity to check quickly the delamination areas even in prolonged waveguides.

9006-18, Session 4

Parametric studies of adaptive optics by self-interference incoherent digital holography

Jisoo Hong, Myung K. Kim, Univ. of South Florida (United States)

Recently, we have presented the self-interference incoherent digital holography (SIDH) scheme that can be applied to the astronomical telescopic imaging with capabilities to compensate for atmospheric aberration for a new approach to adaptive optics (SIDHAO). The SIDH is also used in generating full color three-dimensional imaging of outdoor scenes under natural daylight illumination. The SIDH is one of several incoherent holography techniques based on self-interference with radial shear, or differential curvature, a prominent example being the Fresnel incohernt correlation holography (FINCH).

We are carrying out simulation and experimental studies regarding expected SNR and resolution behavior of the SIDHAO. Some of the findings include the following. i) The aberration-compensated images are almost always significantly better than direct image (imaging without any holographic process) in both SNR and in resolution. ii) With increasing aberration strength, the resolution deteriorates rapidly for direct images, but SIDH with aberration compensation maintains, and sometimes even improves, resolution with increasing aberration, which may be explained by the behavior of auto-correlation of complex phase function. iii) In general, the effect of noise is more severe on the SIDH interferograms than on direct images, because the power from each point source is spread across the ccd. This is expected. But in most cases, on the other hand, the aberration compensation readily overcomes such noise effect. With parameters compatible with typical astronomical observations, the SIDHAO is expected to have at least several star magnitude advantage over direct telescopic image, under otherwise similar conditions.

9006-19, Session 4

Volume calculations from multi-wavelength digital holographic surface topography

Partha P. Banerjee, Logan Williams, Univ. of Dayton (United States); George Nehmetallah, Catholic University of America (United States); Sarat Praharaj, DMS Tech (United States)

In this work multiwavelength digital holography (i.e. two-wavelength digital holographic interferometry) is applied to calculate the volume displacement of various topographic surface features of opaque objects, in addition to 2D contour maps and 3D surface plots. To accurately measure the volume displacement of macroscopic features, long synthetic wavelengths up to several millimeters are generated using tunable IR laser sources. The resulting modulo-2π phase map is unwrapped using the Max-Flow/Min-Cut technique to generate 3D surface displacement plots. A numerical method is proposed to calculate the volume displacement of various surface features. Multiple objects are examined and, when possible, compared to theoretical volume displacement calculations. Practical methods of implementation are considered, including correction of geometric effects introduced by Michelson and Mach-Zehnder recording configurations.

9006-20, Session 4

Special non-diffractive beams generation using holographic techniques

Marcos R. R. Gesualdi, Tárcio A. Vieira, UFABC (Brazil); Michel Zamboni-Rached, Univ. Estadual de Campinas (Brazil)

Non-diffractive waves (NDWs) are very interesting particular cases of optical beams. In this work, we present the experimental generation of special NDWs (Bessel beams, Mathieus beams, Airy beams, Frozen Waves, and others) using holographic techniques. The experimental realization of these NDWs was obtained using a holographic setup for the optical reconstruction of computer generated holograms (CGH), based on a 4-f Fourier filtering system and a spatial light modulator (SLM, LC-SLM or PRC), where CGHs were first computationally implemented, and later electronically implemented, on the SLM for optical reconstruction. The experimental results are in agreement with the corresponding theoretical analytical solutions and hold excellent prospects for implementation to many applications such as optical tweezers, remote sensing, atom guides, optical or acoustic bistouries, electromagnetic or ultrasound high-intensity fields for various medical purposes.

9006-21, Session 5

hidden images of holography: wavefront reconstruction of abnormalities within pulsed holographic recording

Martin J. Richardson, De Montfort Univ. (United Kingdom)

Unplanned abnormalities within the holographic recording often lead to surprising outcomes. Off-axis Pulsed Laser transmission hologram are notorious for this, as one may record large volumes of space when operating conditions are optimized. This paper offers a personal insight into such recordings where unrehearsed abnormalities are observed and documented. Some of these observations are accounted for, while others remain un-explained. These include light scatter, abnormal reference beam and its resultant optical echo in a secondary third order image. Polarization and hitherto unexplained coherence discrepancies that result in phenomenally deep holograms. Unplanned abnormalities add to our knowledge and understanding of the holographic principle of wave-front imaging.

9006-22, Session 5

The place for performance in the digital holographic space

Maria Isabel Azevedo, Martin J. Richardson, De Montfort Univ. (United Kingdom); Elizabeth Sandford-Richardson, De Montfort Univ (United Kingdom); Luís Miguel Bernardo, Helder Crespo, Univ. do Porto (Portugal)

In this series of digital art holograms and lenticulars, we are exploring different kinds of movement developed by Elizabeth Sandford-Richardson, a visual and performer artist, inside the digital holographic space.

During the process of image capture, we are using the HoloCam Portable Light System, equipped with Canon and Nikon cameras positioned at different heights and angles, in order to compare and improve the rendering of holographic space.

Based on the "performativity of performance documentation" a notion introduced by Philip Auslander we revisit some authors that have been working in the "theatrical" practise, mainly in photography, adding the possibility of movement in 3D space.

Having in account that the movement of the viewer in front of a digital holographic image contributes to the performance that he/she is looking for, we could consider the physical space, outside the hologram, and the kind of "performance acts", also part of the work.

In summary, we propose a comparison between the analogue and digital holographic space, time and movement, and its place in contemporary art.

9006-23, Session 5

Time stands still

Yin-Ren Chang, Martin J. Richardson, Robert Chen, De Montfort Univ. (United Kingdom)

Among traditional painting techniques in fine art, cubists appropriate elements of abstraction by discarding the traditional methods of perspective, splitting images into facet-like blocks, overlapping successive fracturing body forms, in order to represent movement and multiple points of view within two-dimensional images. Moreover, cubists try to approach the sculptural medium in a painterly way by superimposing layers of top of each other to create a faceted surface in an object. This art style proposes movement of an object in the play of light from many angles. The application of holography to create similar effect is a potential development as it is a powerful communicative tool, affecting human perception. As a time-based art medium, holography offers fresh opportunities to make spatial-temporal (artistic) statements as a new sensory art experience.

In contemporary holographic art, computer graphic technologies have been the pivotal source of digital holography. The use of computer-based technologies in the arts facilitates a new understanding of shape relationships and appreciation of the configurations that present themselves to our sight.

"Time stands still" aims to discuss the potential employment of computer geometric shape modelling in holography, and its development from modern art. It also explores how 3D visual language is used by the artist and creates links between the material and immaterial through its experimental holographic creative works. This paper tries not only to discuss the relationship between 3D objects and depicting motion, but also to bring to reality the interplay between spatial dimensions and the interaction between a flat surface and a realistic emergent form.

9006-24, Session 5

Innovative re-creation of realities in a holographic digital form

Shuo Wang, Ardeshir Osanlou, Glyndwr Innovation Ltd. (United Kingdom); Peter Excell, Sonia Di Gennaro, Lishen Shi, Richard Hebblewhite, Glyndwr Univ. (United Kingdom)

Only nature can create, whereas humans can only re-create. This article is an exploration of synergies between art and science in digital holography in relation to art practice and the making of holograms as art works. This is achieved through involvement in the re-creation of a real object (a telescope) as a case study. A digital three-dimensional model suitable for holographic hard copy re-creation is produced. To explore special and immersive environment, real geographical landscape background from Google Earth is added to the model. After a brief introduction to visual art within the context of in two and three-dimensional imaging in the form photography and holography, the whole process of producing the three-dimensional model, ready for holographic printing is explained.

9006-25, Session 5

Creative display of museum objects within their cultural context

Shuo Wang, Ardeshir Osanlou, Glyndwr Innovation Ltd. (United Kingdom); Peter Excell, Glyndwr Univ. (United Kingdom)

Most existing holographic display methods concentrate on real object reconstruction, but there is a lack of research on object stories (revealing and presenting histories). To address this challenge, we propose a method, called 4 'ER' (leader, manager, implementer, presenter) to experience and respond objects in a special immersive environment. The key innovation of the 4'ER' method is to introduce the stories (political, historical, etc) into hard copy holography, so as to synergy art and science for museum objects display. The hologram of an imitation of a blue and white porcelain jar from The Palace Museum, Beijing, China has been made, showing good performance and reflecting different pathway to knowledge.

9006-26, Session 6

Improvements of simplified generation technique for holographic stereograms from multi-view images

Kyohei Ikeda, Yasuhiro Takaki, Tokyo Univ. of Agriculture and Technology (Japan)

We previously proposed a simplified generation technique for holographic stereograms from multi-view images. Multiple parallax images are captured at multiple viewpoints using ordinary cameras. We then calculate the wavefront, whose amplitude distribution is the squared root of the parallax image and phase distribution is the quadratic phase converging to the corresponding viewpoint. Wavefronts calculated for all parallax images are summed to obtain an object wave. The problem with this technique is that wavefront cannot be calculated when the spatial frequency of the quadratic phase distribution exceeds the Nyquist frequency determined by the pixel pitch of the spatial light modulator. From outer viewpoints, partial images can be viewed.

In this study, a spherical lens is introduced on the hologram display plane to provide a quadratic phase distribution to wavefronts. In this case, the phase distribution of the wavefront for each parallax image is the phase of the inclined plane wave, whose proceeding direction depends on the viewpoint position. Therefore, the whole images are viewed at all viewpoints.

The reconstructed images generated by our technique are degraded by speckle patterns because random phase distributions are added to the parallax images to obtain smooth motion parallax by increasing the extents of light distributions generated at the viewpoints. In this study, the spatial bandwidths of the wavefronts are limited in order to decrease speckles.

The above two methods were verified experimentally. The whole images could be viewed at all viewpoints. The reconstructed images had smooth motion parallax and less speckles.

9006-27, Session 6

Computer-generated hologram of actual objects from arbitrary viewpoints with range sensors and digital cameras

Keigo Tai, Tsubasa Ichikawa, Yuji Sakamoto, Hokkaido Univ. (Japan)

In computer-generated holograms (CGHs), some methods that generate hologram of actual objects have been proposed. One method uses 3D information of actual objects obtained by one range sensor to generate a hologram, but this method is unable to express the occlusion because 3D information is measured from only one viewpoint. Moreover the method needs to re-capture 3D information to make a CGHs from another viewpoint. To solve these problems, we proposed a method that generates models of actual objects in a computer using more than two range sensor. In this method, CGHs are calculated by using multi-view images rendered from objects' models, so the occlusion is expressed correctly. However, coloring is not performed on the whole object model because a luminosity image is insufficient. Therefore it is difficult to generate CGHs from arbitrary viewpoints at one time.

In this paper, we propose a method using some additional digital cameras with range sensors to generate CGHs of actual objects from arbitrary viewpoints. This method colorizes the whole model using picture taken by additional cameras. Proposed method have an advantage that re-capturing 3D information is unnecessary when CGHs are generated from another viewpoint, because CGHs are calculated with multi-view images rendered from the model colored perfectly. Moreover proposed method is able to express highlights which change with viewpoints in reconstructed images. As results of computer simulations and optical reconstruction, it was confirmed that we succeeded in generating CGHs of actual objects with occlusion from arbitrary viewpoints.

9006-28, Session 6

Fast calculation with point-based method to make computer-generated holograms of the polygon model

Yuki Ogihara, Tsubasa Ichikawa, Yuji Sakamoto, Hokkaido Univ. (Japan)

Computer generated holograms (CGHs) are made by simulating light propagation using a computer.

There are mainly two methods to calculate CGHs; the polygon based method and the point based method.

The polygon based method with Fourier transforms calculates CGHs using a fast Fourier transform(FFT).

However, the calculation of complex objects composed of many polygons requires as many FFTs, so the calculation time become enormous.

On the other hand, in the point based method, it is easy to express complex objects, but requires an enormous calculation time after all.

To accelerate the point based methods, using a graphics processing unit (GPU) are effective for fast calculation. Because a GPU is specialized in parallel computation, and CGH calculation is able to calculate independently for each pixel.

However, expressing planar object by the point based method needs to increase in density of points, and the number of the point light sources increase very much.

In this paper, we propose a fast calculation algorithm to express the planar object by the point based method with a GPU.

The proposed method accelerate calculation by obtaining the distance between a pixel and the point light source from the adjacent point light source by a difference method.

Under certain specified conditions, the difference between adjacent object points becomes constant, so the distance is obtained by only an additions.

As a result, it turned out that proposed method was more effective than the polygon based method with FFT when the number of polygon composed of objects are many.

9006-29, Session 6

The fast scheme for mixed-3D scenes by polygon-based computer-generated holography (CGH)

Yanling Piao, Chungbuk National Univ. (Korea, Republic of); Le Thanh Bang, Weina Li, Chungbuk National University (Korea, Republic of); Nam Kim, Chungbuk National Univ. (Korea, Republic of); Jong-Rae Jeong, Suwon Science College (Korea, Republic of)

Mixed 3D scene of virtual and real object by classical holograms record and reconstruct real-existent wave fields is make it possible to digitally edit, archive, transmit, and optically reconstruct the wave-field of real-existent 3D object. However, the reconstructed image in E-Pro viewing angle limited by the real-existent object which is captured by the Synthetic-aperture lensless Fourier digital holography (LFSA-DH) and using silhouette mask to solve the edge blur problem, the captured object was shaded by the silhouette mask. In order to solve this problem, we use digitally captured a real object and convert to a polygon-based model for mix with virtual object which is CG-modeled 3D objects.

In this paper, we proposed a fast scheme for computer-generated holography (CGH) to mix 3D scenes. The objects in the proposed include the real and virtual objects. Using depth camera to capture the depth and texture information of the real object to make a point cloud model, and the point cloud model converted to a triangular mesh model by using point cloud library (PCL). And then mix the triangular mesh model with virtual 3D object mesh models. The angular spectrum method was used to fast compute the shading and propagation of light from 3D mesh objects. In order to testing the whole system, we optically reconstruct the hologram by display phase-only hologram in spatial light modulator (SLM). Our scheme is possible to record big real object to the hologram and the reconstructed image has no viewing angle problem. The proposed also using less data to show high definition and more convenient to accelerate with graphic processing unit (GPU).The proposed scheme is experimentally verified.

9006-58, Session 6

Numerical inversion and assessment of 2D Laplace transforms using the Brancik algorithm and its use in 3D holography

Monish R Chatterjee, Le Feng, Univ. of Dayton (United States)

An analytic examination of 3D holography under a 900 recording geometry was carried out earlier in which 2D spatial Laplace transforms were introduced in order to develop transfer functions for the scattered outputs under readout [1]. Thereby, the resulting reconstructed output was obtained in the 2D Laplace domain whence the spatial information would be found only by performing a 2D Laplace inversion. Laplace inversion in 2D was attempted by testing a prototype function for which the analytic result was known using two known inversion algorithms, viz., the Brancik and the Abate [2]. The results indicated notable differences in the 3D plots between the algorithms and the analytic result, and hence were somewhat inconclusive. In this paper, we take a close look at the Brancik algorithm in order to understand better the implications of the choices of key parameters such as the real and imaginary parts of the Bromwich contour and the grids sizes of the summation operations. To assess the inversion findings, three prototype test cases were considered for which the analytic solutions are known. For specific choices of the algorithm parameters, optimal values were determined that would minimize errors in general. It was found that even though errors accumulated near the edges of the grid, overall reasonably accurate inversions are possible to obtain with optimal parameter choices that are verifiable via cross-sectional views. Further work is ongoing whereby the optimized algorithm is to be applied to the 3D holography problem.

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2. M.R. Chatterjee, P.P. Banerjee and G. Nehmetallah, OSA Conference on Digital Holography and Three-Dimensional Imaging, PMA6-9 (2007).

9006-30, Session 7

Computational architecture for full-color holographic displays based on anisotropic leaky-mode modulators

Sundeep Jolly, Daniel Smalley, James Barabas, V. Michael Bove Jr., MIT Media Lab. (United States)

The MIT Mark IV holographic display system employs a novel anisotropic leaky-mode spatial light modulator that allows for the simultaneous and superimposed modulation of red, green, and blue light via wavelength-division multiplexing. This WDM-based scheme for full-color display requires that incoming video signals containing holographic fringe information are comprised of non-overlapping spectral bands that fall within the available 200 MHz output bandwidth of commercial GPUs. These bands correspond to independent color channels in the display output and are appropriately band-limited and centered to match the multiplexed passbands and center frequencies in the frequency response of the mode-coupling device. The computational architecture presented in this paper involves the computation of holographic fringe patterns for each color channel and their summation in generating a single video signal for input to the display. 18 such input signals, each containing holographic fringe information for 26 horizontal-parallax only holographic lines, are generated via three dual-head GPUs for a total of 468 holographic lines in the display output. We present first results of the adaptation of the Diffraction Specific Coherent Panoramagram approach to fringe computation for the Mark IV architecture and review the resulting holographic video output and performance metrics.

9006-31, Session 7

Three-dimensional computer-generated holograms with shading and occlusion using computer graphics

Hao Zhang, Yan Zhao, Zheng Wang, Liangcai Cao, Guofan Jin, Tsinghua Univ. (China)

Computer holography is a highly complicated and demanding task when it comes to producing realistic three-dimensional (3D) display. Computer graphics can produce photorealistic images of 3D scenes, which is an ideal way to make 3D computer-generated holograms (CGHs) more realistic. We present a calculation algorithm for generating fully computed 3D CGHs which can produce multiple shading and occlusion effects with the help of computer graphics rendering techniques. Phong reflection model is introduced in the CGH computing, which determines the reflectance distributions of the object surface according to the lighting vectors. The ambient, diffuse and specular reflections are included in the calculation to produce realistic shading effects of the 3D scene. Also, to deal with the occlusion problem, ray casting technique is implemented in the computation. The occlusion culling is produced by determining the visible parts of the 3D scene for each hologram sample with the help of the casting rays. A phase-only spatial light modulator (SLM) is used to perform the optical reconstruction, and the experimental results show that computer graphics rendering techniques can be introduced in the computation of fully computed 3D CGHs to produce photorealistic 3D display.

9006-32, Session 7

Evaluation of digital holographic reconstruction using compressive sensing

Partha P. Banerjee, Haipeng Liu, Logan Williams, Univ. of Dayton (United States)

Compressive sensing is a new alternative to the conventional Fresnel approach for digital holographic reconstruction for sparse objects, and can show a better performance with respect to depth of field and recording range which includes the near-field. In this work, we investigate the limitations of the depth of field and the recording range for compressive sensing reconstruction approach via simulations and experiments. The compressive sensing algorithm used is the Two-Step Iterative Shrinkage/Thresholding (TwIST) algorithm. A He-Ne laser of 543.5 nm is used as the light source and a Gabor holographic recording system is used as the experimental setup. Typical objects comprise two wires separated longitudinally by some distance Δz, with the recording range d representing the smaller of the two distances between the wires and the CCD. We numerically calculate Gabor holograms for different combinations of objects size (which determines the Fresnel number), Δz and d. Reconstruction simulations are then done using TwIST and Fresnel algorithms to compare the performance of the two approaches. This also aids in determining the limitations on object size, separation distance and recording distance needed for satisfactory TwIST performance. Holograms are optically recorded using two cross wires with different dimensions, separations and recording distances, and they are reconstructed using the two approaches, and compared with the numerical simulations.

9006-33, Session 7

Viewing-zone-angle expansion of tiled color electronic holography reconstruction system

Takanori Senoh, Koki Wakunami, National Institute of Information and Communications Technology (Japan); Yasuyuki Ichihashi, National Institute of Information and Communications Technology (Japan); Hisayuki Sasaki, National Institute of Information and Communications Technology (Japan); Kenji Yamamoto, National Institute of Information and Communications Technology (Japan)

NICT has recently developed a large-size full-color electronic holography reconstruction system by tiling nine 4Kx2K LCoSs. The gaps between LCoSs were eliminated by enlarging the LCoS images by lenses so as to cover the gaps. The enlarged LCoS images were tiled in 3x3 structures seamlessly. Then the tiled large size LCoS images were shrunk to the original sizes by large lenses in order to resume the original viewing-zone-angle of the reconstructed holographic images.

Since this system was illuminating each LCoS by a large laser beam from the outside of the system by using PBS for each LCoS, it was difficult to illuminate each LCoS from different angles in order to expand the viewing-zone-angle of the reconstructed holographic images.

In this paper, a study of the viewing-zone-angle expansion by three times for the above system is reported by inserting three point light sources of laser fibers in the optical system. Three point light sources placed horizontally behind the condenser lens for each LCoS illuminate the LCoS from three different angles in time-sequential order. Hence, three continuous viewing-zones are reconstructed without receiving a large beam from the outside. Full-colorization was also realized by switching the laser light source to R, G and B colors. During the experiment, it was found the illumination beam center of slanted beams didn't match the center of LCoSs since the condenser lens was used to enlarge the LCoS image too and the distance between the lens and LCoS is larger than the lens focal length. This problem can be solved by placing laser fibers in a fan-shape. It compensates the center offsets of illumination beams. It was also found the higher-order diffraction light from other viewing zones interfere the reconstructed holographic image observation. This problem can be solved by electronic shutter windows to stop the higher-order diffraction lights.

