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8255-01, Session 1

Spontaneous two-photon emission from semiconductors and its prospect

I. Suemune, Hokkaido Univ. (Japan)

Spontaneous two-photon emission is important in various research fields such as astrophysics, atom physics, nonlinear optics as well as quantum information processing and communication. The generation of entangled photon pairs is the key for realizing quantum repeaters (for example, S. M. Shahriar, Physics, published July 25, 4, 58 (2011)).

In any solid-state devices, the spontaneous two-photon emission is a second-order process which makes the experimental observation a challenge. Therefore two-photon emission processes from semiconductors have been mainly limited to cascade emission processes from quantum dots. However, recently the possibility has been explored with proposals and realization of several different techniques. This mini-symposium aims at the extensive discussion how to realize efficient spontaneous emission of indistinguishable photon pairs from semiconductors.

8255-02, Session 1

Applications of quantum photonics for communications and metrology

A. Hayat, A. Darabi, L. A. Rozema, D. Mahler, Y. Soudagar, X. Xing, A. Feizpour, A. M. Steinberg, Univ. of Toronto (Canada)

We investigate novel quantum photonic devices and applications in quantum communications and enhanced measurements.

We demonstrate spontaneous two-photon emission in semiconductors. This phenomenon is proposed as an electrically-driven source of entangled photons, and a theoretical model is developed eliminating the unphysical divergences of previous methods.

Quantum photonic sources can be employed for novel metrology schemes based on weak measurements, which allow probing of phenomena previously deemed inaccessible. Unlike the uncertainty relation, another relation postulated by Heisenberg setting the limit on measurement precision resulting in disturbance, was proven to be inaccurate, in contrast to widely-accepted limitations of high-precision metrology. We present an experimental realization of Heisenberg's precision limit violation for photon spin, based on weak value measurements employing polarization-entangled photon pairs from downconversion.

We show theoretically that weak measurements can be used to enhance optical nonlinearities at the single photon level, offering an improvement in signal-to-noise ratio in the presence of long-correlation technical noise. Moreover, fermion systems require characterization of an interaction using one particle at a time due to the Pauli principle. This makes slow technical noise unavoidable, and weak value amplification may provide a unique solution.

8255-03, Session 1

Spontaneous two photon emission from a single quantum dot coupled to photonic crystal nanocavity

Y. Ota, S. Iwamoto, N. Kumagai, Y. Arakawa, The Univ. of Tokyo (Japan)

Spontaneous two photon emission (TPE), in which a pair of photons is simultaneously emitted, is important in broad area of research, from astrophysics and atomic physics to nonlinear optics and quantum information processing. In spite of this importance, so far, it has not been possible to observe the spontaneous TPE in solid-state single quantum emitters due to extremely low probability of its occurrence. Here, we for the first time demonstrate spontaneous TPE from a single quantum emitter in the solid state. We performed photoluminescence measurements and investigated the biexciton in a semiconductor quantum dot coupled with a high Q photonic crystal nanocavity. Under the two photon resonance of the biexciton to the cavity mode, enhanced emission from the cavity was observed. Meanwhile, suppression was observed for the single photon cascaded emission processes from the biexciton. These results demonstrate faster TPE process for the biexciton than its single photon processes, due to Purcell effect for the two photon transition. The observed spectra were well reproduced by a master equation based numerical calculations, which reveal negligible contribution from the stimulated processes by photons inside the cavity. Thus, the observed TPE is confirmed to be spontaneous. The demonstrated two-photon source based on quantum dots and nanocavities are appealing for many applications, such as two photon lasers and quantum information technologies based on two photon processes.

8255-04, Session 1

Generation of a two-photon state from a quantum dot in a microcavity

E. del Valle, Technische Univ. München (Germany)

We propose a two-photon source that emits in a highly polarised, monochromatic and directional beam, realised by means of a quantum dot embedded in a linearly polarised cavity. In our scheme, the cavity frequency is tuned to half the frequency of the biexciton (occupation of the quantum dot by two excitons of opposite spins) and largely detuned from the single exciton states thanks to the typically large biexciton binding energy. Single-photon processes are thus effectively suppressed while simultaneous two-photon emission into the cavity mode, is Purcell enhanced. We suppose the quantum dot initially prepared in the biexciton state and analyse how the two-photon state is created by the system in a chain of virtual processes that cannot be broken apart in physical one-photon states. Our understanding is analytical and allows for optimisation of a practical setup, enabling the realisation of a practical source of two simultaneous and indistinguishable photons in a monolithic semiconductor device.

In collaboration with A. Gonzalez-Tudela, E. Cancellieri and C. Tejedor (Universidad Autónoma de Madrid, Spain) and F. P. Laussy (Walter Schottky Institut, München, Germany).