9006-34, Session 7

Focus detection in digital holography by cross-sectional images of propagating waves

Meriç Özcan, Sabanci Univ. (Turkey)

Holographic imaging allows recording of a whole complex wave-field such that phase and intensity profile of the field is recovered when the hologram is reconstructed numerically and it is not necessary to focus the object image during the recording since the wave-field can be computed for any physical distance. However, computing an object's 3D profile with only a single reconstruction requires a prior knowledge of the distance of the object from the camera. When this distance is not known, it is necessary to repeat the image reconstruction at a range of distances followed by evaluation of each image with a sharpness metric to determine the in-focus distance of the object.

Here, we present a method to find the focus distance by processing the image transverse to the propagation direction instead of the processing in the image plane as it is usually done. With this method, it is possible to find the focus distances of multiple objects simultaneously including the phase only objects without staining. We also show that in certain conditions, such as using FFT pruning, calculation time of distance estimation can be reduced significantly which is crucial for real-time operating holography systems. We present the simulations and the experimental results obtained by a digital holographic microscope.

9006-35, Session 7

Static responses of accommodation and convergence to holographic images and real objects

Ryuichi Ohara, Takuo Yoneyama, Masanobu Kurita, Yuji Sakamoto, Hokkaido Univ. (Japan); Fumio Okuyama, Suzuka Univ. of Medical Science (Japan)

In three dimensional display technologies, studies on measuring accommodation and convergence responses to reconstructed images have been reported. However, the physiological characteristics of responses to reconstructed images of electro-holography are not clearly known. In this research, static responses to holographic images and real targets were measured. In addition to measuring responses, it was conducted to evaluate the depths of reconstructed images by comparing with those of real targets, subjectively. A measurement system consisting of an electro-holographic display, real targets, and an auto refractometer was fabricated to measure accommodation and convergence responses at a time. The display for reconstructing holographic images was a binocular eyepiece type electro-holographic display based on a Fourier transform optical system. It was confirmed by a camera that images were located at correct depth and had correct parallax. The shape of targets was Maltese cross and the presented positions were 0.5, 1.0, 1.5 and 2.0 diopters from subjects' eyes. To avoid influences of objects except targets, all experimentations were done in a dark room. As results of measurements, it was confirmed that accommodation and convergence responses to holographic images varied depending on the position of the targets, and the behaviors of holographic images were similar to those of real targets. In addition, results of subjective evaluation showed that holographic images were recognized at nearly the same positions as real targets. Therefore, it was turned out that subjects perceived holographic images at nearly the same positions as real objects in stereoscopic vision.

9006-36, Session 7

Fast hologram generation of long-depth object using multiple wavefront recording planes

Anh-Hoang Phan, Chungbuk National Univ. (Korea, Republic of); Seok-Hee Jeon, Univ. of Incheon (Korea, Republic of); Nam Kim, Jeong-Hyeon Lee, Chungbuk National Univ. (Korea, Republic of)

In this paper we present the method for fast computer generation hologram (CGH) of the long depth object using multiple wavefront recording planes (WRP). The wavefront recording planes are placed between object plane and hologram plane. Each WRP records the wavefront from a section of object. For a long depth object, multiple WRPs can reduce the calculation time in comparison with single WRP. The hologram of object can be real time generated by out proposed method.

In single WRP method, a virtual plane is placed near to the object. The optical field from object to the hologram plane is calculated on the virtual plane first, and then the optical field in WRP is Fresnel transforms to CGH plane by FFT. By this method the calculate time is reduced because every object point in object does not directly calculate on CGH plane but in WRP plane. The WRP plane is close to the object, so the active area of one object point is small (instead of calculate whole size in CGH plane). The calculation time can reduce more if every point is processed parallel.

We proposed a method that using multiple WRPs. In this method, several virtual planes are placed close or inside the object. By this method, the object point is closer to the WRP, so the calculation time is more reducer. However, several FFT transformations are needed to propagate optical field from WRPs to CGH plane in this method. Because of multiple WRP, the problem of pixel matching in hologram plane has to consider. In our scheme the virtual size of WRPs is used to overcome the problem.

9006-37, Session 7

Large field-of-view synthetic aperture holography using rotation stages

Sungmin Kim, Yeonsu Im, Joonku Hahn, Kyungpook National Univ. (Korea, Republic of)

Usually digital holography measures an object wave by using a focal plane array(FPA) sensor and its field of view is very narrow due to the interval of sampling. Many methods have been proposed to increase the field of view of measurement. One simple solution is the synthesis of the holograms with small apertures, which are measured by the FPA sensor respectively. For specific applications such as digital holographic display, the large field of view of the object is required to present the three-dimensional contents to the observer who may change his position

dynamically. In this paper, we use two-axis rotation stage for acquisition of the object wave with large field of view. The optics including a laser and a CCD sensor are fixed, and the object is mounted on the rotation stage. During the rotation of the object, the holograms are taken sequentially and the object wave over the hemispherical surface in k-space is obtained. The increase of solid angle of the curved hologram means the increase of field of the imaging. The resolution of the imaging is closely related with the numerical aperture and the high resolution imaging is expectable. But since it is not easy to match the relative phases of the each hologram, unfortunately the enhancement of the resolution in the reconstructed object wave is negligible.

9006-38, Session PWed

Holograms with random distribution

Arturo Olivares-Pérez D.D.S., Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Santa Toxqui-Lopez, Benemérita Univ. Autónoma de Puebla (Mexico); Israel Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Mauricio Ortiz-Gutiérrez, Rosa Elena Orozco-Muñoz, Univ. Michoacana de San Nicolás de Hidalgo (Mexico)

Numerical results are presented from the behavior of diffraction gratings through micro-holographic spatially localized areas, which consist of micro-coded areas with sinusoidal profile gratings. The random distribution of the micro areas, introduces diffracted orders a random modulation, we observed a characteristic profile of randomness. This is a study of the behavior of the random distribution as a function of the number of coded zones and the micro-area form where the gratings are generated.

9006-40, Session PWed

Reduction of phase temporal fluctuations caused by digital voltage addressing in LC SLM “HoloEye PLUTO VIS” for holographic applications

Nikolay N. Evtikhiev, Pavel A. Cheremkhin, Vitaly V. Krasnov, Vladislav G. Rodin, Sergey N. Starikov, National Research Nuclear Univ. MEPhI (Russian Federation)

Phase liquid crystal spatial light modulators (LC SLM) are widely used in optical applications such as real-time imaging of holograms and diffractive optical elements, which require high stability and linearity of phase modulation. However state of the art LC SLM with high resolution use digital voltage addressing scheme which, unfortunately, leads to phase fluctuations in time period of one frame. Fluctuations characteristics depend on SLM voltage addressing sequence used. We report results of measurement of phase characteristics of LC SLM “HoloEye PLUTO VIS”. This SLM is supplied with three different addressing sequences: “18-6”, “5-5” and “0-6”. Dynamics of phase fluctuations were measured for all signal values (0-255) with temporal resolution of 0.5 ms in time period of one frame for available addressing sequences. Default sequence “18-6” provided phase deviation 0.24 pi. Lowest deviation 0.07 pi was achieved with sequence “0-6”. Due to high periodicity of fluctuations it is possible to implement synchronization of SLM and registering camera or light source to reduce fluctuation effects. This was experimentally implemented using DVI video signal for synchronization of SLM and camera. With its application minimum phase deviation 0.013 pi was achieved with sequence “18-6” which is 5 times lower than achievable without synchronization.

9006-41, Session PWed

Holograms writing on glass

Arturo Olivares-Pérez D.D.S., Israel Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Santa Toxqui-Lopez, Benemérita Univ. Autónoma de Puebla (Mexico)

Holographic gratings recorded in photoresist, are used by common techniques of lithography, for writing on glass. We present a study of the technique used to erode the glass using hydrofluoric acid and copy the holographic element on the glass. We observe that holograms written in glass are very strong and durable.

9006-42, Session PWed

Semi-portable full-color electro-holographic display with small size

Takuo Yoneyama, Tsubasa Ichikawa, Yuji Sakamoto, Hokkaido Univ. (Japan)

Although various 3-D head-worn displays using stereograms have been set out, long time observation by those systems causes uncomfortable feeling and tiredness because stereograms do not satisfy all 3-D visual cues such as accommodation, convergence, and parallax. On the other hand, electro-holography enables observers to view natural 3-D images without feeling uncomfortable due to satisfying these necessary cues.

This time, we fabricated the semi-portable full-color electro-holographic display system with small size for the base of wearable system. In this paper, we describe the structure of our system and the proposed calibration method for arrangement of optical parts. This calibration play an important role in accuracy of reconstructed images.

To make a small system, disturbing optical effects to view the images are compensated in calculation process of holograms without using additional optical parts. Therefore, this system is very simple and easily used everywhere with only a little adjustment. The system has the slide structure between left and right view point like a binoculars to eliminate an influence of individual interpupillary distances (PDs). To reconstruct full-color holographic images, the time sequential color method is adopted. Light sources are full-color LEDs with special optical elements designed by computer simulation, and this component works as full-color point light sources.

To confirm the effectiveness of the proposed system, the reconstructed images were evaluated objectively and subjectively. Results of experiments showed that reconstructed full-color images were located correct depths and satisfied correct accommodation, convergence, and parallax without an influence of individual PDs.

9006-43, Session PWed

Albumin holograms with iron ions

Manuel Jorge Ordóñez-Padilla, Arturo Olivares-Pérez D.D.S., Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Mauricio Ortiz-Gutiérrez, Julio César Juárez-Ramírez, Univ. Michoacana de San Nicolás de Hidalgo (Mexico)

We disclose the preparation of photosensitive films of albumen (egg white) of quail, applying as oxidizing agent, the iron ammonium citrate. Exposed to a He-Cd laser, ? = 442nm, transmission holograms were recorded. We obtained the diffraction patterns reconstructed with He-Ne laser, ?=632.8nm, and measuring efficiencies for first order diffraction as a function of exposure energy. Holographic gratings made with these materials exhibit behaviour of self develop. We analyze the experimental results.

9006-44, Session PWed

Fluorescent holograms with albumin-acrylamide

Manuel Jorge Ordóñez-Padilla, Arturo Olivares-Pérez D.D.S., Israel Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

We describe the preparation of photosensitive films of albumin (egg white) of quail as modified matrix for holographic recording. The albumin is mixed with: propyleneglycol, acrylamide and eosin, to form a photosensitive emulsion with the capacity to record holograms. We obtained diffraction patterns reconstructed with He-Ne laser, ? = 632.8nm, and we measure the efficiencies for first order diffraction as a function of exposure energy. The eosin is a fluorescent agent and also acts as a photosensitizing dye. The work shows the requirements necessary to achieve stability of the films, for use in holographic recording; we report the preliminary experimental results.

9006-45, Session PWed

Betacyanins pigments as photosensitizing agents for holographic recording medium

Santa Toxqui-López, Edgar Hernández-Hernández, Claudia Santacruz-Vázquez, Benemérita Univ. Autónoma de Puebla (Mexico); Arturo Olivares-Pérez D.D.S., Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Veronica Santacruz-Vazquez, Benemérita Univ. Autónoma de Puebla (Mexico)

One of the natural most employed within the food industry are pigments of betalains by their solubility in water to give desired colorations in processed foods such as beverages, dairy, meat. However, this research shows that this type of pigments can be used as photosensitizing agents in the field of holographic recording materials. Betalains are formed by two subgroups: Betacyanins, of red color to purple and Betaxanthins of yellow color to orange. Betacyanins pigments are mainly studied, which are extracted from the beet juice by dehydration. For obtaining films, pigments are mixed with polyvinyl alcohol (PVA) to make solution 2.5% m/v. This solution is deposited on transparent glass substrates by the method of gravity, subsequently carrying out a drying process in normal conditions and totally darkness, after 24 hours films are obtained, which are used to holograms replication. Therefore, for replications are employed masks where the hologram pattern is contained (sinusoidal gratins), it is aligned on the substrate containing the film layer and irradiated with ultraviolet light from a source that is an array of LEDs (blue 430-505 nm).The diffraction efficiency is quantified showing good results.

9006-46, Session PWed

Holographic films from carotenoid pigments

Santa Toxqui-López, Francisco Lecona-Sánchez, Benemérita Univ. Autónoma de Puebla (Mexico); Arturo Olivares-Pérez D.D.S., Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Claudia Santacruz-Vázquez, Benemérita Univ. Autónoma de Puebla (Mexico); Israel Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Carotenoids pigments presents in pineapple can be more than just natural dyes, which is one of the applications that now at day gives the chemical industry. In this research shown that can be used in implementing of holographic recording Films. Therefore we describe the technique how to obtain this kind of pigments trough spay drying of natural pineapple juice, which are then dissolved with water in a proportion of 0.1g to 1mL. The obtained sample is poured into glass substrates using the gravity method, after a drying of 24 hours in laboratory normal conditions the films are ready. The films are characterized by recording transmission holographic gratings (LSR 445 NL 445 nm) and measuring the diffraction efficiency holographic parameter. This recording material has good diffraction efficiency and environmental stability.

9006-47, Session PWed

Floating full-color image with computer-generated alcove rainbow hologram

Takeshi Yamaguchi, Hiroshi Yoshikawa, Nihon Univ. (Japan)

In this paper, we have investigated the floating full color image display with the computer-generated hologram (CGH).

The floating image, when utilized as a 3D display, gives strong impression to the viewer.

In our previous study, to change the CGH shape from the flat type to the half cylindrical type, the floating image from the output CGH has the nearly 180 degrees viewing angle.

However, since the previous CGH dose not have wavelength?selectivity, reconstructed image only has a single color.

Also, the huge calculation amount of the fringe pattern is big problem.

Therefore, we now propose the rainbow-type computer generated alcove hologram.

To decrease the calculation amount, the rainbow hologram sacrifices the vertical parallax.

Also, this hologram can reconstruct an image with white light.

Compared with the previous study of the Fresnel type, the calculation speed becomes 165 times faster.

After calculation, we print this hologram with a fringe printer, and evaluate reconstructed floating full color images.

In this study, we introduce the computer-generated rainbow hologram into the floating image display.

The rainbow hologram can reconstruct full color image with white light illumination.

It can be recorded by using a horizontal slit to limit the vertical parallax.

Threrfore, the slit changes into the half cylindrical slit, the wide viewing angle floating image display can reconstruct full color image.

9006-48, Session PWed

Holographic data storage system combining shift-multiplexing with peristrophic-multiplexing

Kengo Yoshikawa, Yu Tsukamoto, Kaito Okubo, Manabu Yamamoto, Tokyo Univ. of Science (Japan)

In the holographic data storage, the recording density that is over one terabit per square inch was experimentally confirmed by combining the shift multiplexing recording method that used spherical reference wave and peristrophic multiplexing recording method. The shift selectivity in the multi dimension was examined by the experiment and the simulation.

As a result, the shift selectivity in a direction which is normal to the hologram carrier wave formed by signal beam and reference beam was great, on the other hand, a direction parallel to the hologram carrier wave was inferior to the former direction.

Then, the high recording density was able to be achieved by combining the shift multiplexing method in the vertical direction with peristrophic multiplexing by rotating the medium. In the experiment, several thousand multiple holograms were recorded in photopolymer medium (1.5mm) by using a blue laser (wavelength 405 nm).

The hologram size is 0.4mm and the recording time per a hologram is about 0.1 seconds. The medium rotation angle for peristrophic multiplexing is 10 degrees and the medium shift amount is 10?m.

This paper reports on the result of evaluating the high recording density characteristic in such a condition.

9006-49, Session PWed

Examination of systematization of the holographic data storage

Yuta Nagao, Hiroyuki Kurata, Syuhei Yoshida, Manabu Yamamoto, Tokyo Univ. of Science (Japan)

Recently, the holographic data storage is researched as an archive memory of mass data.

The feature of this memory excels in preservation of information and low-cost of a large capacity, high speed, and has enough adaptability as an archive memory of image information. The improvement of the maintenance operation and energy-saving drive are requested under the present circumstances though a large-scale hard disk drive is used in a mass server for the archive.

The holographic data storage can realize these demanded conditions and especially big effect in energy-saving in terms of such a viewpoint.

A large capacity information storage progresses greatly in recent years, and holographic data storage system is suitable for this request.

For high density recording, more than one terabit per squire inch is concretely demanded, and the research and development for it is encouraged.

In the present study, the recording and reproduction method to combine the shift multiplexing method that used spherical reference wave with peristrophic multiplexing method was adopted, and the experimentally verified the high recording density recording method.

The laser wave length is 405 nm, and the medium is photopolymer 1.5mm thickness.

In addition, we made a small system that enables recording and reproduction of the camera input image, this paper reports on the I/O characteristic, and also the result of evaluating the system.

9006-50, Session PWed

A wavefront printer using phase-only spatial light modulator for producing computer-generated volume holograms

Wataru Nishii, Kyoji Matsushima, Kansai Univ. (Japan)

Computer holography that generates the fringe pattern of holograms by computers has been developed in recent several years and producing impressive high-resolution computer-generated holograms (CGH) comparable to conventional optical holograms. However, these high-resolution CGHs are printed by high resolution printers as a two-dimensional fringe pattern, and thus, cannot be reconstructed by white light illumination. On the other hand, conventional optical holography can created volume holograms that can be reconstructed white light. This is because the fringes are recorded in a three-dimensional manner. In this paper, we report a printer that record wavefronts generated by spatial light modulator (SLM) and can produce volume holograms whose fringe is given by numerical calculation. In this scheme, CGH can be produced as volume hologram that reconstructs 3D images under white light illumination. We call this printer “wavefront printer”. Wavefront printers reported in earlier studies commonly use SLMs that make amplitude modulation of light. However, wavefront printer using amplitude SLM needs some technique to removes the conjugate image. This generally results in the narrow space-band product. Therefore, we propose a wavefront printer using a phase-only SLM. However, this type of SLM has the problem of wavefront degradation because of coding noise due to phase-only modulation. We propose a method for reducing the degradation by using polarization modulation that is generated even in phase-only SLM. In this technique, the SLM effectively modulate the amplitude as well as the phase of recording light, thus we can ease the coding noise due to phase-only modulation.

9006-51, Session PWed

Techniques for applying rigorous light-shielding to high-definition computer holography

Sachio Masuda, Kyoji Matsushima, Sumio Nakahara, Kansai Univ. (Japan)

In the past few years, we presented some high-definition computer-generated holograms (CGH) computed by the polygon-based method. In creation of these high-definition CGHs, the technique of the silhouette masking plays an important role to shield light behind the object and prevent the reconstructed object from being see-through. In this technique, the light behind the object is shielded by the silhouette-shaped mask in a plane parallel to the hologram. However, if the CGH has very high physical resolution and thus large diffraction angles, off-axis light is not perfectly shielded and causes leakage light through many gaps between the masks. To remove this leakage light, we have already proposed more rigorous technique for light shielding. In this technique, the wave-field in the polygon plane is calculated by using the numerical technique of rotational transform and masked by using the polygon-shaped masks. However, only the principle of this rigorous technique has been verified, because the rotational transform is very time-consuming in high-definition computer holography. The rigorous light-shielding has never been applied to the actual high-definition computer holography.

In this paper, we propose some techniques to apply the rigorous light-shielding to high-definition computer holography. In addition, we report computation time necessary for calculating a CGH by using the rigorous technique and the comparison with the conventional silhouette method. This paper describes the detail of the techniques as well as the measured computation time. We will also demonstrate some actual high-definition CGHs created by the proposed method in the meeting.

9006-52, Session PWed

Occlusion-removed cylindrical computer generated hologram using 3D point clouds

Yu Zhao, Chungbuk National Univ. (Korea, Republic of); Gang Li, Department of Electrical Engineering, Seoul National University (Korea, Republic of); Mei-Lan Piao, Department of Electrical and Computer Engineering, Chungbuk National University (Korea, Republic of); Hyun Min Lee, Department of Electrical and Computer Engineering, Chungbuk National University, (Korea, Republic of); Nam Kim, Chungbuk National Univ. (Korea, Republic of)

Holography can provide flawless 3D image with complete human depth cues. In holography, the size and shape of the recording surface determine the field of view and information capacity that canbe obtained from object. A general flat hologram has a limited viewable area, we usually cannot see the other side of a reconstructed object. A method of occlusion-removed computer generated cylindrical hologram is proposed. Compared with flat hologram, computer generated cylindrical hologram can reduce the data amount, in the case of calculating 360° optical field of the 3D object, and it is able to provide 360° field of view in horizontal direction.

Viewing angle of the conventional flat hologram is not very large (less than 180°) attributed to their planar observation surface. If we want to synthesize a wide view computer generated hologram, a numerical simulation of the diffraction on the non-planar observation surfaces is required. computer generated cylindrical hologram can be a solution.

In our proposed method the 3D point cloud is obtained by using a depth camera. However, because of using 3D point cloud, correct occlusion effect should be considered. S. Katz etal. proposed a method to address this issue. We apply the method into proposed computer generated cylindrical hologram. The visible points for each hologram point are identified by hidden point removal (HPR) and the optical field of the hologram point is obtained by the point light source method. Approximately 11,000 object points were used for this research, we have realized a CGCH that is viewable in 360°.And a convolution synthesis method has been used in the simulation of the computer generated cylindrical hologram to obtain a good reconstructed image.In addition, the heavy computation load is one of the issues, in computer generated non-planar holograms. Therefore, we propose a calculation method for fast calculation.

9006-53, Session PWed

Development of high-efficiency holographic optical element for LED display

Meilan Piao, Chungbuk National Univ. (Korea, Republic of); Kwon-Yeon Lee, Department of Electronics Engineering, Sunchon National University. (Korea, Republic of); Sang-Keun Gil, Suwon Univ. (Korea, Republic of); Nam Kim, Chungbuk National Univ. (Korea, Republic of)

Holographic optical element (HOE) is volume hologram grating, when a beam of incident light satisfies the Bragg condition it is diffracted by grating. HOE has angular selectivity and wavelength selectivity for diffraction of different wavelengths of the light incident at a particular angle. The diffraction wavelength range of the RGB color lights in the HOE is favorably determined according to the wavelength range of light emitted from the light-emitting diodes (LED) light source. For improving optical efficiency and good color reproduction for LED display, we analyze the relationship between the wavelength of the output light and the intensity of the light or the spectral intensity characteristic of the light source. The RGB combined light source and the HOE in a combination can further increase the purity of each of the RGB colors. And the color balance in the image to be viewed can be improved through optimizing the diffraction efficiency in reference to the visibility of the RGB colors of light.

We investigate the full color and good uniformity HOE for LED display. Practical methods for fabrication of high efficiency HOE by single layer photopolymer were developed. The optical characteristics of the photopolymer were analyzed using three lasers operated at 633, 532, and 473nm, respectively. Observers can see through the display because wavelength selectivity of the HOE provides high transparency. As the reconstruction light source of the hologram, LED of 632nm, 523nm and 465nm in wavelength was used. As a result, the high color uniformity of RGB diffraction beams is obtained and the color matching analysis is used in our experiment system.

9006-54, Session PWed

Birefringence measurement of the cellophane film

Julio César Juárez-Ramírez, Mauricio Ortiz-Gutiérrez, Marco Antonio Salgado-Verduzco, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); Mario Pérez-Cortés, Univ. Autónoma de Yucatán (Mexico); Arturo Olivares-Pérez D.D.S., Manuel Jorge Ordóñez-Padilla, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Juan Carlos Ibarra-Torres, Universidad de Guadalajara (Mexico)

In this work we describe an experimental technique to measure the birefringence of the cellophane film that has good behavior as half wave retarder. This technique is achieved when the film is placed in a polariscope that consists of a light source and properly arranged polarizing elements and a system of fringes is observed. Using Jones formalism for the system the birefringence appears in the phase term of harmonic functions and is calculated by unwrapping phase theory. Some experimental results are shown.

9006-55, Session PWed

Fish gelatin(C) and ammonium dichromate as photosensitive film

Rosa Elena Orozco-Muñoz, Mauricio Ortiz-Gutiérrez, Marco Antonio Salgado-Verduzco, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); Juan Carlos Ibarra-Torres, Univ. de Guadalajara (Mexico); Arturo Olivares-Pérez D.D.S., Santa Toxqui-López, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Mario Perez-Cortés, Universidad Autónoma de Yucatán (Mexico)

In this work we propose a phase material based on fish gelatin from Norland Products© mixed with ammonium dichromate deposited on a glass substrate. The photosensitive film has 110 ?m thickness. In this material we record low frequency (180lines/mm) holographic gratings using a ?=532 nm from an Ar laser and reconstruct the image with ?=594 nm from a He-Ne laser. The diffraction efficiency is 15% for the first order. The material no requires developing process and is very easy to make. Experimental results are shown.

9006-56, Session PWed

Fast generation of CGH of 3D video images by using block-based motion compensation techniques

Seung-Cheol Kim, Xiao-Bin Dong, Eun-Soo Kim, Kwangwoon Univ. (Korea, Republic of)

A new approach, which combines the N-LUT method with block matching motion compensation technique, to fast generating the computer-generated-holograms(CGHs) of three-dimensional (3-D) video images is proposed. Block matching motion compensation is a powerful technique used in MPEG-4 algorithm for video compression. Here, we apply this technique to N-LUT-based CGH generation algorithm by which a higher similarity between adjacent frames can be obtained. In the proposed method, the input video images are divided into blocks of fixed size and the CGHs of every block in reference frames are pre-calculated with the N-LUT method. The motion vectors of every block in the reference frame are extracted between reference frame and current frame, and a compensated frame image can be obtained by shifting every block's position according to the motion vectors. Through this process, 3-D objects data to be calculated for its video holograms are dramatically reduced leading to the greater reduction of the calculation time compared with the conventional temporal redundancy-based N-LUT (TR-N-LUT) method. In the experiments of two input videos have found that the average number of calculated object points and the average calculation time for one object point of the proposed method reduce to 30% and 20.3% respectively compared to those with the conventional TR-N-LUT method.

9006-57, Session PWed

Efficient digital hologram computation using difference between frames and compensated principal fringe patterns

Seung-Cheol Kim, Eun-Soo Kim, Kwangwoon Univ. (Korea, Republic of)

In this paper, a novel approach for fast generation of video holograms of three-dimensional (3-D) moving objects using compensated principal fringe patterns (C-PFP)-based novel-look-up-table (N-LUT) method is proposed. If the object point is changed between frames, two calculations are needed in conventional temporal redundancy-based N-LUT (TR-N-LUT) method, but only one calculation is needed by compensating the difference in intensity and depth values using C-PFP. That is, hologram patterns for moving 3-D object can be calculated by simply multiplying the C-PFP to hologram pattern by difference of depth value. Experimental results with test 3-D video having camera panning reveal that the average number of calculated object points and the average calculation time for one object point of the proposed method, have found to be reduced down to 54.9%, 64.6%, and 62.5%, 73.0%, respectively compared to those of the conventional N-LUT and TR-N-LUT methods

9007-1, Session 1

Light fidelity (Li-Fi): towards all-optical networking *(Invited Paper)*

Dobroslav Tsonev, Stefan Videv, Harald Haas, The Univ. of Edinburgh (United Kingdom)

Li-Fi refers to high speed wireless communications through off-the-shelf white light emitting diodes (LEDs) - the devices that are at the heart of next generation energy efficient lighting. This paper will introduce Li-Fi, present the latest research findings such as our recent 3 Gbps transmission from a single colour LED, and showcase the potentials of this new technology. In this context, it will demonstrate that Li-Fi elegantly supports the trend of ever smaller cells in wireless communications to improve data coverage and mobile user experience without the need for expensive new infrastructure. It will be shown that the data rates in rooms can be improved by a factor of 1000 compared to existing radio frequency based systems such as Wi-Fi. This is because of the more favourable interference conditions in optical cellular networks where the light bulb is the optical base station or access point.

9007-2, Session 2

Dual-mode ultraflow access networks: a hybrid solution for the access bottleneck *(Invited Paper)*

Leonid G. Kazovsky, Thomas Shunrong Shen, Ahmad R Dhaini, Shuang Yin, Marc De Leenheer, Benjamin A Detwiler, Stanford Univ. (United States)

Stanford UltraFlow Access is a research project aiming to create a dual-mode access solution providing two types of services to end users - conventional IP services and flow services optimized for large transactions. Stanford UltraFlow Access is a part of a broader research effort sponsored by NSF looking into dual-mode UltraFlow networks; that effort is conducted by Stanford, MIT and UTD.

This invited ntalk is focused entirely on the Stanford part of the project, i.e., Stanford UltraFlow Access. It describes the architecture of the UltraFlow access network we've developed, its experimental implementation, and our experimental results obtained so far using our experimental testbed.

9007-3, Session 3

Microring resonators: the road to practical implementations

Joyce K. S. Poon, Wesley D. Sacher, Jared C. Mikkelsen, Hasitha Jayatilleka, Univ. of Toronto (Canada)

Despite decades of research, micro-resonator devices have not found widespread commercial adoption and have not replaced workhorse interferometric based photonic devices, such as Mach-Zehnder interferometers or arrayed waveguide gratings. The main roadblocks are the notoriously high sensitivity of the optical characteristics of microcavity devices to dimensional variations, environmental fluctuations, and nonlinearities.

In recent years, the availability of silicon photonic foundries coupled with the need for energy-efficient and compact photonic components for short reach networks (e.g., datacenters, board-to-board) have renewed interest in micro-resonators, especially microring resonators for integrated photonic circuits. The longstanding implementation challenges of micro-resonators motivate a fundamental re-consideration of the design and implementation of microring devices with a focus on fabrication tolerance, tunability, and functionality.

In this talk, I will describe my group's efforts on this front. I will present silicon microrings with improved tolerance to dimensional variations, tunable microring modulators with high extinction ratios, and modulators that break the linewidth limitations of resonant modulation. I will describe how these concepts can be extended to other types of high index contrast waveguide devices, resonant modulators, and lasers, including those in hybrid integration platforms. Innovative architectures and design approaches are needed for microrings to realize their potential as essential elements in large-scale integrated photonic circuits.

9007-4, Session 4

Wireless and wired convergence towards next-generation access networks *(Invited Paper)*

Katsumi Iwatsuki, Tohoku Univ. (Japan); Katsutoshi Tsukamoto, Osaka Institute of Technology (Japan)

The bandwidth of next generation access networks will strongly require beyond that of current optical access, due to the download of huge data, images, and videos, as well as to upload of a large number of sensor data, any time and anywhere. The technical convergence with wired and wireless plays an important role to achieve the next generation access networks. In this presentation, we will talk about perspective on next generation networks considering the resilience against disasters.

9007-5, Session 4

Faster than fiber: demonstration of over 100 Gb/s signal delivery at W-band *(Invited Paper)*

Xinying Li, Jianjun Yu, Fudan Univ. (China)

In order to realize the seamless integration of wireless and fiber-optic networks, the wireless links need to be developed to match the capacity of high-speed fiber-optic communication systems, while preserving transparency to bit rates and modulation formats. Recently, the W-band (75-110 GHz), with wider bandwidth and higher frequency, has attracted increasing interest as a candidate radio-frequency (RF) band to provide multi-gigabit wireless links for mobile data transmission. Furthermore, 100-Gb/s and beyond wireless mm-wave signal can be generated by photonic mm-wave technique, which further promotes the seamless integration of wireless and fiber-optics networks.

In this paper, we summarize several different approaches for the realization of over 100Gb/s fiber-wireless integration system, including optical polarization-division-multiplexing (PDM) combined with multiple-input multiple-output (MIMO) reception, advanced multi-level modulation, optical multi-carrier modulation, electrical multi-carrier modulation, antenna polarization multiplexing and multi-band multiplexing. These approaches can effectively reduce the signal baud rate as well as the required bandwidth for optical and electrical devices. We also investigate the problems, such as wireless multi-path effect due to different wireless transmission distance, existing in the large capacity fiber-wireless integration system. We demonstrate these problems can be effectively solved by advanced digital-signal-processing (DSP) algorithms including classic constant modulus algorithm (CMA). Moreover, based on the combination of these approaches as well as advanced DSP algorithms, we have successfully demonstrated a 400G fiber-wireless integration system, which creates a capacity record of wireless delivery and ushers in a new era of ultra-high bit rate (>400Gb/s) optical wireless integration communications at mm-wave frequencies.

9007-7, Session 4

Optical fiber-wireless components and system for broadband access applications *(Invited Paper)*

Idelfonso Tafur Monroy, DTU Fotonik (Denmark)

The continuous increasing demand from end-users to connect wirelessly to Internet services by smartphones and tablets is creating an unprecedented challenge for service providers to overcome a global bandwidth crunch. Therefore on-going research and developments efforts are directed to exploit new frequency bands such as millimetre wave range for wireless links in combination with optical fibre infrastructure. The combination of millimetre wave and optical fibre technology for wireless service provisioning aims at joining their advantages in flexibility and bandwidth, respectively, to tackle the challenge of mobility and capacity. In this talk we review experimental work on components and systems for high capacity, hybrid optical fibre-wireless communications.

9007-8, Session 4

Asymmetric MQW semiconductor optical amplifier with low-polarization sensitivity of over 90-nm bandwidth

Julie E. Nkanta, Ramon Maldonado-Basilio, Sawsan Abdul-Majid, Univ. of Ottawa (Canada); Jessica Zhang, Canadian Microelectronics Corp. (Canada); Trevor J. Hall, Univ. of Ottawa (Canada)

An exhausted capacity of current Passive Optical Networks has been anticipated as bandwidth-hungry applications such as HDTV and 3-D video become available to end-users. To enhance their performance, the next generation optical access networks have been proposed, using optical carriers allocated within the E-band (1360-1460 nm). It is partly motivated by the low-water peak fiber being manufactured by Corning. At these wavelengths, choices for low cost optical amplifiers, with compact size, low energy consumption and feasibility for integration with other optoelectronic components are limited, making the semiconductor optical amplifiers (SOA) a realistic solution.

An experimental characterization of a broadband and low polarization sensitive asymmetric multi quantum well (MQW) SOA operating in the E-band is reported. The SOA device is composed of nine 6 nm In1-xGaxAsyP1-y 0.2% tensile strained asymmetric MQW layers sandwiched between nine latticed matched 6 nm InGaAsP barrier layers. The active region is grown on an n-doped InP substrate and buried by p-doped InGaAsP layers. The SOA devices have 7-degrees tilt cleaved facets, with 2 µm ridge width, and a cavity length of 900 µm. For input powers of -10 dBm and -20 dBm, a maximum gain of 20 dB at 1360 nm with a polarization insensitivity under 3 dB for over 90 nm bandwidth is measured. Polarization sensitivity of less than 0.5 dB is observed for some wavelengths. Obtained results indicate a promising SOA with broadband amplification, polarization insensitivity and high gain. These SOAs were designed and characterized at the Photonics Technology Laboratory, University of Ottawa, Canada.

9007-9, Session 4

Multi-wavelength and multiband RE-doped optical fiber source array for WDM-GPON applications

Grethell G. Perez-Sanchez, Tecnologico de Estudios Superiores de Coacalco (Mexico) and Ctr. de Investigación e Innovación Tecnológica (Mexico); Indayara B. Martins, Philippe Gallion, Cristophe Gosset, Télécom ParisTech (France); José A. Álvarez-Chávez, Ctr. de Investigación e Innovación Tecnológica (Mexico)

Due to advantages such as large signal to noise ratio, low number of required active devices, minimum opto-electric conversions number and decreased power consumption, GPON ITU-T G.984 connections are been widely used. This technology offers ecologic and very flexible solutions at reduced costs by using the 1550nm and 1490nm band for downlink stream, the 1310nm band for uplink communication and the 1650nm band for fiber testing via Optical Time Domain Reflectometry. The price to pay is an increment on the number of required pump lasers for FTTX technologies. In this paper, a multiband, multi-wavelength, all-fibre source array consisting of an 810nm pump laser diode, three fiber splitters and three segments of Er-, Tm- and Nd-doped fiber is proposed for GPON applications. In the set-up, cascaded pairs of standard fiber Bragg gratings are used for extracting the required multiple wavelengths within their corresponding bands. A thorough design parameter description, optical array details and full simulation results, such as: full multi-wavelength spectrum, peak and average powers for each generated wavelength, linewidth at FWHM for each generated signal, and individual and overall conversion efficiency, will be included in the manuscript.

9007-10, Session 5

Recent standardization activities on radio on fiber (RoF) *(Invited Paper)*

Hiroyo Ogawa, Association of Radio Industries and Businesses (Japan); Toshiaki Kuri, Atsushi Kanno, Tetsuya Kawanishi, National Institue of Information and Communications Technology (Japan)

The Radio on Fiber (RoF) technologies are unique transmission means of radio analog signals through optical fiber cables. ITU-T SG15 is working on Wavelength Division Multipexing Passive Optical Network (WDM PON) to distribute high-speed data to the subscraiber. RoF techologies are curently proposed to transmit radio signals through WDM PON for wireless applications. RoF technologies are also proposed to IEEE802.11 to connect wireless zones as one of backhul links. In addition to RoF standardization, stadardization activities within ITU-R WP1A on millimeter-wave above 275 GHz will be introduced as an important related standard areas of RoF technologies. ITU-R currently approved a Study new Questio which accelerates to study those technologies above 275 GHz from the view point of spectrum technology aspect. This invited paper summarizes RoF standardization activities including spectrum technology above 275 GHz at those standard organizations.

9007-11, Session 5

Small cell configurations and capacity in RoF-DAS over WDM-PON system

Katsutoshi Tsukamoto, Osaka Institute of Technology (Japan); Tatsuhiko Iwakuni, Kenji Miyamoto, Takayoshi Tashiro, Yoichi Fukada, Shigeru Kuwano, Jun-Ichi Kani, Jun Terada, Naoto Yoshimoto, NTT Access Network Service Systems Labs. (Japan)

This paper addresses the wireless channel capacity in small cells provided by RoF-DAS over WDM-PON that can increase the capacity in a small cell with RoF entrance link and MIMO distributed antenna. Considering the SNR of the RF signal transmitted in RoF and the interferences among wireless cells enable results of computer simulation show the optimized cell size to maximize the MIMO channel capacity.

9007-12, Session 5

Opto-electrical predistortion method using nonlinearity of schottky diode for radio-over-fiber systems

Byung-Hee Son, Kwangjin Kim, Ye Li, Young-Wan Choi, Chung-Ang Univ. (Korea, Republic of)

Analog optical links employing radio-over-fiber (RoF) techniques inherently suffer from the cumulative effects of noises and distortions induced by the nonlinearity of optical components. In order to improve the spurious-free dynamic range (SFDR) of optical transceiver for radio-over-fiber (RoF) systems, the linearization techniques have been widely investigated. In previous researches for linearity enhancement, predistorter using optical components, such as laser diode (LD), photo detector (PD) or external modulator, is applied to optical transceiver. These techniques need active and passive components such as amplifier, attenuator and phase shifter which have compensated insertion losses and adjust magnitudes or phases. However, the optical transceivers which is applied these method have high complexity and current consumption to fine tuning.

In this paper, we propose a simple and efficient predistortion method using schottky diodes to compensate the nonlinearity of RoF systems. We have compared the L-I curve in LD with I-V curve in schottky diode and analyzed the nonlinear characteristics. The predistortion circuits have been designed with two path. One path is the nonlinearity generation circuit with schottky diode, while the other path has a time delay. Then, these two paths are recombined to suppress the IMD3 of LD. Experimental results show that the enhancements of about 26 dBc in the IMD3 and about 8.5 dB in the SFDR are achieved at 2.4 GHz.

9007-13, Session 6

Gigabit-class optical wireless indoor communication *(Invited Paper)*

Frank Deicke, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

Currently, there is enormous progress in the field of wireless communication technology increasing bandwidth and usability. There are new WiGig products out there as well as 4G deploying worldwide to serve users with faster data links. On the other hand, optical wireless technologies gain traction more and more in the R&D community to finally think about wireless technologies after the 60GHz line of sight era. According to this, that paper is about optical wireless communication technology to provide Gbit-class communication speed for indoor short and mid-range communication. It will present technology that could overcome current bottlenecks regarding link distance and coverage while offering a low power and small form factor approach.

9007-14, Session 6

High speed infrared optical wireless for home access networks *(Invited Paper)*

Dominic C. O'Brien, Univ. of Oxford (United Kingdom)

Fibre to the home and other high-speed access technologies are leading to data rates of hundreds of Mbits/s being available to domestic subscribers. Home access networks that offer data rates greater than this are required to fully use this bandwidth. Infrared line of sight optical wireless systems can offer high data-rate, low latency communications that is well suited to the indoor environment. This paper describes several infrared demonstration systems that have been implemented as part of an European Community funded programme on home access, and discusses the evolution of this, and other optical wireless technologies.

9007-15, Session 6

Next generation 3-D OFDM based optical access networks using FEC under various system impairments

Pravindra Kumar, Anand Srivastava, Indian Institute of Technology Mandi (India)

Passive optical network based on orthogonal frequency division multiplexing (OFDM-PON) is a promising candidate for high optical access network due to its greater resistance to the fiber dispersion. Also high spectral efficiency is achieved due to the orthogonality between all subcarriers which overlap in the frequency domain. Two-dimensional (2-D) Signal mapper and 1-D Inverse Fast Fourier Transform (IFFT) are the major elements of the conventional OFDM system communication system. In this paper, we use the concept of 3-D signal mapper and 2-D IFFT which is called as 3-D OFDM communication system. The performance of 40 Gb/s 2-D OFDM-PON and 3-D OFDM-PON using multi-level modulation scheme under various system impairments is analytically analyzed and compared for their transmission distance, bandwidth efficiency and BER for coherent optical orthogonal frequency division multiplexing (CO-OFDM) without using any optical dispersion compensation. As bit error rate (BER) depends on minimum Euclidean distance (MED) which is 15.46 % more in case of 3-D mapper as compared to 2-D OFDM. Analytical result show that at BER of 10-3 which is the limit of forward error correction (FEC), there is around 2.8 signal-to-noise (SNR) gain. An optical budget (downlink) of 33 dB is obtained for 40 Gb/s optical access networks using 2-D OFDM and that is about 34.3 dB for 3-D OFDM when using 16-QAM and about 31.3 dB for 2-D OFDM and 32.6 for 3-D OFDM when using 64-QAM.