8255-05, Session 1

Two-photon emission process with Cooper-pair injection into semiconductors

H. Sasakura, I. Suemune, H. Kumano, C. Hermannstaedter, Hokkaido Univ. (Japan)

The polarization-entangled photon pair sources based on solid-state device have drawn increasing attention because of key roles in quantum information networks, which are expected to ultimately raise security level compared to the current communication system. We have investigated the photon generation process on a Nb/n-InGaAs/p-InP superconductor/semiconductor-diode light emitting device both experimentally and theoretically. Electron Cooper-pairs injected from a superconducting electrode into a semiconductor recombine with holes injected from a p-type electrode. The measured electroluminescence decay time for the optical-fiber communication band emission rapidly decreases with decreasing temperature below the superconducting transition temperature of the niobium electrodes. The measured decay time at the temperature above the superconducting transition temperature (Tc) of the niobium electrodes is constant and corresponds to ~2.25 ns of the reference LED without the niobium electrodes, whereas it decreases abruptly below Tc. At 0.8 K, decay time constatnt is shortened down to ~1.1 ns. The formation of electron Cooper-pairs initiates in the Nb electrode below Tc and the onset temperature of the EL decay time shortening precisely agrees with Tc. This agreement as well as the significant decay time shortening below Tc demonstrates the major role of the injected Cooper-pairs for the enhanced recombination rate in the LED. The temperature dependence of the radiative recombination rate can be explained by a theoretical model. From the decay time change with the superconductivity, we can derive the ratio of the Cooper-pair and normal-electron contributions in the recombination process and it is as 43% and 57% at 3 K, respectively. From the view point of practical sources, one of the most impotant elements are the statistical mixture of the entangled photon pairs which corresponde to the photons originating from the electron Copper-pair (43%) and polarization-uncorrelated photons which correspondes to the single photon emission (57%). The results suggest that the electron Cooper-pair can be highly involved in the interband transition and accelerate the photon generation processes. Our results indicate the possibility to open up new interdisciplinary fields between superconductivity and optoelectronics.

8255-06, Session 2

Frequency chirp stabilization in semiconductor distributed feedback lasers with external control

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The frequency chirp under direct current modulation originates from variations in the carrier density and from the finite difference in carrier density between the laser on and off states. Indeed, it is known that the diode laser's current modulation generates amplitude (AM) and optical frequency (FM) modulations. Consequently, modulation of the carrier density also modulates the gain and so the optical index causing the resonant mode to shift. This frequency chirping is also known to broaden the modulated spectrum, which is a serious limitation for high-speed applications and chirpless optical fiber communications. This paper aims to show that the laser's frequency chirp can be manipulated using an external control. The chirping response is evaluated via the determination of the chirp-to-power ratio (CPR) through a Mach-Zhender interferometer. Experiments conducted both under small- and large signal configurations demonstrate that when the external optical feedback is properly adjusted, the CPR can be drastically decreased down to constant values over a wide range of modulation frequencies as compared to the free-running case. These preliminary results obtained on quantum well distributed feedback lasers (QW DFB) demonstrate the feasibility to stabilize the frequency chirp through the manipulation of fundamental laser's parameters such as the effective linewidth enhancement factor. In order to confirm the frequency chirp manipulation, self-consistent calculations based on the transfer matrix method are presented. Various complex cavity designs such as tapered DFB lasers will be also investigated. Finally, further studies will investigate the case of nanostructure based semiconductor lasers.

8255-07, Session 2

Rate equation analysis of dynamic response in strongly injection-locked cascaded semiconductor microring lasers

G. A. Smolyakov, M. Osinski, The Univ. of New Mexico (United States)

Directly modulated laser sources with very high modulation bandwidths exceeding 100 GHz are highly desirable for the rapidly growing applications of RF optical fiber links. 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. A novel optical injection-locking scheme for modulation bandwidth enhancement has been recently proposed involving distributed Bragg reflector master laser monolithically integrated with strongly injection-locked unidirectional microring laser. Enhanced high-speed performance of that scheme has been confirmed in numerical modeling by comparing it with the scheme where optical injection was provided by a waveguide directional coupler adjacent to the ring laser. Typical for all optical injection-locking schemes, however, the modulation response showed a very significant reduction in the modulation efficiency between low frequency and the resonance frequency, which limited the usefulness of that injection-locking scheme to narrow-band applications. One possible way to overcome the low-frequency roll-off problem and to attain tailorable and broad modulation bandwidth is to use cascaded injection locking. Using this concept, we modified the injection-locking scheme to a cascaded system with two strongly injection-locked unidirectional ring lasers, where the modulated optical output of the first ring laser is used to injection-lock the second ring laser. Improved high-speed performance of the proposed cascaded injection-locking scheme was confirmed in numerical modeling by comparing it with the scheme based on a single strongly injection-locked unidirectional microring laser.