9007-16, Session 6

Experimental demonstration of NG-PONs power budget enhancement techniques

Ali Emsia, Technische Univ. Darmstadt (Germany) and The Univ. of Arizona (United States); Mohammadreza Malekizandi, Dieter Briggmann, Quang Trung Le, Technische Univ. Darmstadt (Germany); Ivan B. Djordjevic, The Univ. of Arizona (United States); Franko Küppers, Technische Univ. Darmstadt (Germany)

Based on today's bandwidth demand, Next Generation Passive Optical Networks (NG-PONs) systems require higher bandwidth, longer reach, and more number of customers. The bandwidth demand of customers has evolved from ordinary telephone services to Internet, video, Web, online gaming applications, a few to be mentioned. To meet such a traffic demand is quite an effort, while reducing the cost of network deployments. Different technologies proposed to leverage the rate from 10G to 40G. Wavelength Division Multiplexing (WDM) PON can be used to achieve this rate. WDM technology delivers higher bandwidth for both upstream and downstream transmission. Furthermore, it can bring point-to-point connectivity to different remote locations, Quality of Service (QoS) is guaranteed owing to dedicated bandwidth, higher security, and low Optical Distribution Network (ODN) loss will be expected.

In this paper, we experimentally investigate power budget extension

configurations for Nx10 Gbps NG-PONs. We consider Differential Phase Shift Keying (DPSK), Differential Quadrature Phase Shift Keying (DQPSK), and Orthogonal Frequency Division Multiplexing (OFDM).

Our budget enhancement techniques are based on Semiconductor Optical Amplifier (SOA) and Erbium Doped Fiber Amplifier (EDFA). We thoroughly study which configuration is suitable for aforementioned modulation formats and select the best technique for future PON systems. And, we show that the proposed configurations comply with current standards such as XG-PON1.

9007-17, Session 6

Power budget extension for higher-order modulation formats in PONs

Mohammadreza Malekizandi, Ali Emsia, Dieter Briggmann, Quang Trung Le, Technische Univ. Darmstadt (Germany); Ivan B. Djordjevic, The Univ. of Arizona (United States); Franko Küppers, Technische Univ. Darmstadt (Germany)

As demand for higher bandwidth is drastically increasing, frequency efficiency is going to be an issue in Passive Optical Networks (PONs). Moreover, network operators plan to reduce the number of central offices (COs) while extending the reach of the optical links, this enables them to reduce the deployment costs. This paper demonstrates the advantages of advanced modulation formats and a suitable configuration for the power budget enhancement of hybrid Wavelength Division Multiplexing Time Division Multiplexing-Passive Optical Networks (WDM-TDM-PON). The proposed technique can offer higher data rate, better bandwidth efficiency, and large number of customers. Differential (Quadrature) Phase Shift Keying (DQPSK) signals and Orthogonal Frequency Division Multiplexing (OFDM) will be considered. Simulations are performed using different modulation formats to evaluate the behavior of the proposed PON extender. Finally, Transmission of 1 Tbps WDM/TDM-OFDM-PON over 60 km optical link is presented here. The simulation results, prove that 1600 users can be covered with 40 Gbps peak data rate.

9007-18, Session 7

Multi-band multi-service sensing: metamaterials myth and reality *(Invited Paper)*

Mohsen Kavehrad, The Pennsylvania State Univ. (United States)

Demands by the communications industry for greater bandwidth push the capability of conventional wireless technology. Part of the Radio Spectrum that is suitable for mobility is very limited. Higher frequency waves above 30 GHz tend to travel only a few miles or less and generally do not penetrate solid materials very well.

Unmanned Aerial System applications require electronic scanning antenna capabilities, in challenging environmental conditions, over very large bandwidths. In addition to that, it is desirable to have as much reduction as possible in size, weight, power and cost.

Metamaterials are recently being introduced by periodic repetition of some inclusions in a host medium, which may be described as effective media characterized by a set of equivalent constitutive parameters. Self-similarity in creating periodic structures is the basis of building volume or 2D holographic components. The latter does more than periodic repeats. Similar, but more advanced concepts (fractal in nature) are used to model phase screens used in modeling the atmospheric turbulence.

Unfortunately, metamaterials (MTMs) are anisotropic (direction-dependent) and this makes their application limited in terms of use as antennas for mobile platforms. However, conceptually, controlled-anisotropy can be applied to make phased-arrays, beam-forming, and beam scanning. This issue then begs the question of cost comparison with conventional materials that can be found in nature, e.g., low-cost optics lenses, or conventional RF scanning antennas.

As for lensing and fixed platform imaging, the story is very different, as super-lens is expected to be a byproduct.

Nevertheless, even if metamaterials become readily available, the atmosphere around the globe cannot be replaced. Neither, broadband wireless connectivity to a mobile can be achieved via fiber optics.

This paper, presents a Hybrid radio-frequency (RF) and Wireless Optical solution to provide adaptive sensing in an opportunistic fashion, with or without metamaterials. A byproduct of the latter will be broadband and reliable global connectivity.

9007-20, Session 7

Four-channel CWDM system design for multi-Gbit/s data communication via SI-POF

Mladen Joncic, Matthias Haupt, Ulrich H. P. Fischer, Hochschule Harz (Germany)

Polymer Optical Fibers (POF) have advantages over alternative data communication media such as glass fibers, copper cables, and wireless systems. They are e.g. pliable, durable, and cost effective, has small weight and short bend radius. Due to their advantages, POFs are a promising candidate for broadband in-house networks. To increase the capacity of a single POF, multiple bandwidth-efficient channels can be transmitted over the same fiber. The technique is known as wavelength division multiplexing (WDM).

This paper reports on the current development status of a four-channel coarse WDM (CWDM) transmission system for Multi-Gbit/s in-house data communication via SI-POF. The block diagram of the experimental setup and the complete description of established communication system will be given in the full paper. The key photonic component in a CWDM system under development is a demultiplexer (DEMUX). To spatially separate different wavelength channels, a four-channel DEMUX with low insertion loss (<5 dB) and low crosstalk (<-30 dB) is realized in bulk optics technology at the Harz University. The operating principle, the description of the opto-mechanical setup, and the transfer function of the DEMUX will be shown. In addition, an optical link power budget analysis, based on the experimentally obtained data, will be carried out for all four channels. Finally, Multi-Gbit/s data transmission experiments will be performed with violet, blue, green, and red laser diodes via up to 50 m SI-POF links, and the results and their analysis will be presented.

9007-21, Session 7

Gaussian mixture sigma-point particle filter for optical indoor navigation system

Weizhi Zhang, Wenjun Gu, The Pennsylvania State Univ. (United States); Chunyi Chen, Changchun Univ. of Science and Technology (China); M. I. Sakib Chowdhury, Mohsen Kavehrad, The Pennsylvania State Univ. (United States)

With the fast growing and popularization of smart computing devices, there is a rise in demand for accurate and reliable indoor positioning. Recently, systems using visible light communications (VLC) technology have been considered as candidates for indoor positioning applications. A number of researchers have reported that VLC-based positioning systems could achieve position estimation accuracy in the order of centimeter.

This paper proposes an Indoors navigation environment, based on visible light communications (VLC) technology. Light-emitting-diodes (LEDs), which are essentially semiconductor devices, can be easily modulated and used as transmitters within the proposed system. Positioning is realized by collecting received-signal-strength (RSS) information on the receiver side, following which least square estimation is performed to obtain the receiver position.

To enable tracking of user's trajectory and reduce the effect of wild values in raw measurements, different filters are employed. In this paper, by computer simulations we show that Gaussian Mixture Sigma-Point Particle Filter (GM-SPPF) outperforms other filters such as basic Kalman filter and sampling importance-resampling particle filter (SIR-PF), at a reasonable computational cost.

9007-22, Session 7

Visible light indoor positioning system based on gain difference between tilted multiple optical receivers

Se-Hoon Yang, Eun-Mi Jeong, Hyun-Seung Kim, Yong-Hwan Son, Sang-Kook Han, Yonsei Univ. (Korea, Republic of)

Novel concept for integrating visible light produced by LEDs with indoor positioning using tilted multiple optical receivers is presented in this paper. Generally, positioning system based on visible light communication (VLC) estimates transmission distance through received signal strength (RSS), which is based on intensity modulation and direct detection (IM/DD) method. In order to estimate position using trilateration through transmission distances, receiver needs to know the positions of three or more reference nodes. Thus, the system has limitation that optical receiver should receive signals from at least three different transmitters without interference. For this reason, a carrier allocation or TDM technique have been utilized and positioning area is limited by overlapped area of different transmitters. Furthermore, additional information on characteristics of transmitter, which have a decisive effect on signal strength, is required even though the inter-cell interference problem is solved because the characteristics of transmitters can be varied for different indoor environments.

We propose an artificially tilted multiple optical receivers structure to control incidence angle gain and positioning algorithm using the received power difference. PDs are densely placed, thus, transmission distances between LED and PDs and radiation angles are the same. Inter-cell interference is fundamentally removed and positioning area is extended when compared with previous researches. In order to estimate the position, the transmitter's location code from single LED was received using multiple optical receivers. The validity of the proposed scheme was experimentally demonstrated by determining the local position of single transmitter and angle gain profile of receivers.

9007-26, Session PWed

Broadband transceiver design of distributed amplify-and-forward MIMO relays in correlated channels

Chia-Chang Hu, Kang-Tsao Tang, National Chung Cheng Univ. (Taiwan)

Combined optimization of the source precoder, relay weighting matrices, and destination decoder is proposed in dual-hop amplify-and-forward (AF) multiple-input multiple-output (MIMO) multiple-relay networks with the source-to-destination link in correlated channels. This broadband cooperative transceiver design is studied based on the minimum mean-squared error (MMSE) criterion under correlated fading channels. The optimization problem belongs neither concave nor convex so that an iterative nonlinear matrix conjugate gradient (MCG) search algorithm is applied to explore local optimal solutions. Simulation results show that the broadband cooperative transceiver joint architecture performs better the non-cooperative transceiver design in terms of the bit-error-rate (BER).

9007-23, Session 8

Experimental validation of a delay-line interferometer based in-band OSNR monitor using a multivariable control system

Ahmed S. Almaiman, Mohamed R. Chitgarha, Wajih A. Daab, Morteza Ziyadi, Amirhossein M. Ariaei, The Univ. of Southern California (United States); Wendy X. Zhao, Vijay Vusirikala, Google (United States); Alan E. Willner, The Univ. of Southern California (United States)

Optical performance monitoring has recently received much interest as network operators and equipment manufacturers are increasingly seeking to utilize inexpensive and stable monitors throughout the network. One of the most basic parameters indicating optical system performance is the optical signal-to-noise ratio (OSNR). OSNR monitoring system using a delay-line interferometer (DLI) cascaded with a filter has recently been demonstrated for various modulation including quadrature-phase-shift-keying (QPSK) and quadrature-amplitude-modulation (QAM) formats. This technique showed OSNR measurement accuracy of less than 0.5 dB error at 22 dB OSNR for 200Gb/s signals; however, maintaining the stability of the OSNR monitor, tuning the system to the desired optical channel, and controlling the different parameters of the monitor module (i.e, DLI phase, filter wavelength, and reading photodiodes) requires a multivariable control system of the optical performance monitor. In this paper, we take advantage of a microcontroller and low cost electronics to: 1) move the tunable filter to the desired wavelength; 2) tune the DLI phase; 3) measure the optical power on the DLI constructive and destructive ports with <0.1 dB error; and 4) perform OSNR calculations with < 0.5 dB error. Before the OSNR measurements, the system performs the initial calibration routine to find the signal and noise coherence distribution factors. After examining the performance of the proposed system, we provide a study of the accuracy, stability, and latency of the optical performance monitor. We also study the future field deployability of the system by providing the necessary control functions.

9007-24, Session 8

Linearized broadband optical detector: study and implementation of optical phase-locked loop

Janusz A. Murakowski, Garrett J. Schneider, Univ. of Delaware (United States); Christopher A. Schuetz, Univ. of Delaware (United States) and Phase Sensitive Innovations (United States); Shouyuan Shi, Dennis W. Prather, Univ. of Delaware (United States)

Optical phase-locked loop (OPLL) is used to improve linearity of an optical link for transmission of analog signals. The finite loop delay and the presence of a low-pass filter, required for the stable loop operation, lead to a nontrivial frequency response. Here, we investigate the frequency-dependence of linearity improvement in OPLL in detail. To this end, we derive a nonlinear differential equation governing the dynamics of OPLL and use this equation to predict both the linearity improvement and the stability condition. We show that at low frequencies, within the bandwidth of the loop filter, the linearity improvement as measured by the increased spur-free dynamic range (SFDR) is approximately constant, and equal to the value obtained for instantaneous feedback. At higher frequencies, the linearity improvement degrades, and at very high frequencies the advantage offered by OPLL disappears. The detailed behavior in the transition frequency region is a function of the linearity improvement at low frequency. Furthermore, we find a simple, closed-form relation among the loop delay, the open-loop gain, and the loop-filter bandwidth that must be satisfied for stable operation of the OPLL.

We propose an OPLL configuration with the shortest delay, and therefore highest possible linearity improvement over the widest bandwidth, to date.

9007-25, Session 8

Low-frequency analog signal distribution on digital photonic networks by optical delta-sigma modulation

Atsushi Kanno, Tetsuya Kawanishi, National Institute of Information and Communications Technology (Japan)

A real-time surveillance of a social mass behavior or imaging of nature against a disaster requires a distributed sensor network, so-called machine-to-machine network, with accurate time stamps. Nowadays, a global positioning system or a standard time and frequency radio signal provide accurate clock for the devices. However, at a basement or tunnels, these signals could not be delivered. A radio-over-fiber technology is a promising candidate to provide the signal to the radio dead zone, but the analog-based optical link is easily perturbed by external environments such as vibrations. On the contrary, additional digital signal processors (DSPs) are indispensable to generate the analog signal on a conventional binary optical link.

We propose a binary optical signal transmission system with a sigma-delta modulation utilized for a high-speed analog-to-digital converters and a slow-speed photodetector for direct conversion from the binary to an analog radio signal. A 10-Gb/s XFP optical transceiver, which was connected with the DSP-based sigma-delta modulator, provided the binary signal, and transmitted over the fiber to a low-bandwidth photodetector, whose typical bandwidth was much less than 1 GHz, for direct conversion to an analog signal. The observed phase noise of the sinusoidal signal was much less than -100 dBc/Hz at the offset frequency of 100 kHz.

The proposed system for distribution of the low frequency analog signals on a photonic digital network is capable for clock signal distribution at a radio dead zone as well as for a high-quality audio signal transmission for a next generation theater.

9008-1, Session 1

Photonic networks that exploit digital coherent technologies *(Invited Paper)*

Yojiro Mori, Ken-ichi Sato, Nagoya Univ. (Japan)

Digital coherent optical transmission technologies have recently been introduced to the world. They can fully utilize the information of the optical electric field, which enables us to develop spectrally-efficient transmission systems by means of polarization-division multiplexing and multilevel-modulation formats such as quadrature-phase-shift keying (QPSK) and higher-order quadrature-amplitude modulation (QAM). Thanks to the recent rapid advances in the research and development of electronics, demodulation of these signals can be realized effectively by utilizing sophisticated digital signal processors (DSPs). Additional signal processing e.g. dispersion compensation can also be done in the digital domain. Such digital coherent technologies have successfully been implemented in commercial systems. However, transmission performances of photonic networks are limited by system impairments that include intra- and inter- band crosstalk, spectrum squeezing caused by optical add/drop multiplexers (OADM), and the nonlinearity of optical fibers. Current digital coherent technologies do not resolve these problems comprehensively, which necessitates further research. In this paper, we investigate the impacts of the system impairments through extensive computer simulations and show the maximum transmission distances of multilevel-coded signals. Various transmission systems applied for gridless networks and Nyquist wavelength-division-multiplexing (WDM) networks, which need digital coherent technologies, are evaluated. We also discuss DSP algorithms that are suitable for each network and permit digital coherent technologies to become more versatile tools in the creation of future photonic networks.

9008-2, Session 2

Universal transmitter for wireless and optical access converged networks *(Invited Paper)*

Quang Trung Le, Franko Küppers, Technische Univ. Darmstadt (Germany)

In the last decades, both optical and wireless technologies have been employed to deliver high QoS-access and bit rates of hundreds of Megabits per second, responding to the explosion of bandwidth demand in last-mile connections. The convergence of optical and wireless technologies will open a new era of the future internet which offers high data rate connections to everyone, everywhere and with any kind of connection media. The integration of ultrawideband-over-fiber into passive optical network (PON) is therefore of great interest when it benefits the high bandwidth capability from optical network technologies and the high flexibility from wireless network technologies. This approach consists of the implementation of UWB antennas as network terminations in PON architectures, especially in wavelength division multiplexing PON (WDM PON) which will be, by worldwide consensus, the future generation of optical access network. This later can only be done with a reasonable cost when a universal optical transmitter, which is capable of generation both UWB and WDM PON signals, is available. Direct modulation of semiconductor laser was demonstrated to be suitable for high bit-rate PON systems, however the generation of UWB signals by this technique is still challenging. In this paper, using the chirp properties of directly modulated semiconductor lasers, UWB signals is generated. Different UWB signal waveforms and polarities are obtained and the received electrical spectra conforms to the requirements of indoor UWB systems. The effect of chromatic dispersion on UWB waveforms is analyzed in order to properly transmit UWB signals through WDM PON infrastructure.

9008-3, Session 2

Comparison of discrete multi-tone and pulse amplitude modulation for beyond 100 Gbps short-reach application

Masato Nishihara, Yutaka Kai, Toshiki Tanaka, Tomoo Takahara, Fujitsu Labs., Ltd. (Japan); Lei Li, Weizhen Yan, Fujitsu Research and Development Center Co., Ltd. (China); Bo Liu, Fujitsu Labs., Ltd. (China); Zhenning Tao, Fujitsu Research and Development Center Co., Ltd. (China); Jens C. Rasmussen, Fujitsu Labs., Ltd. (Japan)

Demand on the traffic of optical transmission system is growing continuously and beyond 100 Gbps system is strongly expected for both core network and short reach application. Especially, for short reach application, a single wavelength system is desirable because high simplicity and low cost are important as well as the high capacity. Advanced multi-level modulation is an attractive solution for short reach application because of its high spectral efficiency. Discrete multi-tone (DMT) technique and pulse amplitude modulation (PAM) technique are the strong candidates of advanced modulation method.

DMT technique is multi-level and multi-carrier modulation technique, which transmits data only by the real part and does not use the imaginary part. It is widely employed in the DSL system from its simple configuration. Recently, several works introduce DMT technique to the optical transmission to achieve the simple and cost effective system. PAM technique is the multi-level modulation, which encodes data in the amplitude of a series of signal pulses. Both techniques can be realized by simple configuration using digital signal processing.

We compared the 100 Gbps transmission characteristics of DMT and PAM by simulation and experiment. The comparison was done by using same devices and the digital signal processing was changed to clarify the features of the modulation formats. We studied the transmission distance dependence for 0.5 to 40 km. Impact of the frequency responses of the optical devices were also studied. Finally we discuss the features of the both modulation techniques from the viewpoint of the short reach optical transmission.

9008-4, Session 3

Compact optical devices for high-speed digital coherent link *(Invited Paper)*

Shin Kamei, NTT Photonics Labs. (Japan)

Digital coherent technology based on multi-level modulation formats and coherent detection with digital signal processing is thought as an attractive solution for high-speed short/middle-range links as well as long distance transmissions. This paper describes recent progress in relation to the key optical devices for high-speed digital coherent transmission, namely coherent receivers, advanced-format modulators and related components. Miniaturization and higher performance have been achieved on silica-based planar lightwave circuit (PLC) platform and its integration with other key materials.

9008-5, Session 4

Analysis and characterization of semiconductor optical amplifiers for application in photonic switching networks

Phillip RudgeBarbosa, Decio Maia Jr., Edson Moschim, Univ. Estadual de Campinas (Brazil)

Despite many possible functionalities in amplification, switching and lambda conversion semiconductor optical amplifiers [1-4], may reveal performance limitations in system applications. The practical use of SOAs requires then a thorough understanding and characterization of the devices, so that the interplay of various parameters and dynamic features can be evaluated. It is our interest to apply SOA devices as high performance photonic switches in optical packet (OPS) and burst (OBS) switching networks [3,4].

In the present work we investigate the combination of amplification and switching functions within the same scope. This includes ASE (amplified spontaneous emission) accumulation when multihopping over various optical nodes occurs in OPS/OBS networks. It will be clear that ASE and noise accumulation, not power budget, will limit the network's extension. Results of the operation of SOAs as photonic gates is presented with very fast rise-fall times, excellent extinction ratio and relatively low noise. Then we show a deeper insight into the SOAs characteristics, including spectral amplification and noise figures using different laser sources and variable input and operation powers. Results are discussed in detail, and several conclusions follow.

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9008-6, Session 5

Tunable 1550nm VCSELs using high-contrast grating for next-generation networks *(Invited Paper)*

Christopher Chase, Yi Rao, Michael Huang, Bandwidth10 (United States); Connie J. Chang-Hasnain, Univ. of California, Berkeley (United States)

Low cost tunable lasers are highly desirable for many applications such as WDM-PON and WDM links in data centers. Tunable lasers give systems designers much more flexibility in their system design as well as allow for lower cost of ownership as they allow a single laser to transmit on many channels, reducing the number of spares that need to be stocked and allowing for remote reconfiguration of a transceiver's wavelength, enabling new system architectures. We demonstrate wavelength-tunable VCSELs operating at 1550 nm using high contrast gratings (HCGs) as the top output mirror on VCSELs. Tunable HCG VCSELs with a ~25 nm mechanical tuning range and over 2 mW output power were realized. Error-free operation of an optical link using directly-modulated tunable HCG VCSELs transmitting at 1.25 Gbps over 10 channels spaced by 100 GHz and transmitted over 25 km of single mode fiber is demonstrated, as well as 3.5 Gbps over 4 channels, showing the suitability of the wavelength-tunable HCG VCSEL as a low cost source for WDM communications systems in PON and data center applications. Preliminary wavelength stability study shows <100 pm drift through 185 billion cycles of the tuning mechanism. Additionally, we will show fixed wavelength HCG VCSELs operating error free over a 80 km single mode fiber link at 10 Gbps and discuss progress toward 10 Gbps wavelength-tunable VCSELs for data center and access network applications. Tunable HCG VCSELs have much potential in next generation DWDM communications systems in access networks and data centers.

9008-7, Session 6

A hybrid optical switch architecture to integrate IP into optical networks to provide flexible and intelligent bandwidth on demand for cloud computing

Wei Yang, Trevor J. Hall, Univ. of Ottawa (Canada)

With the increasing deployment of public and private clouds, the nature of the Internet traffic has undertaken a fundamental transformation from a pure packet-based pattern to today's predominantly flow-based pattern. Consequently, the current Internet infrastructure cannot continue to adequately serve cloud traffic. Routers, well optimized to cope with packets yet being used today, are a poor fit for traffic flows. An infrastructure that integrates simple flow aggregation technology with optical express will help cope with both the growth of the Internet traffic and the uncertain increase of flow patterns in the future.

In this work, we propose an optical switch architecture that has an electronic control plane, and a photonic and electronic hybrid data plane to provide flexible and intelligent bandwidth on demand in the next generation Internet infrastructure. The hybrid data plane of the optical switch architecture consists of a reconfigurable optical add/drop module (ROADM) and load-balanced packet switch modules. This data plane aims to provide flexible and cost-effective services for the Internet data flows. The electronic control plane of the hybrid optical switch architecture is responsible for signaling and reservation to offer intelligent and dynamic service provisioning. By interoperating with the inter domain control system presented in our previous work at PhotonicsWest2013, the hybrid optical switch architecture integrates IP into optical networks. This proposal greens the Internet infrastructure from the current layer-in-layer design to a fully integrated IP optical networking, and offers guaranteed end-to-end service for traffic between data centers and from data centers to end users.

9008-8, Session 6

A design for an internet router with a digital optical data plane *(Invited Paper)*

Joe Touch, The Univ. of Southern California (United States); Joseph Bannister, The Aerospace Corp. (United States); Stephen Suryaputra, Alan E. Willner, The Univ. of Southern California (United States)

This paper presents a complete design for an optical Internet router based on decomposing the steps required for IP packet forwarding. Implementations of hopcount decrement and header matching are integrated with a simulation-based approach to variable-length packet merging that avoids recirculation, resulting in an all-optical data plane. A method for IPv4 checksum computation is introduced, and this and previously designed components are extended from binary to higher-density (multiple bits per symbol) encodings. The implications of this design are considered, including the potential for chip-level and system integration, as well as the requirements of basic optical processing components.

9008-9, Session 7

High-performance transmission in analog photonic links *(Invited Paper)*

Zhiyu Chen, Lianshan Yan, Hengyun Jiang, Jia Ye, Wei Pan, Bin Luo, Xihua Zou, Southwest Jiaotong Univ. (China)

Analog photonic link (APL) has been considered to be a promising technique due to the low insertion loss, broad bandwidth and immunity to electromagnetic interference. It is essential for many microwave systems, such as avionics, modern electronic warfare, and wireless communication systems. However, polarization effect, chromatic dispersion (CD), fiber Kerr effect and RF nonlinearity are four main problems in APL. All of them degrade the performance of the link. Therefore, APL needs to be optimized according to the different requirements in various applications. In this paper, we firstly have established a propagation model and provided the general expressions for the analog signal in photonic link based on coupled-mode theory and the small-signal analysis. Such model could describe the interaction of polarization effect, CD and nonlinearity. In addition, we also have investigated different compensation schemes for these impairments, such as CD compensation based on pre-distortion or modulation diversity transmitter, nonlinearity compensation using phase modulator and optical filter, and simultaneous compensation for both of them based on mixed polarizations. After compensations, the spurious-free dynamic range (SFDR) of the link could be improved greatly. Furthermore, recent experimental results show that APL might be a support technique for the 4G or higher speed optical-wireless communication systems in near future.

9008-10, Session 7

Green photonics realized by optical complex systems

Hiroto Nanri, Wakao Sasaki, Doshisha Univ. (Japan)

We have experimentally demonstrated a new smart grid model which supply and distribute DC electric power and can control electric power flow autonomously among individual homes, by using an optical self-organized node with optical non-linear characteristics based on optical complex systems, and these homes are assumed to be installed by distributed power supplies such as photovoltaics or wind power generation, and electric power storage devices, and also supposed to be supplied partly by the commercial electric power grid utilities.An electric power network is composed of nodes and devises called Power Gate Unit (PGU).?The nodes have optical nonlinearity for self-organizing information about surplus or shortage of electric power as to individual homes. Informations about surplus or shortage of electric power are sent from any two separated nodes of the network so that these informations are to be adaptively selected while passing each node, and finally one optimum routing of the minimum transmission loss between original two sources should be established. The PGU is a distributing unit of actual electric power based on information about surplus or shortage of electric power at each individual home. The PGU at each home is electrically connected to both the onsite power supplies and household load such as a photovoltaic solar panel, a DC motor, and a storage battery as well as the commercial electric power grid utilities. In this work, we composed our experimental self-organized DC power grid with above components and supposed the supplied maximum power from the commercial electric power grid utilities to be limited to 5V-0.5A. The PGU has the function to discriminate surplus or shortage electric power of the solar panel or the storage battery. According to the discriminations, the PGU distributes electric power of solar panel or the storage battery to the household load, otherwise PGU accepts electric power sent from other PGU's through network nodes. We set limited value of current flow to 0.1A fed to the individual household load, in our experiments a DC motor, by using a current limitation circuit in PGU. In this network, information about surplus or shortage of electric power will propagate through the nodes. In the experiments, surplus electric current 0.4A at a particular node was distributed toward a PGU of another node suffering from shortage of electric current. We also confirmed in the experiments and simulations that even when signal propagation path was disconnected accidentally the network could recover an optimized path. The present smart grid system we have attained may be applied by optical fiber link in the near future because our essential components controlling PGU, i.e. the nodes are electro-optical hybrid which are easily applicable to fiber optical link so as to control electric power transmission line.

9008-11, Session 7

Latency causes and reduction in optical metro networks *(Invited Paper)*

Vjaceslavs Bobrovs, Sandis Spolitis, Girts Ivanovs, Riga Technical Univ. (Latvia)

The dramatic growth of transmitted information in fiber optical networks is leading to a concern about the network latency for high-speed reliable services like financial transactions, telemedicine, virtual and augmented reality, surveillance, and other applications. In order to ensure effective latency engineering, the delay variability needs to be accurately monitored and measured, in order to control it. This paper in brief describes causes of latency in fiber optical metro networks. Several available latency reduction techniques and solutions are also discussed, namely concerning usage of different chromatic dispersion compensation methods, low-latency amplifiers, optical fibers as well as other network elements.

9008-12, Session 7

Optimization in spectrum-sliced optical networks *(Invited Paper)*

Karcius Day Rosario Assis, Federal Univ. do Recôncavo of Bahia (Brazil); Alex Ferreira dos Santos, Univ. Estadual de Campinas (Brazil); Raul C. Almeida Jr., Univ. Federal de Pernambuco (Brazil)

Current communication in optical networks presents a wide range of granularities, making it hard to use the optical spectrum efficiently under the WDM framework. In Spectrum Sliced Optical Networks, the WDM rigid frequency grid is replaced by a more flexible structure, in which the spectrum is organized in frequency slots, and each traffic flow is assigned to an appropriate set of contiguous slots. The classical RWA problem is then replaced by a Routing and Spectrum assignment (RSA) problem. This paper addresses optimization techniques in elastic networks. We have proposed a novel routing scheme based on Spectrum-Elastic Optical Path Networks technical features. We have built numerical example to illustrate the performance of our routing approach. Comparing to other routing techniques our approach save more bandwidth on the spectrum.

9008-13, Session 7

Distributed optical multiplexing with precise frequency allocation using fiber frequency conversion *(Invited Paper)*

Tomoyuki Kato, Ryo Okabe, Shigeki Watanabe, Fujitsu Labs., Ltd. (Japan)

No Abstract Available

9008-14, Session 8

Multidimensional SPC-based bit-interleaved coded-modulation for spectrally-efficient optical transmission systems *(Invited Paper)*

Hussam G. Batshon, Hongbin Zhang, Tyco Electronics Subsea Communications (United States)

With the exponential growth of global internet traffic, it becomes important to increase spectral efficiency for transmission systems in order to meet the challenge of continuing capacity growth. Polarization-division multiplexing (PDM) and multi-level quadrature-amplitude modulation (QAM) such as 16-QAM and above allow spectral efficiencies beyond 4 b/s/Hz. However, for long-haul optical transmission systems, performance is penalized by amplified spontaneous emission noise like AWGN channel, carrier phase fluctuations and nonlinearity interference. The decreased Euclidean distance between each signal point in the constellation in high-level QAM reduces tolerance to phase noise and nonlinearity distortion. Such reduction in tolerance causes extra implementation penalty in high-level QAM modulation and limits the transmission distance. In order to counteract this penalty, coded modulation is used. In coded modulation, part of the redundancy that is usually assigned to forward-error correction (FEC) is moved into symbol modulation to increase the minimum Euclidean distance of a received sequence of symbols. Demodulation is done by a multi-symbol soft-decoder using either maximum likelihood or maximum a posteriori algorithm. In recent publications, LDPC-based bit-interleaved coded-modulation (BICM) with iterative soft-demapping and decoding proved that it can approach the capacity of AWGN channel, hence increase achievable transmission distance. We review different multidimensional single-parity check (SPC)-based BICM schemes suitable for high spectral efficiency transoceanic transmission systems, and their experimental verification.

9008-15, Session 8

Digital signal processing for high spectral efficiency optical networks *(Invited Paper)*

Junwen Zhang, Jianjun Yu, ZTE USA (United States) and Fudan Univ. (China); Nan Chi, Fudan Univ. (China)

Digital signal processing (DSP) for high spectrum efficiency transmission system are investigated in both long-haul and short haul optical networks. For long-haul transmission, two different super-Nyquist WDM systems based on advanced post (receiver side) and pre (transmitter side) DSP are demonstrated and studied. A novel DSP scheme for this optical super-Nyquist filtering 9-QAM like signals based on multi-modulus equalization (MMEQ) without post filter are proposed and experimentally demonstrated, which directly recovers the Nyquist filtered QPSK to a 9-QAM like signal. This improved filtering tolerance and transmission performance are demonstrated in an 8-channel 112-Gb/s wavelength-division-multiplexing (WDM) experiment with a 25GHz-grid over 2640-km single-mode fiber (SMF). Alternatively, a novel digital super-Nyquist signal generation scheme is proposed to further suppress the Nyquist signal bandwidth and reduce the channel crosstalk without using optical pre-filtering and using. Only optical couplers are needed for super-Nyquist WDM multiplexing. Using this scheme, we successfully generate and transmit 10 channel 32-GBaud (128-Gb/s) PDM-9-QAM signals within 25-GHz grid over 2975-km at a net SE of 4 bit/s/Hz (after excluding the 20% soft-decision FEC overhead). We extend the DSP for short haul optical transmission networks by using high order QAMs. We propose and experimentally demonstrate a high speed CAP-64QAM system using direct modulation laser (DML) based on direct detection and digital equalizations. Decision-directed least mean squares (DD-LMS) are used to equalize the CAP-64QAM. Using this scheme, we successfully generate and transmit up to a record 60-Gb/s CAP-64QAM over 20-km stand single-mode fiber (SSMF) based on the DML and direct detection.

9008-16, Session 8

Blocking analysis of dynamic routing, wavelength assignment, and spectrum allocation in flexible grid WDM networks

Ankitkumar N. Patel, Philip N. Ji, NEC Labs. America, Inc. (United States); Jigarkumar S. Patel, Jason P. Jue, The Univ. of Texas at Dallas (United States); Ting Wang, NEC Labs. America, Inc. (United States)

Metropolitan Area Networks (MANs) bridge traffic between access and core networks, and thus, the traffic in MANs is highly dynamic with diverse granularities. Flexible grid transport can support such traffic with higher spectral and energy efficiencies by provisioning transparent optical channels within optimum spectral widths based on offered line rates, modulation formats, and transmission reaches. In this paper, we introduce the flexible grid transport network architecture for MANs. We address the dynamic routing, wavelength assignment, and spectrum allocation problem, and conduct blocking analysis over ring and mesh network topologies. To estimate the blocking of point-to-point connections, we design a novel homogeneous irreducible Markovian model. The Markovian model concisely represents the states of an optical fiber, and accurately estimates their steady-state probabilities. We also develop an analytical model using the reduced load approximation technique and design the blocking estimation algorithm to estimate the blocking of multi-hop connections. The performance of the proposed Markovian and analytical models is evaluated through simulations over various networks offering different sets of line rates. The numerical results show that the proposed models provide reasonable estimation of blocking for connections those require smaller spectral width and for networks those are sparsely connected. Furthermore, this blocking estimation improves as the required spectral width for connections increases and networks become dense. The state space complexity of the Markovian model is linear and the convergence time of the analytical model is short. These models are applicable to estimate the network capacity in the design phase of metro networks.

9008-17, Session 8

Toward ultra-broadband elastic optical networks: reconfigurable quasi-Nyquist transmitter for metro- and long-haul scenarios *(Invited Paper)*

Neil Guerrero Gonzalez, Carolina Franciscangelis, Luis H. H. de Carvalho, Edson P. da Silva, Júlio C. M. Diniz, Júlio César R. F. de Oliveira, CpqD (Brazil)

Elastic optical networks are being currently investigated as flexible transmission systems able to support dynamic bandwidth demands from future Internet applications such as IPTV, video on demand and cloud computing. As next generation ultra-dense wavelength division multiplexing (UD-WDM) systems, elastic optical networks maximize spectrum-efficiency and system-bandwidth utilization based on flexible accommodation of diverse traffic demands. Therefore, research on novel network architectures and system components such as data-rate variable transponders, hybrid amplification schemes and broadband optical switches is expected to enhance network features such as resource management flexibility, geographical context adjustability and capacity system upgradeability from Gbps to Tbps. Future elastic optical network are envisioned in a flex-grid ROADM configuration, carrying out mixed modulation formats and bit rates. Moreover, reach-adaptable line rates based on bandwidth adjusting are expected to cover both metro and long-haul applications by a single optical fiber system infrastructure.
In this paper we report experimental validations on deployed Brazilian optical fiber of a data-rate variable transmitter, which provides high modulation formats with low spectral occupancy and allows applications

on different transmission networks scenarios. We report successful signal generation and transmission of both 3 x 224 Gb/s (spectral efficiency, SE, 6.25b/s/Hz) DP-16QAM and 3 x 112 Gb/s DP-QPSK quasi-Nyquist WDM systems (SE 3,41b/s/Hz), with a 700km and 4500km optical reach respectively.

9008-18, Session 9

Specialty optical fibers for mid-IR photonics *(Invited Paper)*

Bishnu P. Pal, Ajanta Barh, Somnath Ghosh, Ravendra K. Varshney, Indian Institute of Technology Delhi (India)

In this talk we would present our recent extensive work on designs of a variety of application-specific specialty optical fibers for use at the mid-IR wavelengths. These ranged from chalcogenide and soft glass-based fibers for realizing all-fiber mid-IR light sources through wavelength translation using commercially available pump sources, generation of supercontinuum light in the mid-IR region, generation of parabolic pulses exploiting similariton concept, ultra-large mode effective area fibers for large throughput and power transmission, etc. Designs revolve around management of nonlinearity, loss and dispersion and should in principle find application also in futuristic optical communication for overcoming capacity crunch.

9008-19, Session 9

Parametric spectro-temporal analyzer (PASTA) for ultrafast optical performance monitoring *(Invited Paper)*

Chi Zhang, University of Hong Kong (Hong Kong, China); Kenneth K. Y. Wong, The Univ. of Hong Kong (Hong Kong, China)

No Abstract Available

9008-20, Session 9

Flat amplification over C-band by quasi phase-matched fiber optical parametric amplifier using pump-phase shifers *(Invited Paper)*

Shigehiro Takasaka, Furukawa Electric Co., Ltd. (Japan)

No Abstract Available

9008-21, Session 9

Optical beat interference noise reduction in OFDMA optical access link using self-homodyne balanced detection

Sang-Min Jung, Yong-Yuk Won, Sang-Kook Han, Yonsei Univ. (Korea, Republic of)

A Novel technique for reducing the OBI noise in optical OFDMA-PON uplink is presented. OFDMA is a multiple-access/multiplexing scheme that can provide multiplexing operation of user data streams onto the downlink sub-channels and uplink multiple access by means of dividing OFDM subcarriers as sub-channels. The main issue of high-speed, single-wavelength upstream OFDMA-PON arises from optical beating interference noise. Because the sub-channels are allocated dynamically to multiple access users over same nominal wavelength, it generates the optical beating interference among upstream signals.

In this paper, we proposed a novel scheme using self-homodyne balanced detection in the optical line terminal (OLT) to reduce OBI noise which is generated in the uplink transmission of OFDMA-PON system. When multiple OFDMA sub-channels over the same nominal wavelength are received at the same time in the proposed architecture, OBI noises can be removed using balanced detection. Using discrete multitone modulation (DMT) to generate real valued OFDM signals, the proposed technique is verified through experimental demonstration.

9008-22, Session 10

Low-cost 10G optical line terminal of WDM-PON for mobile backhaul application

Do-Won Kim, Jeong-in Kim, Jae Ho Song, Hee Yeal Rhy, Sang Jin Yoo, Gwang yong Yi, Ericsson-LG (Korea, Republic of)

The cost-effective optical line terminal (OLT) with data rate of 10 Gbps for WDM-PON system has been developed using VCSEL transmitter optical sub-assemblies (TOSAs). The OLT was designed for application to the mobile backhaul network multiplexing 32-ch of C-band wavelengths. The wavelengths of each channel of the VCSELs have been controlled for dense wavelength division multiplexing (DWDM) of 0.8 nm channel spacing through pulse width modulation (PWM) control of the bias current and temperature of each VCSEL. The thermo-electric cooler (TEC) has set the temperature of the VCSEL to be fixed and the bias current to VCSEL has been adjusted to precisely position the wavelength of VCSEL at the center wavelength of the arrayed wavelength grating (AWG) channel. The wavelength of the VCSEL has been detected with the monitor PD which is connected with 10:1 splitter to the common output port of the AWG. Two monitor schemes for the control of wavelength of VCSELs has tested and compared. One monitor structure has 32-ch of monitor PD for detection of each channel. The other structure has single monitor PD, which detects the dithering signal of 100 kHz supplied to each VCSEL successively with bias current. The electric filter and lock-in amplifier have used for the detection of the dithering signal. The microprocessor and a field programmable gate array (FPGA) are programmed for monitor and control of the wavelengths of VCSELs. The generated Ethernet data and pseudo random bit sequence (PRBS) signal with data rate of 10 Gbps processed the optical signal from VCSELs have been transmitted to the ROSA of the assembled OLT after passing through 20, 40 km with the bit error rate less than 10-9.

9008-23, Session 10

Optical OFDM transmission for long-haul, metro/access, and data center applications *(Invited Paper)*

Anand Srivastava, Indian Institute of Technology Mandi (India)

Optical orthogonal frequency division multiplexing (OFDM), initially was proposed for dispersion compensation in long-haul optical communications systems in 2006. Since then there has been extensive innovation towards developing intermediate forms of optical OFDM that are more suited to specific applications.

This invited talk presents on the developments of optical OFDM for Long-haul, metro/access and data center applications.