8255-08, Session 2

Optical spectral analysis of the nonlinear dynamics in long-wavelength single-mode VCSELs subject to orthogonal optical injection

A. Valle, A. Quirce, P. Perez, L. Pesquera, Univ. de Cantabria (Spain)

Optical injection can induce a rich variety of nonlinear dynamics in the light emitted by a semiconductor laser. Nonlinear dynamics of optically injected Vertical-Cavity Surface-Emitting Lasers (VCSELs) emitting at the telecom wavelength of 1550 nm has been recently studied. Most of the studies consider linearly polarized light from a tunable laser that is injected orthogonally to the linear polarization of a free-running VCSEL, the so-called orthogonal optical injection.

We perform an experimental and a theoretical analysis of the polarization-resolved nonlinear dynamics of a 1550 nm wavelength single-mode VCSEL when subject to orthogonal optical injection. We measure high-resolution (10 MHz) optical spectra, and simultaneous time traces of the power of the linear polarizations emitted by the VCSEL. Different injected powers and detunings between the frequency of the injected signal and the free-running frequency of the VCSEL are considered. Special attention is paid to the case of negative frequency detuning, for which irregular dynamics has been observed in both linear polarizations. For periodic dynamics, both linear polarizations show spectra with equally spaced peaks, with a separation that corresponds to the frequency detuning. As the injected power increases much more peaks are observed with less separation between them. By increasing the injected power we obtain irregular dynamics that is characterized by optical spectra for both linear polarizations with wide pedestals and much less defined peaks. Simultaneous polarization switching and injection locking phenomena are obtained when increasing the injected power. A good overall qualitative agreement is found between our theoretical and experimental results.

8255-09, Session 2

Dynamics of polarization switching in a 1550-nm VCSEL subject to single and double polarized optical injection

A. Hurtado, I. D. Henning, M. J. Adams, Univ. of Essex (United Kingdom)

We report a first experimental analysis of the time dependent dynamics associated with the Polarization Switching (PS) that can be induced in the two orthogonal polarizations of the fundamental mode of a 1550nm-Vertical Cavity Surface Emitting Laser (VCSEL) subject to polarized optical injection. We have investigated two different experimental configurations, namely single and double polarized optical injection into the 1550nm-VCSEL with polarizations parallel and orthogonal to that of the light emitted by the solitary device. We have simultaneously analysed the temporal stability as well as the switching and recovery times for the two orthogonal polarizations at the VCSEL output. Sub-ns response times were obtained for both experimental configurations. For single orthogonally-polarized optical injection we have found that the operation speed is ultimately limited by the relaxation oscillation frequency of the VCSEL. On the other hand, when the device is subject to double optical injection (parallel- and orthogonally-polarized) a significantly enhanced operation speed was obtained. We believe that this improved time response is due to the faster carrier dynamics associated with the switching between the two injection-locked states induced alternatively by the two polarized optically-injected signals. This enhanced operation speed for the PS attained in VCSELs at the important telecom wavelength of 1550nm offers exciting prospects for novel uses of these devices in optical signal processing and optical switching applications in present and future optical networks.

8255-10, Session 3

Free carrier effects in 1.3-um quantum dot lasers leading to a negative differential gain

H. Shahid, D. T. D. Childs, B. J. Stevens, R. A. Hogg, The Univ. of Sheffield (United Kingdom)

The measurement and prediction of the evolution of the gain spectrum with temperature and current density is of vital importance to describe the operation of semiconductor lasers and amplifiers. The understanding of many body effects such as band gap renormalization, broadening due to intra band scattering, and Coulomb enhancement of the optical transition at high carrier densities has been of significant interest for bulk and quantum well devices. GaAs based quantum dot based optical devices are currently commercialized in the 1000-1300nm region, yet despite this there are few reports on many body effects in such devices. Of particular interest is the theoretical prediction of negative differential gain in quantum dot lasers, brought about by gain saturation yet increasing de-phasing effects with increasing current density.

We report on the study of the gain spectra of quantum-dot lasers at high carrier densities. By using the wavelength of individual Fabry-Perot modes a temperature sensor the junction temperature can be maintained at a constant level, allowing the observation of free carrier effects alone. In this way we are able to measure the gain spectra at excitation levels up to ~8 e-h pairs per quantum dot. At high current densities (> ~2 e-h pairs per QD) we observe a broadening of the ground-state gain peak which we attribute to increasing de-phasing effects in the quantum dots. This results in a ~15% reduction in peak ground-state gain at the highest drive currents.