Long-haul optical transmission links are evolving more and more towards dynamically reconfigurable networks. OFDM has recently received a lot of attention as an effective technique to eliminate virtually all inter-symbol interference caused by chromatic dispersion and polarization mode dispersion. Furthermore, the confined and narrow spectrum of OFDM makes it an ideal candidate for networks with many reconfigurable optical add and drop multiplexers. OFDM-PON is now getting widely explored in the future metro-access network. The high performance network

which can be operated at >100 Gbps, spans up to 100 km provides for a variety of desirable characteristics including enhanced resource allocation flexibility, scalability and potentially lower equipment cost/complexity while also supporting multi-wavelength operation. In addition, the OFDMA-PON enables the convergence of the optical infrastructures with standard wireless services providing for the integration of wired and wireless technologies to form a hybrid access network to support ubiquitous broadband services. Next generation wireless back-hauling over the OFDMA-PON is also discussed with solutions being provided to facilitate this mechanism.

Finally, use of OFDM for increasing the capacity of multimode fiber (MMF) based optical interconnects for data center applications will be presented. This approach provides a solution to modulation bandwidth limitations of the lasers and to the intermodal dispersion of the MMF which leads to frequency-dependent attenuation.

9008-24, Session 10

Fibre-to-the-telescope: MeerKAT, the South African precursor to square kilometre telescope array (SKA) *(Invited Paper)*

T. B. Gibbon, E. K. Rotich, H. Y. S. Kourouma, R. R. G. Gamatham, A. W. R. Leitch, Nelson Mandela Metropolitan Univ. (South Africa); R. Siebrits, R. Julie, S. Malan, W. Rust, F. Kapp, T. L. Venkatasubramani, B. Wallace, A. Peens-Hough, P. Herselman, Square Kilometre Array (South Africa)

Scientific curiosity to probe the nature of the universe is pushing boundaries of big data transport and computing for radio telescopes. MeerKAT, the South African precursor to Square Kilometre Array (SKA), has 64 antennae separated by up to 12km. By 2018, each antenna will stream up to 160Gbps over optical fibre to a central computing engine. The antennae digitizers require accurate clock signals distributed with high stability. This paper outlines requirements and key design aspects of the MeerKAT network with timing reference overlay. Fieldwork results are presented into the impact of birefringence and polarization fluctuations on clock stability.

9009-1, Session 2

Sub-band wavelength conversion for terabit superchannel CO-OFDM networks

Shanhong You, Soochow Univ. (China); Chao Li, Qi Yang, Wuhan Research Institute of Posts and Telecommunications (China); Ming Luo, Wuhan Research Institute of Posts and Telecommunications (China); Ying Qiu, Xiao Xiao, Shaohua Yu, Wuhan Research Institute of Posts and Telecommunications (China)

A flexible and efficient channel bandwidth assignment is highly required for next optical generation networks. Among various techniques to enhance the wavelength routing capability, wavelength conversion plays an important role on improving network reconfigurability. In this paper, we experimentally demonstrate a sub-band wavelength conversion of a wide-band optical orthogonal frequency-division multiplexing (OFDM) signal based on four-wave mixing (FWM) using high-nonlinear fiber (HNLF) to solve the spectrum conflicts in the flexible coherent optical OFDM (CO-OFDM) networks. Combining with the wavelength selective switch (WSS) in a reconfigurable optical add/drop multiplexer (ROADM), some spectrum-overlapped sub-bands are successfully relocated to 'seamlessly' form a new wide-band signal, which efficiently eliminates the spectrum conflicts, and achieves a good spectral efficiency.

9009-2, Session 3

PLC-based mode multi/demultiplexer for MDM transmission *(Invited Paper)*

Nobutomo Hanzawa, Nippon Telegraph and Telephone Corp. (Japan); Kunimasa Saitoh, Hokkaido Univ. (Japan); Taiji Sakamoto, Takashi Matsui, Kyouzou Tsujikawa, Nippon Telegraph and Telephone Corp. (Japan); Masanori Koshiba, Hokkaido Univ. (Japan); Fumihiko Yamamoto, Nippon Telegraph and Telephone Corp. (Japan)

We propose a PLC-based multi/demultiplexer (MUX/DEMUX) for mode division multiplexing (MDM) transmission application. The PLC-based mode MUX/DEMUX can realize low insertion loss and a wide bandwidth of working wavelength. We designed a two-mode (LP01 and LP11 modes) and a three-mode (LP01, LP11, and LP21 modes) MUX/DEMUX using asymmetric parallel waveguide with a uniform height for MDM transmission in C-band. The mode multi/demultiplexing of the LP01 and LP11 modes can be realized by matching the effective indices of the LP01 and LP11 modes between parallel waveguides. That of LP21 mode also can be realized by matching the effective index and using the LP11b mode in a parallel waveguide with a uniform height. In this paper, we show an example of waveguide parameters and the numerical simulation results of the two-mode and three-mode MUX/DEMUX. Moreover, we fabricated the two-mode and three-mode MUX/DEMUX by using our designing waveguide parameter. As a result, we achieved a low insertion loss of <1.0 dB and high mode extinction ratio of >15 dB in two-mode MUX/DEMUX, and we realized the multi/demultiplexing of LP21 mode by using LP11b mode.

9009-3, Session 3

Optical XOR circuit using combined technology of photonics and electronics

Koichi Takiguchi, Ritsumeikan Univ. (Japan)

Digital signal processing technology in the optical domain is important for realizing various high-speed and low-power-consumption high-functionality which analogue signal processing cannot achieve. An exclusive OR (XOR) circuit is especially useful, which can achieve modulation and demodulation, encoding and decoding, error detection and correction, and a linear feedback shift register. I propose and demonstrate a novel and simple optical XOR circuit for binary signals, which is composed of a balanced photo-detector (PD) and an LN-based Mach-Zehnder intensity modulator. The intensity P1 and P2 of two optical signals into the balanced PD output an electrical signal whose amplitude E depends on their intensity combination. The XOR operation is achieved between P1 and P2, and E except that E becomes -1 in a case when P1 and P2 are different. The intensity modulator is driven with E so that the intensity P of its optical output signal becomes the maximum when E is -1 and 1. Thus, the XOR operation is completely realized between P1 and P2, and P. I evaluated the characteristics of XOR circuit by inputting two different sequences of 10 Gbit/s binary data with various patterns. These primary measured results confirm that the XOR circuit operates properly. The fiber-to-fiber loss of circuit coincided with that of modulator, and was 3.6 dB. The extinction ratio of XOR output was more than 7 dB. My proposed simple circuit is suitable for the future hybrid integration of photonics and electronics. To achieve the bit rate exceeding the speed limit of electrical XOR circuit and to further decrease the power consumption are key issues.

9009-4, Session 4

Blind SNR estimation for QAM constellations based on the signal magnitude statistics

Stefanos Dris, Christos Spatharakis, Paraskevas Bakopoulos, Ioannis Lazarou, Hercules Avramopoulos, National Technical Univ. of Athens (Greece)

Future software-defined optical networks will be capable of dynamic adjustment of modulation format and symbol rate, as well as of impairment-aware routing, in order to ensure efficient resource utilization and sufficient QoS in the face of changing link conditions. A key ingredient to enable such flexibility will be performance monitoring at the physical layer, with impairment information (such as noise), obtained from the DSP in the coherent receiver.

To this end, we present a novel non-data-aided algorithm that can accurately estimate the SNR of QAM constellations from the received signal magnitude statistics. We derive analytical expressions to extend the Koay inversion technique (which only works with constant-modulus signals) to allow application to multi-modulus QAM signals of any order. Performance is evaluated for formats up to 64-QAM. In contrast to the ubiquitous decision-directed error vector magnitude (EVM) method, we demonstrate that our scheme retains accuracy at low SNR, where incorrect symbol decisions degrade the EVM measurement. Moreover, it does not need phase information; it can therefore be applied prior to carrier phase recovery and, more importantly, we show that this makes it inherently resistant to nonlinear effects such as SPM/XPM which severely affect the SNR estimation derived from the EVM. We demonstrate that our scheme does not suffer performance degradation at high SNR,

which is the case with other magnitude-only estimators, such as those based on the method of moments. Compared to the latter, our approach achieves a Normalized Mean Square Error ~7 times lower (for 16-QAM at SNR = 18dB).

9009-5, Session 4

Hardware efficient frequency domain equalization in few-mode fiber coherent transmission systems *(Invited Paper)*

Zhongqi Pan, Xuan He, Yi Weng, Univ. of Louisiana at Lafayette (United States)

Space-division-multiplexing (SDM) has been emerging as the next generation technology for cost-effective growth in capacity to keep up with the capacity demand of future Internet. Among several promising approaches, mode-division-multiplexing (MDM) in few mode fibers (FMF), in which each channel is on one orthogonal spatial mode, is now being investigated intensively. One key challenge in FMF transmission system is random mode coupling among different fiber modes, which can cause severe channel crosstalk. Multi-input and multi-output (MIMO) approach has been proposed and demonstrated to untangle some of the crosstalk between the spatial modes using digital signal processing (DSP). MIMO processing can be implemented either in time domain or in frequency domain. Compared with time domain equalization (TDE), frequency domain equalization (FDE) has been proved more hardware and power efficient in considering fiber's large DMGD in FMF transmission systems. Several researches have shown that FDE can achieve similar tracking speed and system performance as TDE does, while can dramatically reduce the number of complex multipliers in hardware implementation. In an adaptive MIMO processing, the convergence speed is another important consideration that may significantly affect system performances. We have investigated several FDE algorithms through simulations by adaptively controlling the step size of each individual frequency bin to increase FDE's convergence speed, and proposed a single-stage adaptive FDE to compensate both chromatic dispersion and DMGD simultaneously to decrease the hardware complexity.

9009-6, Session 4

Frequency, phase, and polarization-tracking algorithms for arbitrary four-dimensional signal constellations

Hadrien Louchet, VPIphotonics GmbH (Germany); Konstantin G. Kuzmin, VPIphotonics GmbH (Belarus); Andre Richter, VPIphotonics GmbH (Germany)

The need for software-defined transmissions raises new challenges for the transceiver design: Multiple modulation formats have to be supported to accommodate for varying bandwidth demand and physical characteristics of different optical paths. In order to keep the receiver complexity and cost low, most of the digital signal processing functionalities should be shared by the different formats.

Training-sequence-based channel equalization schemes are interesting to this extend as they are modulation-format independent. However, they can be used to accommodate only for static or slowly-varying transmission impairments such as chromatic dispersion and PMD as the tracking of dynamic effects like phase noise would require increasing their overhead to an unacceptable level.

In this paper we address the problems of carrier frequency and phase recovery as well as the tracking of fast polarization rotations for arbitrary constellations in two or four dimensions.

We first report how not only carrier frequency recovery, but also sampling error correction can be performed using a modulation-format independent frequency-domain approach.

We then report a framework where the combined impact of phase error and fast polarization rotation can be described by a rotation in four-dimensional signal space. We present two approaches (one based on a modified version o the Kabsh algorithm, one using the Quaternion representation) to efficiently estimate and compensate this rotation.

We finally investigate the dynamic performance of the reported algorithms using numerical simulations.

9009-7, Session 4

All-optical 2R regenerator of 16-QAM signals

Lu Li, Michael Vasilyev, The Univ. of Texas at Arlington (United States)

We propose an all-optical regeneration scheme for 16-QAM signal. An incoming signal is 50/50 split into I and Q arms. Each arm contains three phase sensitive amplifiers (PSAs); between the PSAs the signal propagates through highly nonlinear fiber (HNLF) and acquires nonlinear phase shift due to self-phase modulation (SPM). At the end, another 50/50 coupler combines the regenerated I and Q signals.

In each arm, the first PSA is used to amplify one quadrature of incoming signal and deamplify the other quadrature in order to squeeze the phase noise. Since data encoded on the deamplified quadrature is also erased by the first PSA, signal in each arm retains only the data on amplified quadrature. After the first PSA, only amplitude noises remain on the two power levels of each signal.

The amplitude noise is regenerated by the SPM in the HNLF, followed by the PSA. The SPM converts the amplitude noise to the phase noise and thus causes rotation of the uncertainty (noise) ellipse around the signal phasor in the complex plane. With a proper nonlinear phase shift, the long axis of the noise ellipse can be significantly compressed by the PSA. To suppress the noise on both signal levels with 1:9 power ratio, there are two HNLF+PSA combinations in each arm.

Our modeling shows better than 4 dB noise reduction for all constellation points. Moreover, the higher signal levels experience even greater noise suppression, which is beneficial for their nonlinear propagation through the transmission fiber.

9009-8, Session 4

Pulse-shaping for spectrally-efficient coherent optical networks: OFDM, Nyquist signaling, and DFT-spread OFDM *(Invited Paper)*

Rene M. Schmogrow, Philipp C. Schindler, Christian Koos, Wolfgang Freude, Karlsruher Institut für Technologie (Germany); Juerg Leuthold, ETH Zurich (Switzerland)

Pulse-shaping is a powerful tool to increase the spectral efficiency of signals transmitted over optical fiber. Two main contenders, namely OFDM and Nyquist signaling have emerged as promising candidates for future optical networks. As a third option, DFT-spread OFDM combines the two techniques. Although all techniques are well-known in wireless and wireline communications, the extremely high data rates are challenging when designing real-time optical transmitters and receivers, particularly in view of the special impairments imposed by the optical transmission channel. After giving a theoretical overview on OFDM and Nyquist signals, we show the system design for the three pulse-shaping techniques and discuss the processing requirements and the potential performance in terms of spectral efficiency and out-of-band signal suppression. We further investigate the impact of modulator nonlinearity and limited resolution of DACs and ADCs on the different signals. Finally, we demonstrate real-time OFDM and Nyquist pulse generation with data rates beyond 100 Gbit/s transmitted on a single optical carrier and in a single polarization.

9009-9, Session 5

Characterization of multi-mode fibers and devices for MIMO communications *(Invited Paper)*

Nicolas Fontaine, Alcatel-Lucent Bell Labs. (United States)

Space-division multiplexing (SDM) systems transmit over multiple spatial-paths to increase capacity or photon efficiency.

In these links, coupling between the spatial paths scramble each input signal across all the output channels.

This scrambling is described by a $N times N$ frequency dependent transfer matrix which can be undone using multiple-input multiple-output processing.

Using a swept-wavelength interferometer with spatial diversity, we can completely characterize the amplitude and phase transmission between each input and output across the entire C-band in a single 100-ms scan.

Matrix eigenanalysis of the transfer matrix enables extraction of the system's insertion loss, mode-dependent loss, and the principle-states of polarization.

Results will include transfer matrix measurements of few-mode fibers, coupled-core fibers, photonic lantern spatial-multiplexers, and SDM compatible wavelength routing components.

9009-10, Session 5

Few mode fibers with low DMD slope realizing zero-DMD in wide wavelength range for MIMO processing *(Invited Paper)*

Ryo Maruyama, Nobuo Kuwaki, Shoichiro Matsuo, Fujikura Ltd. (Japan); Masaharu Ohashi, Osaka Prefecture Univ. (Japan)

Because the network traffic has increased rapidly, it is predicted that the current system utilizing the conventional single mode fibers approaches a limit of the traffic capacity due to the optical nonlinear effects and the fiber fuse. To overcome the limit, it is considered that innovations for not only transmission system but also fiber are essential and Few-Mode Fiber (FMF) and Multi-Core Fiber have been attracted considerable attention by means of increasing the transmission capacity. In addition, it has been reported actively that multiple-input- multiple-output (MIMO) is applied to suppress signal degradation due to mode coupling in mode division multiplexing (MDM) using FMF. However, although a MIMO system allows to generate some mode coupling into mode multiplexer, demultiplexer and FMF, the computation needed to recover the signals becomes more complex as increase of the differential mode delay (DMD) of FMF. Thus, FMF with low DMD is of benefit to MDM transmission utilizing MIMO. Furthermore, low DMD in the wide wavelength region is more attractive for MDM-WDM combined transmission applications. For realizing the requirement, DMD compensation transmission line has been proposed and its line with DMD of several picoseconds has already reported. However, there have been little reports on the long FMF line with low DMD in the wide band.

In this paper, we propose Two-Mode Optical Fibers with minimally low DMD slope, which are suitable to compensate DMD in the wide band. The 102.6 km long DMD compensation transmission line within |4.0| ps/km in the C+L band is successfully demonstrated.

9009-11, Session 6

Multi-element fiber for space-division multiplexing *(Invited Paper)*

Jayanta K. Sahu, Saurabh Jain, Victor Fernandez, Timothy C. May-Smith, Andrew S. Webb, Periklis Petropoulos, David J. Richardson, Univ. of Southampton (United Kingdom)

This paper introduces Multi-Element Fibers (MEF) as a practical alternative technology for both high-capacity space-division-multiplexed (SDM) transmission and multi-port fiber amplifiers, and reviews progress achieved to date. The MEF geometry is obtained by drawing multiple fiber-elements together in a common coating. Once the coating is removed, the fiber-elements can be accessed as individual fibers, negating the need for MUX/DEMUX devices. An alternative fiber geometry, termed multicore fiber, is being investigated elsewhere for SDM transmission in which the number of cores is limited by the core-to-core separation (for low-crosstalk operation) as well as the overall cladding diameter of around 225?m. At larger diameters, silica fiber is more susceptible to failure. However, in the case of MEF the number of fiber-elements is not expected to degrade the overall fiber strength providing the individual fiber-element strength is maintained. Error-free transmission of 1014Gbps has been demonstrated over a length of 28.5km in a 3-element MEF. There was no measureable crosstalk due to the independent nature of the fiber-elements. Furthermore, a core-pumped Er-doped 7-MEF amplifier has been realised with 33dB average gain and <5dB noise figure for an input signal of -23dBm at 1530nm. In addition, a cladding-pumped 5-element MEF comprising of a central undoped multimode-pump fiber-element and surrounded by the four Er/Yb-doped signal fiber-elements is demonstrated. A maximum gain of 37±2dB has been obtained in the C-band for each signal fiber-element. The signal fiber-elements were cascaded in a cladding-pumped 5-element MEF to reduce the gain ripple to ~2dB in the wavelength region of 1544-1565nm.

9009-12, Session 6

Low crosstalk, bending loss reduced and SSMF compatible single mode multicore fibre for telecommunication applications

Michal Szymanski, Michal Murawski, Zbigniew Holdynski, Tadeusz Tenderenda, Lukasz Ostrowski, Military Univ. of Technology (Poland) and InPhoTech Ltd. (Poland); Anna Ziolowicz, Military Univ of Technology (Poland) and InPhoTech Ltd. (Poland); Pawel Mergo, Univ. of Maria Curie-Sklodowska (Poland); Krzysztof Poturaj, Krzysztof Skorupski, Univ. of Maria Curie-Sklodowska (Poland) and InPhoTech Ltd. (Poland); Marek Napierala, Military Univ. of Technology (Poland) and InPhoTech Ltd. (Poland); Pawel Marc, Leszek R. Jaroszewicz, Military Univ. of Technology (Poland); Tomasz Nasilowski, Military Univ. of Technology (Poland) and InPhoTech Ltd. (Poland)

Space-division multiplexing (SDM) technique implemented as multi core fibres (MCFs) is a promising candidate for enlarging transmission capacities in the next generation long-haul transmission links. The intense and extensive research effort made in this field is constantly motivated by the necessity of finding a solution to anticipate capacity crunch as a result of the capacity limits of currently used optical links. MCFs will potentially allow to introduce a large scale-up per fibre capacity, especially while combining with others multiplexing techniques along with significant cost reduction comparing to standard, single core fibres. In respect of compatibility with current transmission systems based on single core fibres (SCFs) as well as core to core crosstalk (XT) which seem to be crucial aspects to address, the favourable solutions are uncoupled MCFs.

In this paper we propose a novel MCF design meant for reduction of core to core XT and low bending induced loss as well as providing a high compatibility with standard single mode fibres (SSMFs). To achieve these goals we accommodate a microstructure fibre (MSF) technology in which cores are arranged on a hexagonal grid. This approach allowed us to obtain low level of core to core XT and bending loss with relatively simple geometry of fibres themselves. To achieve high SDM efficiency we focused on 7 and 19 core designs.

The performance of the proposed fibres was investigated both, theoretical and experimentally. Our theoretical investigations using numerical methods and preliminary experimental evaluation show that with our fibres we are able to achieve at least competitive results comparing to other designs presented in literature while using simpler solution.

9009-13, Session 6

Nonlinear propagation in multi-mode fibers *(Invited Paper)*

Georg Rademacher, Stefan Warm, Klaus Petermann, Technische Univ. Berlin (Germany)

Due to the ever increasing capacity demands for optical communication links, single-mode fibers will soon not be able to support the exponential growth of data rates. A strong candidate to overcome the upcoming capacity crunch is space-division multiplexing (SDM) where different parallel paths in one fiber are used to transmit independent data streams. Suitable candidates for SDM are e.g. multi-mode fibers (MMF), where different orthogonal modes are independently addressed.

In this paper, we discuss nonlinear interaction between signals that propagate in different fiber modes. Based on the nonlinear effect of four-wave mixing, phase-matching between spectral components that propagate in different fiber modes is studied. With the knowledge of intra- and intermodal four-wave mixing, all Kerr-effect based nonlinearities can be expressed in an analytical way. We propose a method to calculate the maximal achievable Optical Signal to Noise Ratio (OSNR) for each mode, based on the assumption that the nonlinear interference can be taken into account by an additive noise term.

We analyzed a sample transmission link that uses a 55-mode graded-index multi-mode fiber, aiming at minimizing the group-delay differences between signals that travel in different fiber modes. It is shown that each of the 55 modes can achieve an equal or higher OSNR compared to a standard single-mode fiber.

9009-14, Session 6

Fabrication and characterization of all-fiber 90-degrees optical hybrids using a 4x4 coupler for signal analysis

Wendy-Julie Madore, Mikael Leduc, Ecole Polytechnique de Montréal (Canada); Stephane Couture, Sylvain O'Reilly, ITF Labs. (Canada); Suzanne Lacroix, Nicolas Godbout, Ecole Polytechnique de Montréal (Canada)

We report our progress on the fabrication of all-fiber 90 degrees optical hybrids as well as the characterization technique for phase analysis. An optical hybrid is a device having two input and four output ports. The first input is a modulated signal (S) and the second is a reference signal (R). The amplitudes of the output signals are proportional to the sum and difference of the amplitudes of the local oscillator used as a reference R and the amplitudes of the two quadratures of the signal S.

A 4x4 fiber coupler in a square cross-section geometry can fulfill the requirements for optical hybrids. Such a device can be manufactured by a standard fusion-tapering technique. The design and fabrication parameters (degree of fusion, length and taper ratio) can be adjusted to obtain the properties of a 90 degrees optical hybrid. Using two adjacent input ports, the device exhibits the amplitude equipartition and required phases between the output signals. The ideal 4x4 coupler is lossless, polarization-independent, and working over the C-band for telecommunications. As it enables the unambiguous measurement of the optical amplitude and phase of a signal with respect to a known reference, such a component is firstly designed for coherent demodulation.

We fabricated and characterized 4x4 couplers that meet all the requirements of 90 degrees optical hybrids. We then tested the device as a demodulator in a standard telecommunication phase-modulation scheme and obtained the expected constellations.

9009-15, Session 6

Coupling mechanism in multimode fibers *(Invited Paper)*

Luca Palmieri, Univ. degli Studi di Padova (Italy)

The steady increase of bandwidth demand in worldwide communications has revived the interest about multimode optical fibers as a tool to increase capacity by spatial division multiplexing. Two approaches has been proposed so far. One exploits special fibers designed to minimize mode coupling, so that each group of degenerate modes can be seen as a separate transmission channel. The other considers propagation in high-mode-coupling regime and resorts to MIMO technology to compensate mode dispersion. In principle, these approaches can be applied to fibers with an arbitrary number of modes. In practice, technical constraints limit the application to the so called "few-mode" fibers, where only few groups of degenerate modes can propagate.

The theoretical models adopted so far to describe propagation in these fibers do not consider in details the mechanisms at the origin of mode coupling. Specifically, mode coupling is caused by any perturbation that breaks the ideal cylindrical symmetry of the fiber, and depending on the way this symmetry is broken, different kinds of coupling take place. A detailed analysis of these mechanisms may help to develope more accurate propagation models and optimized fiber designs. In this paper coupling among the first few higher-order modes of multimode fibers is analyzed for the most common perturbations. The analysis is based on standard coupled mode theory and includes also the effects of spinning process.

9009-16, Session 7

Spatial-spectral flexible optical networking: enabling switching solutions for a simplified and efficient SDM network platform *(Invited Paper)*

Ioannis Tomkos, Panagiotis Zakynthinos, Dimitrios Klonidis, Athens Information Technology (Greece); Dan Marom, The Hebrew Univ. of Jerusalem (Israel); Stylianos Sygletos, Andrew Ellis, Aston Univ. (United Kingdom); Elio Salvadori, Domenico Siracusa, CREATE-NET (Italy); Marianna Angelou, George Papastergiou, Optronics Technologies S.A. (Greece); Nicholas Psaila, Optoscribe Ltd. (United Kingdom); Jordi F. Ferran, W-onesys S.L. (Spain); Shalva Ben-Ezra, Finisar Israel Ltd. (Israel); Felipe Jimenez, Juan Pedro Fernández-Palacios, Telefónica Investigacion y Desarrollo S.A. (Spain)

No Abstract Available

9009-17, Session 7

Experimental demonstration of high spectral-efficiency transmission with a novel non-interferometric vector modulator and custom DSP algorithms for coherent PON architectures

Ioannis Lazarou, Christos Spatharakis, Vasilis Katopodis, Stefanos Dris, Paraskevas Bakopoulos, National Technical Univ. of Athens (Greece); Bernhard Schrenk, Austrian Institute of Technology (Austria); Hercules Avramopoulos, National Technical Univ. of Athens (Greece)

The unending need for increased download speeds, fuelled by new bandwidth-demanding applications, has put the optical metro-access segment in the spotlight. Coherent technology has been established as the only viable roadmap for 100G and 400G delivery in core networks, whereas advanced modulation formats are gradually penetrating the metro, indicating that convergence of the metro and access sections is next on the cards. Conventional IQ-modulators are suited to long-haul networks where the main focus is performance rather than cost; however, a vector modulator tailored to the metro-access segment is missing. The requirements for such a device are reduced fabrication and operating costs, as well as lower power consumption, translating to simple structure, low electrical driving signals and CMOS electronics compatibility. Towards this direction we demonstrate for the first time a flexible, low-loss and energy-efficient non-interferometric vector modulator based on a SOA/EAM cascade, capable of generating multiple formats up to 16-QAM. The modulator layout relies on off-the-shelf components and can be integrated on a single InP chip with small footprint, underpinning its suitability for coherent PONs. Its operating principle is based on successively modulating the signal's phase and amplitude in the SOA and EAM respectively. A conventional coherent receiver is used for detection, enhanced with a full set of custom-designed, novel DSP algorithms suitable for demodulation of the non-square QAM constellation shapes. Performance was experimentally validated with 12- and 16-QAM signals transmitted over 25km of SMF, yielding BERs below the FEC limit in both cases.

9009-18, Session 7

Super-Nyquist shaping and processing technologies for high-spectral-efficiency optical systems *(Invited Paper)*

Zhensheng Jia, Hung-Chang Chien, Junwen Zhang, Ze Dong, Yi Cai, Jianjun Yu, ZTE USA (United States)

The implementations of super-than-Nyquist pulse generations, both in an electrical field using a DAC or optical filter via a WSS at transmitter, are analyzed and compared. The corresponding signal processing algorithms at receiver are presented.

9009-19, Session 7

Hybrid MDM/OCDM system with mode and code multi-/demultiplexers *(Invited Paper)*

Takahiro Kodama, Tomoki Isoda, Koji Morita, Akihiro Maruta, Osaka Univ. (Japan); Ryo Maruyama, Nobuo Kuwaki, Shoichiro Matsuo, Fujikura Ltd. (Japan); Naoya Wada, National Institute of Information and Communications Technology (Japan); Gabriella Cincotti, Univ. degli Studi di Roma Tre (Italy); Ken-ichi Kitayama, Osaka Univ. (Japan)

In recent years, space division multiplexing (SDM) has attracted a lot of attention to overcome the capacity crunch of a single mode fiber. A much larger transmission capacity can be achieved by combining SDM with conventional wavelength division multiplexing (WDM) and polarization division multiplexing (PDM). Hybrid multiplexing scheme with SDM will become a key technique in the future optical access systems, as well as in core and metro networks. In the present paper, we describe a novel all optical hybrid mode-division multiplexing (MDM)/ optical code division multiplexing (OCDM) system. Compared to WDM systems, OCDM presents the unique features of finer bandwidth granularity, and larger data confidentiality. We successfully demonstrated for the first time an asynchronous on-off keying (OOK) modulation, 2 mode x 4 code x 10 Gbps transmission over 2km two mode fiber (TMF) without dispersion compensation at single wavelength, by using 16-chip (200 Gchip/s), 16-phase-shift keyed (PSK) optical codes (OC) generated by a multiport encoder/decoder (E/D) and optical mode multiplexer/demultiplexer. This approach allows a smooth migration from previous OCDM systems, and we investigate the main noise effects, related to OC and mode crosstalks. We experimentally evaluated the mode crosstalk tolerance with a power variance between the two LP01 and LP11 modes, and observe a large tolerance value.

9009-27, Session 7

All-optical tunable multilevel amplitude regeneration using coherent nonlinear wave mixing

Zahra Bakhtiari, The Univ. of Southern California (United States)

Multilevel data modulation formats become quite important to the optical communications community due to the increasing demand for higher bit rates and transmission capacity [1-3]. A higher spectral efficiency modulation format can be achieved through amplitude multiplexing, such as multilevel amplitude shift keying (M-ASK) with simple receiver Architecture. However a high sensitivity to amplitude noise is a common problem of all multilevel amplitude signals. Amplitude noise reduces the space separation of different amplitude levels in the eye diagram which is considered to be a major transmission impairment for multilevel amplitude formats [4]. Typical methods for regeneration of OOK signals include: (a) using optical limiters, which can be achieved by optical parametric amplification (OPA) based on four wave mixing [5], (c) using self-phase modulation effect and offset filtering [6]. In general, these amplitude regeneration techniques tend to be limited to a single amplitude level and NOLM based method has been used specifically for two amplitude level signal regeneration [7]. However, a laudable goal might be the regeneration of higher multilevel amplitude signals in a tunable fashion such that variable level of amplitude noise can be accommodated. In this paper, we demonstrate 10 Gbaud optical amplitude regeneration of two and four level amplitude modulated signals based on coherent optical nonlinear mixing using HNLF respectively.

9009-24, Session PWed

Compressed data for the movie industry

Bradley S. Tice, Advanced Human Design (United States)

The use of algorithmic complexity to effect a maximal compression of a sequential string of binary data to increase storage capacity and transmission loads will be examined for use in the movie industry. The technical presentation will detail the fundamental operations of an algorithmic program of compression of binary data structures for use in storage and transmission purposes.

9009-25, Session PWed

Simulation of reconfigurable multifunctional continuous logic devices as advanced components of the next generation high-performance MIMO-systems for the processing and interconnection

Vladimir G. Krasilenko, Vinnitsa Social Economy Institute (Ukraine); Aleksandr Nikolskyy, Vinnytsia National Technical Univ. (Ukraine); Alexander Lazarev, Vinnitsa National Technical Univ. (Ukraine)

We consider design and modeling of hardware realizations of reconfigurable multifunctional continuous logic devices (R MCL D) as advanced components of the next generation high-performance MIMO-systems for the processing and interconnection. The R MCL D realize function of two-valued and continuous logics with current inputs and current outputs on the basis of CMOS current mirrors and circuits which realize the limited difference functions. We show advantages of such elements consisting in encoding of variables by the photocurrent levels, that allows easily to provide optical inputs (by photodetectors (PD)) and optical outputs (by LED). The conception of construction of R MCL D consists in the use of a current mirrors realized on 1.5?m and 0.35 ?m technology CMOS transistors. Presence of 55-65 transistors, 1 PD and 1 LED makes the offered circuits quite compact and allows their integration in 1D and 2D arrays. In the presentation we consider the capabilities of the offered circuits, show the simulation results and possible prospects of application of the circuits in particular for time-pulse coding for multivalued, continuous, neuro-fuzzy and matrix logics. The simulation results of NOT, MIN, MAX, equivalence (EQ) and other functions, implemented R MCL D, showed, that the level of logical variables can change from 5 ?A to 10 ?A for low-power consumption variants. The base cell of the R MCL D have low power consumption <1mW and processing time about 1-11?S at supply voltage 2.4-3.3V. Modeling of such cells in OrCad is made.

9009-26, Session PWed

Metrology for QKD: an industrial quantum optical communication technology

Anas Al Natsheh, Kajaanin Ammattikorkeakoulu (Finland)

The lack of validation and standardisation is a barrier to the wider commercialisation of QKD. A joint research project [1] aims to develop metrological techniques, standards and methods for new industrial quantum optical communication technologies. The project is focused on faint-pulse QKD, the most commercially advanced technology. It is funded under the European Metrology Research Programme, is of three years' duration, and started in September 2011.

A faint-pulse QKD system operating in the 1550 nm spectral region comprises a photon emitter, an optical channel, and a photon receiver. Random number generators are also essential to QKD. Characterising parameters of these components which can affect the security and/or efficiency of a QKD system is the focus of this project. Among these are: clock frequency, mean photon number, timing jitter, wavelength, spectral line width, spectral and temporal indistinguishability, and polarisation state (emitter); photon detection probability, dark count probability, afterpulse probability, dead time, recovery time, maximum count rate, timing jitter and spectral responsivity (receiver).

An overview of the project, and a review of its achievements to date, will be presented. The latter includes new quantum measurement devices and instrumentation, and work to characterize an open system quantum random number generator.

[1] The partners in the Metrology for Industrial Quantum Communications (MIQC) project are: the National Measurement Institutes of the Czech Republic (CMI), Estonia (Metrosert), Finland (MIKES), Germany (PTB), Italy (INRIM) (co-ordinator), the United Kingdom (NPL), and South Korea (KRISS); idQuantique; the Austrian Institute of Technology (AIT); Aalto University; Oulu University; and the Polytechnic of Milan.

9009-20, Session 8

All-fibre mode multiplexers *(Invited Paper)*

Tim A. Birks, Stephanos Yerolatsitis, Itandehui Gris-Sánchez, Univ. of Bath (United Kingdom)

We made two types of three-mode multiplexers with three single-mode input cores and one enlarged output core. Light in each input core evolved adiabatically into just one of the LP01, even-LP11 and odd-LP11 modes of the output core. In the first type, the transition between inputs and output was formed by the controlled collapse of selected holes in a photonic crystal fibre with three cores in an equilateral triangular array. In the second type, three standard single-mode fibres were made dissimilar and tapered together within a fluorine-doped silica capillary. In both cases the output light patterns matched the LP01 and LP11 distributions as expected, with broadband operation across at least 100 nm in the near-IR, low insertion losses and mode purities exceeding 10 dB.

9009-21, Session 8

Multicore EDFA for long-distance transmission *(Invited Paper)*

Makoto Yamada, Osaka Prefecture Univ. (Japan); Hirotaka Ono, NTT Photonics Labs. (Japan); Shoichiro Matsuo, Fujikura Ltd. (Japan)

Optical multi-core fiber transmission is very attractive in terms of achieving the ultra high capacity of an exabit/s class transmission. The availability of this approach has been confirmed by a recent study that demonstrated transmission at over 1 petabit/s using a 12-core fiber. If we are to construct a practical transmission system, we must realize an EDFA for multi-core fiber (MC-EDFA). The key to realizing an MC-EDFA is finding a way to integrate a number of single-core amplifiers with a low crosstalk and uniform amplification characteristics.

Two approaches have been considered for its realization. One approach employs discrete core pump amplification by using a reduced cladding bundled EDF and a multicore EDF, in which optical signals passing through different cores of an MCF are amplified with each core pumping after being separated into individual signals. The other is clad pump amplification where the amplifier carries out the clad pumping of all of the active cores.

In this paper, we report recent progress on discrete pump amplification using a reduced cladding bundled EDF and a multicore EDF, and clad pump amplification using Yb^{3+} co-doped multicore EDF. We also present newly developed amplification techniques for achieving low crosstalk and uniform amplification characteristics, and introduce transmission results obtained using the multicore EDFA we developed.

9009-22, Session 8

Bandwidth and dynamic range of a pulsed local oscillator coherent optical receiver: application to the linear optical sampling

Philippe Gallion, Xin You, Christophe Gosset, Frédéric Grillot, Télécom ParisTech (France) and Ctr. National de la Recherche Scientifique (France)

The optical linear sampling uses, before the detection, the coherent

optical mixing, in a balanced and symmetric a 4X4 hybrid mixer, of the signal to be analyzed, with a pulsed local oscillator (LO) providing simultaneously a temporal gating and a mixing gain for the optical field. Synchronous real-time linear optical sampling may be used to overcome post-detection electronics. It allows OTDM coherent demultiplexing of Tb/s QAM signals, and compensation of linear system impairments in a parallel coherent receiver, taking benefits of dedicated digital signal processing. Another application is the under sampling technique, providing a low cost, blind and asynchronous characterization method of optical data flows, free of receiver bandwidth limitation at high bit rate.

The Error Vector Magnitude (EVM) of the signal under test is directly related to the accuracy of its 2 quadrature measurements and therefore depends on the optical frequency detuning of the 2 mixed signals and on Signal-to-Noise Ratio (SNR) of the optical sampling process.

We derive the optical transfer function, as a function of the optical frequency detuning of the 2 mixed signals. We point out that the transfer function is the amplitude envelope of the optical modes acting in the locking of the modes of the pulsed laser local oscillator.

Using quantum theory of homodyne detection and assuming an additive Gaussian circular with a spectral density h?/2, at each optical port of the optical mixer, a general discussion on the SNR of pulsed coherent detection is provided. It includes the influence of the sampling pulse time jitter. Results are discussed in the under sampling context, but may be obviously extended to real time signal detection systems.

We derive the optical transfer function as a function of the optical frequency detuning for the 2 mixed signals. We point out that for mode a locked laser used as a pulsed local oscillator, the transfer function is the amplitude envelope of the optical modes acting in the locking

By using quantum theory of homodyne detection, and assuming an additive Gaussian circular with a spectral density, at each optical port of the optical mixer, a general discussion on the SNR of pulsed coherent detection, including the influence of the sampling pulse time jitter is derived. Results are discussed in the under sampling context, but may be obviously extended to real time signal detection systems.

9009-23, Session 8

Tunable optical delay line based on nonlinear effects in a polarization-maintaining fiber Bragg grating

Mingming Sun, Han Chen, Xiaohan Sun, Southeast Univ. (China)

An optical delay line based on nonlinear birefringence effects in a Polarization-Maintaining Fiber Bragg Grating (PMFBG) with continuously tunable optical delay is proposed. Figure 1 shows the schematic block diagram of the proposed phase shifter. First, a continuous-wave (CW) light wave from a laser source is sent to a Mach-Zehnder modulator (MZM) which is modulated by a microwave signal. After amplified by an Erbium Doped Fiber Amplifier (EDFA), the modulated optical signal is then sent to a PMFBG via a PC and an optical circulator (OC). The phase-shifted optical carrier are spited by a polarizing beam splitter (PBS) into two principal axes as the x and y mode optical signal. The two quadrature model lead in a different time delay due to the PMFBG, therefore we can see the RF signal phase shift at the output of two photo-detectors (PD). A 92 ps delay (approximate 360° phase shifter at 10GHz) is demonstrated by tuning the polarization angle of PC from 0 to 900.

Conference 9010: Next-Generation Optical Networks for Data Centers and Short-Reach Links

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9010-1, Session 1

Optics for large-scale data centers: key metrics and trends *(Invited Paper)*

Hong Liu, Ryohei Urata, Chris J. Johnson, Google (United States)

Photonic components already play a critical role in datacenter network deployments. We will review the performance metrics for variants of existing technologies as well as emerging optical technologies will further accelerate the ability of the datacenter to scale.

9010-2, Session 1

Data center networks and network achitectures *(Invited Paper)*

Hiroshi Esaki, The Univ. of Tokyo (Japan)

The recent IT system using the broadband Internet has strategically use the Data Centers, for cloud computing service and Big Data services. For about ten years, we have a research on "Ftuture Internet" with clean slate approach, but had not achieved any practical and concrete innovative architecture. On the contrary, we have worked on the system architecture research based on "Internet of Design", which consider the system with regards to the essense of the Internet architecture. In this paper, the direction of new Internet architecture and the system architecture of data center, that is the strategic ompoment of the future network. Especially for the data center network, multiple-layered overlayed recursive sliced virtual networks must be accommodated, with flexible and efficient resource usage and management. In order to solve this complecated situation, simple architecitural disciple should be applied, which is the essence of Internet architecture.

9010-3, Session 2

A global standardization trend for high-speed client and line side transceivers *(Invited Paper)*

Hideki Isono, Fujitsu Ltd. (Japan)

The required information bandwidth of IT society is increasing rapidly. Under these situations, high-speed and high-capacity optical communication systems such as 100G/400G have been developed and deployed in the recent industry. Especially high speed optical transceiver is the key components in order to realize this high-speed transmission system, and the practical development of 100G/400G transceiver is accelerated in the industry.

In order to develop these leading edge products timely, the authorization of the global standards is strongly demanded for creating the industry consensus. Based on these backgrounds, Forum standardization bodies such as OIF/IEEE802.3 have been energetically discussing new standards in recent few years. With regard to 40G/100G standardization activities, OIF leads telecom field and IEEE802.3 leads datacom field respectively, and both standardization activities become important from the view point of their impact to the industry. The recent topics of these two standardization bodies are precisely reviewed and its future direction is introduced. Especially topics with regard to 100G/400G transceivers and its related components are highlighted.