8255-11, Session 3

Temperature effects on the characterization of new quantum dot dual mode lasers for terahertz generation

B. Gonzalez Izquierdo, H. Lamela Rivera, Univ. Carlos III de Madrid (Spain); V. Sichkovskyi, J. P. Reithmaier, Univ. Kassel (Germany)

An important expected advantage of semiconductor quantum dot (QD) lasers over the conventional quantum well (QW) lasers is extremely weak temperature sensitivity of the threshold current. Ideally, threshold current of a QD laser should remain unchanged with the temperature and the characteristic temperature T0 should be infinitely high if the overall injection current was showed entirely into the radiative recombination in QD's (Y. Arakawa et al., Appl. Phys. Lett., vol. 40, no. 11, 1982). In fact, because of the presence of free carriers in the optical confinement layer (OCL), a fraction of the injection current is wasted therein.

Previous works have demonstrated that the threshold current is increased when the temperature is increased as well (J. Piprek et al., JOQE, Vol. 36, No. 3, 2000). In this work, we will study and model the temperature effects on the output power as well as the threshold current density in new AlGaAs/GaAs/InGaAs Quantum Dot Lasers. Temperature dependences of the threshold current density components associated with the radiative recombination in QD's are calculated by means of the rate equations of the system including the thermal effects. The characteristic temperature of QD laser T0 is calculated through the experimental results which show to fall off profoundly with increasing temperature when the temperature conditions wherein threshold current density is controlled by radiative recombination in the optical confinement layer instead of radiative recombination in QD's (P. Abraham et al., Semicond. Sci. Technol. 14, 1999). Therefore, by controlling the temperature of this new QD Laser, we can obtain dual mode sources for Terahertz applications. This work is supported by MITEPHO project (www.uc3m.es/portal/page/portal/grupos_ investigacion/optoelectronics/european projects/mitepho) which is coordinated by GOTL research group in Carlos III de Madrid University with foundation grant agreement number 238393 (EU-FP7) in order to develop compact tunable dual-mode diode lasers and terahertz spectroscopy in sensing and biomedical applications.

8255-12, Session 3

Numerical simulation of nonlinear mode interactions in ridge-waveguide semiconductor lasers

H. Kalagara, P. G. Eliseev, M. Osinski, The Univ. of New Mexico (United States)

In semiconductor lasers and amplifiers, when a driving wave of sufficiently high intensity interacts with a probe wave, the modal and group index parameters of the probe wave are perturbed. The group index (ng = c/v) for the probe wave increases to certain value (where v c corresponds to superluminal propagation).The points where the group index passes zero are called critical anomalous dispersion (CAD) points. This nonlinear perturbation of modal and group index parameters is demonstrated in numerical simulations for the InGaAs/AlGaAs/GaAs double quantum well (DQW) laser structure and also for the GaAs/AlGaAs separate confinement heterostructure. The magnitude of nonlinear perturbation of probe wave depends on the intensity of the driving wave, the relaxation rate of the energy levels, and on the optical confinement in the laser structure. The CAD points (represented as Z1, Z2) for various intensity values of driving wave are found and plotted for both the structures. The CAD points Z1, Z2 form a closed loop; the superluminal regime starts appearing for sufficiently high intensity of driving wave, it increases as the intensity increases, and then starts to decrease and finally disappears for very high intensity. For the InGaAs/AlGaAs/GaAs DQW structure, the superluminal regime appears at a higher value of the driving wave intensity (5 kW/cm2) when compared to GaAs/AlGaAs SCH laser (0.2 kW/cm2). The loop closes at a lower value of the driving wave intensity for the DQW when compared to SCH structure, due to lower optical confinement factor of the DQW laser structure. The nonlinear perturbation also depends on the relaxation rate of the carriers in addition to the intensity of driving wave. For the DQW laser structure, the superluminal regime is obtained only for relaxation rate < 1010 s-1. This is because the perturbation spectrum broadens as the relaxation rate of the energy levels increases, which leads to decrease of magnitude of the interaction effect. The magnitude of nonlinear effect in the SCH structure is much higher than that in the DQW structure, because of better optical confinement in the SCH structure. The threshold intensities for the appearance of CAD points, the influence of relaxation rate and optical confinement on the appearance of superluminal regime for the DQW and SCH structures are compared.

8255-13, Session 3

Hybrid quantum well/dot structures for broad spectral bandwidth devices

S. C. Chen, K. J. Zhou, Z. Zhang, D. T. D. Childs, A. J. Ramsay, R. A. Hogg, The Univ. of Sheffield (United Kingdom)

The realization of broad spectral band-width emitters and amplifiers is of considerable interest for a range of applications such as optical coherence tomography (OCT), fiber-optic gyroscopes and wavelength division multiplexing (WDM) systems. Recently, quantum dot (QD) based devices have attracted significant attention due to their inhomogeneous size distribution and state-filling effects. A broadened emission can be achieved through chirping the emission energy of layers in a multilayer stack, growing an inhomogeneous dot distribution, or post-growth annealing. However, due to the increasing degeneracy of higher energy QD states it is only possible to readily achieve 3dB bandwidths of around 150nm with such structures.

Here we report the first hybrid quantum well (QW) and QD structure to achieve broad spontaneous emission and gain spectra. These structures consist of an InGaAs QW (emission peak at ~1125nm coincident with the QD second excited state) and 6 InAs dot-in-well (DWELL) layers (ground-state emission at ~1300nm). We show room temperature spontaneous emission with a 3dB bandwidth of ~250nm (from surface emission mesa diodes) and modal gain spanning ~300nm, obtained from multisection devices. We show that the spontaneous emission and gain is due to the combination of QD ground states, first excited state, and quantum well emission. We describe how this is achieved only by careful design of the structure, balancing thermal emission from the QW and transport/capture processes in the QDs. We will also compare results from a range of epitaxial structures to describe how broadband gain/emission can be achieved in this new type of structure.

8255-14, Session 4

Bandstructure influences on InGaN light-emitting diode efficiency

W. W. Chow, Sandia National Labs. (United States)

Bandstructure properties in wurtzite quantum wells (QWs) depend on carrier density because of screening of quantum-confined Stark effect (QCSE). An approach for incorporating these changes in an InGaN light-emitting-diode (LED) model is described. Bandstructure is computed for different carrier densities by solving Poisson and k·p equations. The information is used as input in a dynamical model for populations in momentum-resolved electron and hole states.

In addition to direct input of bandstructure properties, the model provides consistent treatment of spontaneous emission, carrier capture and leakage, and nonequilibrium effects. Thus, the spontaneous-emission fitting parameter is eliminated and effects, such as plasma heating, are taken in account within an effective relaxation rate approximation for carrier-carrier and carrier-phonon scattering.

Application of the model is demonstrated with two examples. The first shows that higher defect recombination in QWs than barriers, when combined with bandstructure changes, can give rise to an efficiency droop. The second example describes the Auger contribution in maintaining efficiency droop to high current densities, as observed in experiments. By including bandstructure changes, the necessary Auger coefficient is in better agreement with microscopic calculations than estimates from experimental curve fitting using the ABC model.

In summary, the model allows systematic incorporation of contributions to LED efficiency. It is possible that the differences in observed droop behavior (involving wavelengths, polar versus non-polar substrates, electron-blocking layers, etc.) arise from differences in relative importance of various mechanisms. The k-resolved LED model can provide a more precise estimation of their relative strengths than the often-used ABC model.

8255-15, Session 4

Computational study of white InGaN/GaN nanowire LEDs with continuously varied indium composition

M. Deppner, F. Roemer, B. Witzigmann, Univ. Kassel (Germany)

Gallium nitride based light emitting diodes have emerged as powerful devices which could replace incandescent and fluorescent lamps within the next years. The development of phosphor-free white LEDs is still an ongoing field of research because of the lack of high efficiency green LEDs.

A promising approach is the growth of InGaN/GaN nanowires with a continuously varied Indium content along the structure (Guo et al., Nano Lett. 2010, 10, 3355-3359). The graded mole fraction profile yields a multitude of energy levels which can sum up to white light emission. The formation of strain and polarization charges is reduced because of the incremental varying lattice constants in combination with the facility of lateral relaxation of the wire.

We report on the computational analysis of those nanowire structures in order to understand the electroluminescent behavior and to establish fundamental design guidelines. The simulation software calculates the electrostatic potential and the carrier densities in the entire structure by solving the Poisson and the drift/diffusion equations. The luminescence is determined on the basis of a free carrier theory and enters the continuity equations as recombination term. Strain and polarization charges are analyzed as a function of the nanowire diameter and the Indium distribution along the wire.

The electro-optical characteristics basically depend on the wire geometry, the mole fraction profile and the corresponding strain and polarization effects. Using comparative simulations we will present an optimized design that balances the wire diameter and the Indium distribution featuring a white luminescence spectrum.

8255-16, Session 4

Enhancing the luminescence and efficiency of InGaN/GaN core-shell nanowire LEDs by numerical modelling

F. Roemer, M. Deppner, B. Witzigmann, Univ. of Kassel (Germany)

GaN based LEDs have emerged to powerful and efficient light sources which are increasingly utilized for illumination purposes. Actual research on this field pursues the development of phosphorous-free white LEDs integrating efficient InGaN/GaN based blue, green, and red emitters.