9010-4, Session 3

Scaling hybrid-integration of silicon photonics in freescale 130nm to TSMC 40nm-CMOS VLSI drivers for low-power communications links *(Invited Paper)*

John E. Cunningham, Oracle (United States)

Within the Ultraperformance Nanophotonic Intrachip Communication (UNIC) program at Oracle, we have been aggressively developing active nanophotonic devices (modulators, detectors, WDM components), circuits, that target ultimate operation of Si photonic links at 15 Gbps and 300 fJ/bit energy consumption. These links are envisioned to operate between computing elements in a large array of chips called a "Macrochip." We present our recent developments in packaging and integration technologies for a marcochip

9010-5, Session 3

High-density optical interconnects by using silicon photonics *(Invited Paper)*

Yutaka Urino, Tatsuya Usuki, Junichi Fujikata, Masashige Ishizaka, Koji Yamada, Photonics Electronics Technology Research Association (Japan); Tsuyoshi Horikawa, National Institute of Advanced Industrial Science and Technology (Japan); Takahiro Nakamura, Photonics Electronics Technology Research Association (Japan); Yasuhiko Arakawa, The Univ. of Tokyo (Japan)

One of the most serious challenges facing the exponential performance growth in the information industry is a bandwidth bottleneck in inter-chip interconnects. Optical interconnects with silicon photonics have been expected to solve the problem because of the intrinsic properties of optical signals and the industrial advantages of silicon for use in the electronics industry. We therefore propose an optical interconnect system by using silicon photonics to solve the problem. We examined integration between photonics and electronics and integration between light sources and silicon substrates, and we propose a photonics-electronics convergence system based on these examinations. We also investigated the configurations and characteristics of optical components for the system, including silicon spot-size converters, silicon optical waveguides, silicon optical splitters, silicon optical modulators, germanium photodetectors, and arrayed laser diodes. We then demonstrated the feasibility of the system by fabricating a high-density silicon optical interposer by using silicon photonics hybridly integrated with arrayed laser diodes and monolithically integrated with the other optical components on a single silicon substrate. The pad pitches of optical modulators and photodetectors were designed to be 100 microns so that LSI bare chips were able to contact to them electrically by flip-chip bonding. Since this system was optically complete and closed and no temperature sensitive component was used, we did not need to align the fibers, control the polarization, or control the temperature throughout the experiments. As a result, we achieved error-free data transmission at 20 Gbps and high bandwidth density of 30 Tbps/cm2 with the silicon optical interposer.

9010-6, Session 4

High-speed low-power short-reach optical interconnects for high-performance computing and servers *(Invited Paper)*

Daniel M. Kuchta, IBM Thomas J. Watson Research Ctr. (United States)

This invited talk will review of much of the recent optical link results that have come out of IBM Research. It will cover various records of direct high speed modulation (56Gb/s), low energy efficiency (1pJ/bit for a complete link), and high density packaging, both polymer waveguide and glass fiber based. It will also cover results obtained on 7 core and 4 core multimode multicore fiber and small core, 26um and 32um multimode fiber. Packaging approaches used for embedded optics in IBM's High Performance Computing Blue Gene Q and Power 775 systems will be discussed as well as the reliability planning for these large systems which both use more that 500K optical links each. Prospects for optical technologies needed to build Exascale systems will be addressed.

9010-7, Session 4

Burst switching without guard interval in all-optical software-define star intra-data center network

Philip N. Ji, Ting Wang, NEC Labs. America, Inc. (United States)

Optical interconnect and switching technologies have been introduced in intra-data center networks (DCNs) in the past few years to take advantage of the fiber's high capacity and the optical switching's low power consumption property. Recently we proposed a novel star MIMO OFDM-based all-optical DCN that offers simultaneous any-server-to-any-server communication with fine granularity flexible bandwidth allocation and sharing, as well as uniform low latency and low power consumption. We also added burst switching to improve bandwidth utilization gain through statistical multiplexing at packet level, and software-defined networking architecture to increase control flexibility. In this paper, we introduce the control procedure for the star all-optical DCN in detail for the first time. The timing, signaling, and operation are described for each step, including burst assembling, centralized wavelength and subcarrier assignment planning, OFDM signal generation and modulation, tunable electrical-to-optical conversion, parallel detection at the receiver, and burst disassembling. Through this centralized control process, the bandwidth resource can be shared and utilized efficiently across the entire DCN. Furthermore, this procedure allows burst switching without guard interval, provided that an appropriate burst assembling period is selected. Eliminating guard interval enables continuous operation and maximizes system efficiency. The guidelines for the burst assembling period selection are discussed, based on the centralized controller's processing time, WDM OFDM signal generation time, OFDM demodulation time, OFDM subcarrier capacity, and statistical multiplexing requirement. With the flexible and efficient control, the star all-optical DCN is a promising technology for next-generation data center application.

9010-8, Session 4

Optimization of spectral band utilization in gridless WDM optical network

Indayara B. Martins, Télécom ParisTech (France); Ivan A. Aldaya-Garde, Tecnológico de Monterrey (Mexico); Grethell G. Perez-Sanchez, Ctr. de Investigación e Innovación Tecnológica (Mexico); Philippe Gallion, Télécom ParisTech (France)

The effects of gridless spectrum allocation in Wavelength Division Multiplexed (WDM) optical networks is examined. The signal advanced modulation formats and multi rate transmissions, which are key parameters in the optical system project, are taken into account. Analytical calculations and simulations are conducted to evaluate the impact of the gridless spectrum allocation on both the spectral consumption and the signal quality of transmission (QoT). The consumed spectrum, as well as the impact of linear and nonlinear impairments on the signal transmission, are compared to WDM network adopting standard ITU grid. In order to analyze the influence of these physical effects, some key network design parameters are monitored and evaluated, such as the guard band size, signal occupied bandwidth, laser power and the number of channels. The simulation setup consisted on three WDM channels with different transmission rates and modulation formats. The guard band, signal band, and laser power were swept and the resulted Bit Error Rate (BER) was estimated from the eye-diagram. The applied signal modulation formats were On/Off Keying (OOK), Quadrature Phase Shift keying (QPSK), and Dual Polarization State Phase Modulation (DP-QPSK), whereas the transmission rate per wavelength was varied from 10 Gb/s to 100 Gb/s. Results reveal that gridless transmission system reduces the spectral consumption while offering an acceptable QoT. This work was carried out with both analytical modeling and numerical calculation using the VPI transmission system, Optisystem as well as Matlab.

9010-9, Session 4

Combined CATV and very-high-speed data transmission over a 1550-nm wavelength indoor optical wireless link

M. I. Sakib Chowdhury, Mohsen Kavehrad, The Pennsylvania State Univ. (United States); Weizhi Zhang, Ctr. for Information & Communications Technology Research (United States); Peng Deng, The Pennsylvania State Univ. (United States)

We report details of an experimental demonstration involving a 15 meter pointed indoor optical wireless link in the 1550-nm wavelength range, that is comprised of an uni-directional Cable Television (CATV) signal and a bi-directional link comprised of two 10 Gbps data links. Four port wavelength division mux-demuxes have been used on both ends of the link. The CATV transmission system is connected to port 1 of the mux-demux. CATV signal consists of both analog and digital parts, and its bandwidth is 1 GHz. The laser is directly modulated by the CATV signal, and at the receiver end, the optical signal is demodulated and fed to a TV. Port 2 of the mux-demux is left unused. Ports 3 and 4 are used for th! e 10 Gbps links. A bit error rate tester has been used to generate the 10 Gbps signals that are converted to optical wavelengths by enhanced Small Form Factor Pluggable (SFP+) modules at both ends of the setup. Collimators are used at both ends to transmit the combined optical signal that is the output of the mux and to receive the optical signal by focusing it onto a single-mode fiber as the input of the demux. We present results on the CATV portion of the setup and the bit-error-rate performance of the two 10 Gbps links. This experiment shows the feasibility of using pointed optical links in datacenters as secondary links to alleviate the loads of highly utilized wired connections and improve the overall throughput performance of datacenters.

9010-10, Session 4

Dynamic optical circuit switching

Noam Sapiens, The Hebrew Univ. of Jerusalem (Israel); Larry Rudolph, Massachusetts Institute of Technology (United States); Aharon J. Agranat, The Hebrew Univ. of Jerusalem (Israel)

Data centers, cloud computing and other "big data" applications employ the use of storage area networks (SANs) as the backbone infrastructure

of conveying large amounts of data between nodes. As the fundamental data piece size increases in these applications, SAN systems suffer manifest deterioration in performance.

Dynamical Optical Circuit Switching (DOCS) is a scheme for constructing reconfigurable ad-hoc physical circuits between selected pairs of nodes thus enabling direct transport of data. This scheme acts as an auxiliary interconnection network that upon request creates physical circuits between pairs of nodes in the system. Each circuit constitutes a direct data communication path between the nodes, enabling the nodes to converse directly avoiding the cumbersome multi-hops route through the SAN.

DOCS employs wavelengths routing (WR) in WDM optical fiber links. The underlying principle of WR is to assign a specific wavelength to each node. A message painted with a specific wavelength will be routed directly to the node to which this wavelength was assigned.

The effectiveness of equipping the SAN with a DOCS interconnection layer for boosting the performance of the latter was tested in a series of simulations. These show that SANs have a breakpoint behavior when increasing the number of computer systems, number of storage elements and data traffic volume. On the other hand, a SAN system implementing DOCS does not show this behavior and remains unaffected by the addition of load in all parameters of the simulation.

9010-11, Session 5

Silicon photonics integrated circuits for high-speed data center interconnects *(Invited Paper)*

Saeed Fathololoumi, Dazeng Feng, Hong Liang, Wei Qian, Roshanak Shafiiha, Pegah Seddighian, Bhavin J. Bijlani, Daniel C. Lee, Zhi Li, Joe Zhou, Aaron J. Zilkie, Shashank Jatar, B. Jonathan Luff, Mehdi Asghari, Kotura, Inc. (United States)

Silicon photonics is emerging as the technology that offers low-energy, low cost and high bandwidth optical solutions to address connectivity bottlenecks. Kotura has developed a complete manufacturable silicon photonic platform and has demonstrated 100 Gbps quad small form factor pluggable transceiver using wavelength division multiplexing. In this talk, we review the operation principles of monolithic and hybrid silicon photonic circuits for 100 Gbps applications and beyond. This includes reviewing the key building blocks of the high performance transceiver chip, such as hybrid silicon lasers, GeSi modulators, Ge photodetectors and multiplexers/demultiplexers.

9010-12, Session 5

A 25-Gb/s 100-m multi-mode fiber optical link based on a 1.3um lens-integrated surface-emitting laser and a CMOS receiver *(Invited Paper)*

Takashi Takemoto, Hiroki Yamashita, Yasunobu Matsuoka, Koichiro Adachi, Yong Lee, Hitachi, Ltd. (Japan)

Current data centers (DCs) are not just a collection of servers and storages; they work as one machine to respond efficiently to the demands from users, for example, web searching and web transaction processing. Thus, the network switch connecting servers-to-servers and servers-to-storages has been a key device for DCs. To accommodate the increasing traffic inside, low-power 25-Gb/s short-reach communications (including DC network with transmission length of more than 100 m) are required. The VCSEL-based optical links (with 850-nm or 1.0-um wavelength) provide high-speed and low-power transmission independent of link length. Beyond 100 m, however, a chromatic dispersion causes serious degradation of the optical link. To address the issue, a 25-Gb/s optical link with 1.3-um wavelength, which consists of lens-integrated surface-emitting laser (LISEL) and CMOS-based optical receiver, is developed because it provides smaller chromatic dispersion and higher PD responsivity than that of VCSEL-based optical links. The optical receiver consists of a PD with high-responsivity (0.8 A/W) and a CMOS TIA chip, which are directly mounted on an 8 x 8 mm multi-layer ceramic package. The TIA greatly improves sensitivity by adopting a data-driven power-supply noise and an offset voltage cancelling methods. Moreover, to enlarge the bandwidth of the LISEL, a linear equalizer is also incorporated. The LISEL and the high-sensitivity receiver make it possible to extend the transmission length of fiber link and achieve low-power operation by increasing the loss budget margin. Transmission experiment at data rate of 25 Gb/s through 100-m multi-mode fiber was conducted in success.

9010-13, Session 5

The first Brazilian integrated 100G QPSK transmitter on a 4 x 3 mm silicon photonic chip *(Invited Paper)*

Júlio César R. F. de Oliveira, Bernardo B. C. Kyotoku, Fellipe G. Peternella, Alexandre P. Freitas, Neil Guerrero Gonzalez, CpqD (Brazil)

The first Brazilian high speed integrated 100G-QPSK transmitter and coherent receiver on a 5 x 5 mm silicon photonic chip is presented. The novel photonic component allows optical signal generation and demodulation of advanced modulation formats in 25GHz bandwidth, as well as, optical signal to noise ratio (OSNR) monitoring. The integrated coherent receiver supports signal demodulation of single polarization QPSK signals. Furthermore, in this paper we also present our vision on required integrated photonics targeting 400G optical transmission systems.

9010-14, Session 6

Nanoplasmonic waveguides and modulators for advanced optical interconnects *(Invited Paper)*

Zhaolin Lu, Kaifeng Shi, Riaz R. Haque, Rochester Institute of Technology (United States)

Plasmonic circuits merge electronics and photonics at the nanoscale, creating the ability to combine the superior technical advantages of photonics and electronics on the same chip. In particular, surface plasmons as hybrid electrical-optical waves give rise to strong confinement and great enhancement of electromagnetic field at the dielectric-metal boundaries, which render their propagation to be extremely sensitive to minor changes in the optical properties of materials (metals or dielectrics) at the boundaries. This provides the unprecedented opportunity for electro-optic modulation. We report the development of electro-optic modulators by the incorporation of novel nanoplasmonic waveguides and advanced optical materials. First, nanoscale metal-insulator-metal plasmonic waveguides have been developed for the advantages of (1) small mode size and enhanced electric field, (2) acceptable propagation loss, and (3) efficient light coupling from a dielectric waveguide into an MIM waveguide. Novel plasmonic waveguides can also be developed based on transparent conducting oxides, which obeys the Drude model dispersion very well. In particular, they can realize so called "epsilon-near-zero" and supports extremely confined surface plasmons in the near infrared regime. Our recent work also demonstrated the extraordinary optical and electro-optic properties of graphene. In particular, greatly enhanced light absorption (up to 42.7%) by monolayer graphene over a broad spectral range is experimentally achieved. With a suitable gate voltage, the

optical properties of both transparent conducting oxides and grapheme can be significantly modified, resulting active plasmonic materials. Efficient electro-optic modulation is then achieved by either integration of graphene or transparent conducting oxide-based active materials.

9010-15, Session 6

Silicon photonic Bragg-grating couplers for optical communications *(Invited Paper)*

Wei Shi, Univ. Laval (Canada); Venkatakrishnan Veerasubramanian, David V. Plant, McGill Univ. (Canada); Nicolas A. F. Jaeger, Lukas Chrostowski, The Univ. of British Columbia (Canada)

We discuss recent progress and challenges in realizing nanophotonic Bragg-grating devices on the silicon-on-insulator platform for next-generation optical communications applications, such as on-chip optical interconnects and signal processing. In particular, we focus on grating-assisted, wavelength-selective couplers, known as contra-directional couplers (contra-DCs). In contrast to conventional two-port Bragg gratings operating in the reflection mode, contra-DCs are four-port devices with very weak backreflections and, therefore, can be easily integrated with other photonic components on a chip. In order to provide a reliable on-chip wavelength-division multiplexing (WDM) solution for high-speed optical interconnects, we have developed high-performance add-drop filters and, furthermore, wavelength multiplexers/demultiplexers with combined advantages of flat-top responses, low insertion loss (< 1 dB), and low crosstalk (< -20 dB). These WDM devices are ultra-compact and highly tolerant to temperature fluctuations (> 100 K), showing great potential for large-scale integration and low-power consumption. We further discuss multiple novel devices enabled by silicon photonic contra-DCs, including a microring resonator that resonates at a single wavelength (i.e., does have a free-spectral range) and a four-port Bragg photonic resonator for high-speed, low-power optical switching. By a novel, coupler-chirped design with uniform Bragg gratings, we have recently achieved an on-chip, continuously tunable photonic delay line with low insertion loss. These system-orientated devices indicate great potential for large-scale integration of Bragg-grating-defined functions using CMOS-compatible nanophotonic technology.

9010-16, Session 6

Monolithic silicon waveguides in bulk silicon wafers *(Invited Paper)*

Chia-Ming Chang, Olav Solgaard, Stanford Univ. (United States)

Silicon photonics has been extensively studied in recent years because of its compatibility with electronics and its potential for solving interconnect bottlenecks using optical interconnects. The implementation of silicon photonic devices for optical interconnects usually requires silicon-on-insulator (SOI) platform as the buried oxide layer can provide optical field confinement. However, the SOI platform has several limitations, including non-standard CMOS technology, yield issues due to residual stress in device silicon layers, different BOX requirements for electronics and photonics, and difficulty for 3D photonics. In this paper, we describe a local oxidation approach that allows us to fabricate silicon photonic devices from standard silicon. Such a method can be further extended to demonstrate 3D photonics that can address the issue of limited real estate in a single device silicon layer.

Using the local oxidation method, we demonstrate submicron oval optical waveguides with propagation loss of 2.34 dB/cm in standard silicon wafers, which is comparable to existing low loss SOI channel waveguides (2-3 dB/cm). This local oxidation method is also well-suited to implement 3D photonic devices. We demonstrate self-aligned double-layer silicon waveguides in standard silicon. Our method simplifies the integration of photonics with electronics in standard silicon wafers for on-chip optical interconnects, and provides the potential to build 3D photonics that are very challenging in an SOI platform.

9010-17, Session 6

Monolithically-integrated Ge CMOS laser *(Invited Paper)*

Rodolfo E. Camacho-Aguilera, Massachusetts Institute of Technology (United States)

Germanium on Si growth techniques have permitted the developement of fully-CMOS modulators, photodetectors and, recently, light emitters. Ge light emitters have been demonstrated by our group with emission by changing the Ge band structure with the aid of tensile strain and heavy doping. Furthermore, Ge shows a temperature dependence that contradicts the trend in other semiconductors.

Development of Ge diodes and lasers through application of in-growth 0.2% biaxial strain and insitu n-type doping concentration >10^19cm^-3 has led to believe that Ge can be fully integrated on all-to-all photonic integrated chip. Ge laser and diodes were demonstrated, showing a net gain >1000cm^-1 and with an emission bandwidth larger than 200nm. This would permit Ge lasers to be used in different communication bands. Moreover, the operation temperature ranging from 25oC – 120oC makes it a viable option to other lasing semiconductors. Analysis suggest that the lasing threshold can be reduced down to 1kA/cm^2 depending on its architecture. New architectures and future process advances will prove Ge to be the most viable option for on-chip photonic integration.

9010-18, Session 7

Germanium light-emitting diodes on silicon for very-short-reach interconnect *(Invited Paper)*

Misuzu Sagawa, Katsuya Oda, Kazuki Tani, Yuji Suwa, Jun-ichi Kasai, Tadashi Okumura, Shin-ichi Saito, Tatemi Ido, Photonics Electronics Technology Research Association (Japan) and Photonics-Electronics Convergence System Technology (Japan) and Hitachi, Ltd. (Japan)

Many components and photonic integrated circuits based on silicon photonic technology are studied and reported intensively for very short-reach interconnect. However, light sources based on IV-group material are still to be developed for monolithic light sources on silicon. Heavily n-doped tensile-strained germanium is one of the strong candidates for this purpose. Here, we review and discuss our recent results with Ge light emitting devices on Si theoretically and experimentally.

Our approach to enhancing light emission is to apply process-induced strain to the Ge active layer. According to our first-principles calculations, larger optical gain in Ge with less carrier density is obtained at a larger tensile strain. Thus, we apply process-induced stress to the Ge active layer by fabricating a Si_3N_4 stressor on it in addition to the thermally induced strain caused by the difference of the thermal expansion ratios. An increase in intensity and the red-shift of the PL peaks indicated that additional tensile strain was applied successfully to the Ge active layer. As for light emitting devices, we proposed a laterally injected light emitting device. In this device, the current is laterally injected into the Ge active layer through the thin Si layer. In this structure, mode loss caused by free carrier absorption is expected to be small since the guided mode does not overlap much with the heavily doped Si layer. The electroluminescence property showed a super-linear increase in integrated EL intensity with the injection current, which indicates direct recombination enhancement due to L-valley filling.

9010-19, Session 7

Advances in silicon photonics WDM devices
(Invited Paper)

Philippe Absil, IMEC (Belgium)

System performance scaling imposes an increase of package-to-package aggregate bandwidths to interface chips in high performance computing. This scaling is expected to encounter several I/Os bottleneck (pin count, speed, power consumption) when implemented in the electrical domain. Several optical interface technologies are being proposed among which silicon photonics, considered as a promising candidate. In this paper we will review the recent progress made in this technology that may enable multi-channel WDM links package-to-package interconnects: 1V drivers with micro-ring modulators and compact manufacturable microring filters with efficient thermal tuning.