Core-shell nanowire LEDs present a novel strategy for efficient green and red emission growing the active InGaN region laterally on GaN pillars. This design increases the active area compared to a planar LED. Above, it has the potential for reducing the effect of the lattice mismatch strain on the efficiency by having non-polar quantum wells on the side walls.

The multitude of design parameters creates the need for a predictive, physics based simulation.

In this context we present a multidimensional and fully coupled physics simulator for modelling nanostructured LEDs. The simulation model couples bulk and low dimensional carrier transport and the electrostatic potential. For computing quantization and luminescence the kp Schroedinger problem is solved. The solver targets a self-consistent solution between the drift-diffusion transport problem and spatially resolved kp Schroedinger problem. The physics simulator has been calibrated with the characteristics of planar GaN-based quantum well LEDs.

Using this simulator we investigate the effect of the dimensions of the nanowire, the design of the active quantum wells, and the current injection strategy on the luminescence spectra and the efficiency of core-shell nanowire LEDs. The results have been found to provide a consistent picture and are used to define strategies for an optimized implementation.

8255-17, Session 4

The effect of exciton dimensionality on resonance energy transfer: advances for organic color converters in hybrid inorganic/ organic LEDs

J. J. Rindermann, Univ. of Southampton (United Kingdom); G. R. Pozina, B. Monemar, L. Hultman, Linköping Univ. (Sweden); H. Amano, Nagoya Univ. (Japan); P. G. Lagoudakis, Univ. of Southampton (United Kingdom)

Hybrid optoelectronic devices combine the superior electrical properties of inorganic semiconductors with the strong optical absorption and emission found in organic materials and colloidal quantum dots (QDs). Such hybrid material combinations can be used in light emitting diodes where a GaN-based UV/blue-emitting diode pumps a color-converting overlayer of organic or QD material. They promise to show higher color conversion efficiencies than conventional phosphors, and enable in-room white light communication with modulated LEDs. Organic materials and QDs not only parade with superior physical properties, but their production is cheap and enables independence from phosphors based on rare-earths which are becoming increasingly scare.

In this work we study resonance energy transfer (RET) from a GaN QW to a F8BT overlayer separated by a 4 nm thin capping layer. RET is a dipolar coupling mechanism that is extremely efficient for the transfer of excitation energy to the color converter in closely packed configurations. We study experimentally and theoretically the effect of exciton dimensionality on RET: only at elevated temperatures greater than 100 K excitons escape from traps in the potential disorder of the QW and undergo efficient RET when their wave vector is sufficiently small (44% and 23% efficiency at 130 K and 300 K respectively). Emission and re-absorption of light is 100 times less efficient. Based on our quantitative simulations we propose that efficient RET can be enabled for capping layers up to 20 nm thick. This finding has immediate implications for the commercialization of such devices as it enables thicker capping layers which carry current.

8255-19, Session 5

Numerical method for precise simulation of optical modes in VCSELs

S. Burger, M. Rozova, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); J. Pomplun, F. Schmidt, JCMwave GmbH (Germany)

Due to their small dimensions and complex design vertical-cavity surface-emitting lasers (VCSELs) with very promising properties can be demonstrated. This includes circular beam profiles and high modulation bandwidths. Optical mode solvers are used to design VCSEL geometries and material distributions for improved performance. For some state-of-the-art VCSELs (e.g., photonic-crystal VCSELs) real three-dimensional geometric setups have to be modelled in the numerical analysis. A recent benchmark has revealed limitations of approximative methods and discrepancies between results from implementations of rigorous methods [1]. The main reasons for this are the geometrical complexity of non-axially symmetric VCSELs requiring full 3D Maxwell-solvers, and strong scattering of light at corners and edges of geometrical objects in the setup [1].

We have developed finite-element method (FEM) based solvers for the Maxwell eigenvalue and for the Maxwell scattering problems. The method is based on higher order vectorial elements, adaptive unstructured grids, and on a rigorous treatment of transparent boundaries [2].

In this contribution we demonstrate accurate FEM results for photonic crystal VCSELs in the setup of [1]. We further show results from a convergence study comparing 3D results to results obtained with an axially symmetric FEM solver for an axisymmtric setup [3]. Values for the resonance wavelength (computed with the 3D solver) converge to an accuracy of better than one percent of a nanometer (relative accuracy about 10^(-6)). A relative accuracy of the laser threshold of about 1 percent is reached in 3D simulations.

[1] M. Dems, et al., Numerical Methods for modeling Photonic-Crystal VCSELs, Opt. Expr. 18, 16042 (2010).

[2] S. Burger, et al., Finite-element method simulations of high-Q nanocavities with 1D photonic bandgap, Proc. SPIE 7933, 79330T (2011).

[3] P. Bienstman, et al., Comparison of optical VCSEL models on the simulation of oxide-confined devices, IEEE J. Quant. Electr. 37, 1618 (2001).

8255-20, Session 5

A meshless based solution to vectorial mode fields in optical microstructured waveguides

D. Burke, T. J. Smy, Carleton Univ. (Canada)

A meshless solution to vectorial mode fields has been applied to various micro-structured optical waveguides. The Finite Cloud Method, FCM, has been used to solve coupled field equations for both transverse components of the magnetic field as well as the effective index of refraction for the waveguides. Two methods using either a step-index or a graded-index have been implemented and compared. An approximation to the solution is found using a distribution of points and a cloud about each point, with no mesh and minimal geometric linking knowledge between the points. This gives the ability to use a highly irregular point distribution which can be easily modified or tailored to micro-structured fibers in order to accurately represent the vectorial modal solution.
In addition, a Bayliss-Gunzburger-Turkel-like transparent boundary conditions (TBC) and an iterative process is compared with a perfectly matched layer (PML), both of which allow for the solution of leaky modes for the structures. Results for ridge waveguides and solid core fibers having low index contrast are in high agreement with the solutions from commercial solvers. Further results with high contrast air hole structures are compared with other solution methods giving promising results and highlight this methods versatility, accuracy and efficiency for a wide range of problems.

8255-21, Session 5

On the performance of numerical modeling for diffractive grating using couple mode theory

D. Wang, OSRAM SYLVANIA Inc. (United States)

A well known coupled mode theory is used to analyze the diffractive volume gratings using the scalar wave equation: , and k =ko+jα is the complex wave number including absorption constant α, ko =2πn/λ. Both n and α have large components no, αo for the bulk grating recording material, and small modulation terms with amplitudes n1, α1, i.e., index modulation resulting from spatial variations inside the diffractive grating. E includes two components: incident light with an amplitude I and diffracted light with its amplitude D. Coupled differential equations for the incident and diffracted beams are established from the scalar wave equation. The optical power is transferred from the incident beam to the diffracted lighting indie the diffractive grating, and the diffraction efficiency can be evaluated by the optical power coupling and transferring process, which is determined by Bragg condition, modulation index, the absorption constant and thickness of the grating.

A numerical solution to coupled differential equations has been developed using finite difference method. Detailed optical power transfer process inside the grating was first simulated under different deviations from Bragg conditions to analyze the combination effects from key parameters such as grating material absorption coefficient, modulation index and grating thickness. Different polarization modes, TE and TM were used to simulate and model the coupling process and diffraction efficiency. Finally, our solutions to these couple mode equations were compared with the results from standard numerical recipe using Runge-Kutta formulas. The convergence and stability, numerical accuracy of these numerical solutions were evaluated.

8255-22, Session 5

Choice of the perfectly matched layer boundary condition for iterative solvers of the frequency-domain Maxwell's equations

W. Shin, S. Fan, Stanford Univ. (United States)

The Perfectly Matched Layer (PML) boundary conditions are widely used to simulate an infinite space in numerical solvers of Maxwell's equations. We show that the convergence rates of iterative solvers of the frequency-domain Maxwell's equations are greatly enhanced by using the stretched-coordinate PML (SC-PML) instead of the uniaxial PML (UPML), which are the two most commonly used PMLs. We use the finite-difference frequency-domain (FDFD) method to construct a system of linear equations out of Maxwell's equations. The resulting system of linear equations is solved by iterative methods such as the quasi-minimal residual (QMR) method and biconjugate gradient (BiCG) method. Then, the convergence rates of the iterative methods are measured for a variety of 3D electromagnetic systems to demonstrate that SC-PML induces much faster convergence than UPML. To explain such superiority of SC-PML over UPML, the condition number of Maxwell's equations is estimated using the variational method. As a result, SC-PML is shown to produce a much smaller condition number than UPML; this accounts for the significant difference in the convergence rate for the two PMLs, because iterative methods converge faster in general when the condition number of the equation they solve is smaller. Finally, we show that the slow convergence for UPML can be amended by preconditioning the frequency-domain Maxwell's equations appropriately.

8255-23, Session 5

The light path tree algorithm for non-sequential field tracing

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Field tracing generalizes the concepts of ray tracing. In particular harmonic fields are traced through the system instead of ray bundles. Hence field tracing utilizes and provides more information about the light in optical systems. The error due to the physical approximation can be minimized and consequently many effects as e.g. diffraction and interference are modeled much more accurate than by ray tracing. In this talk, we introduce a new approach for the analysis of multiple reflections that occur between the optical interfaces of an optical system. We establish a non-sequential formulation of the multiple reflection problem by combining individual propagation steps between two optical interfaces at a time.

The analysis of the convergence of the tracing algorithm is based on Neumann series. The resulting non-sequential simulation algorithm is being described by the light path tree. The tree starts with nodes representing source fields. Higher levels of the tree correspond to summands of the Neumann series. Nodes of these higher levels of the tree are associated with harmonic fields at optical interfaces. Connections between nodes represent propagation steps of harmonic fields. The light path tree algorithm is both, the theoretical tool to describe the algorithm, and the practical tool for the implementation of the non-sequential field tracing algorithm.

Some examples and convergence results obtained with the software VirtualLab (www.lighttrans.com) are presented. In particular we are going to validate the light path tree algorithm for the special case of stratified media by comparing it to the layer matrix solution method.

8255-24, Session 6

Fundamentals of excitation and resonance of a near-field transducer in the presence of a conductive magnetic recording medium

J. R. Piper, P. Hansen, L. Hesselink, Stanford Univ. (United States)

Plasmonic Near-Field Transducers (NFTs) find use in Energy-Assisted Magnetic Recording (EAMR) schemes, where a high-anisotropy recording medium is locally heated to the Curie temperature, allowing conventional magnetic recording heads to overcome the medium's high coercivity. In this way, magnetic bit volume can be reduced, and areal recording density increased, while maintaining adequate thermal stability of the recorded information. NFTs with optical spot sizes on the order of 50 nm have been demonstrated, in line with areal density goals of multiple Tb/sq in. However, the NFT-media coupling efficiency is low (on the order of a few percent), and the conditions for excitation and resonance are poorly understood. In this work, we use theoretical analysis, including mathematical topology and systematic FDTD simulations, to evaluate the resonance conditions of a canonical EAMR setup including rectangular dielectric waveguide, elliptic cylinder gold NFT, and conductive planar recording medium. Multiple factors affecting resonance and coupling efficiency are examined, including polarization and angle dependence; spacing between NFT, waveguide, and recording medium; and variations in NFT size and incident wavelength.

8255-25, Session 6

Investigations of deterministic IR surface plasmon properties in doped zinc oxides

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IR plasmonics is expected to play a key role in chip-scale nanophotonic system development due to lower propagation loss, improved chemical specificity in sensor applications, and the possibility of hybrid dielectric/plasmonic subsystems. In order to excite a surface plasmon, the optical frequency must be lower than the plasma frequency of the surface plasmon host. Noble metals satisfy this requirement but are known to either be lossy when the plasmon is tightly bound or suffer poor mode confinement when loss is low. This work investigates the excitation, propagation, and related losses of doped metal oxides and their use as plasmonic host materials in the mid- to long-wave (6-12 µm) infrared regime. A particular material may be useful for plasmonics when an acceptable tradeoff between loss and mode confinement is obtained. By varying the stoichiometry in pulse laser deposited Ga and Al doped ZnO, the plasmonic properties can be controlled via a fluctuating free carrier concentration. This deterministic approach enables us to investigate and develop the most appropriate stoichiometry of ZnAlO and ZnGaO in regards to plasmonic applications for particular IR wavelengths. Presented are theoretical and experimental investigations pertaining to ZnAlO and ZnGaO as surface plasmon host materials. These materials not only offer potential use as IR plasmon hosts, but also offer new integrated device possibilities due to stoichiometric control of electrical and optical properties.

8255-26, Session 6

Dispersion analysis of subwavelength square apertures at optical frequencies

E. Lansey, The City College of New York (United States); J. N. Gollub, Phoebus Optoelectronics, LLC (United States); D. T. Crouse, The City College of New York (United States)

We present an analytical method for studying some of the resonance properties of square subwavelength nanoscale apertures embedded in metal films at optical and near IR frequencies. This concise approach allows an accurate prediction of resonance responses in real metals, captures both propagating and evanescent modes, and can easily be implemented in other analytical and numerical techniques, such as a rigorous coupled wave analysis.

A full and accurate analysis of cavity modes using finite element or finite difference time domain simulations requires significant computer resources and long calculation times. Thus, a quick method to determine the wavelengths of cavity modes is of great utility for the design of optical structures. Dispersion analysis, discussed here, is a useful approach for quickly determining the waveguide cavity modes that can be excited in a particular aperture.

In this approach we avoid analyzing the detailed behavior of the fields inside the metal walls, but still obtain the effects of the implicit buildup of charges within those walls. We frame our approach using traditional waveguide analysis, using the approximate skin depth boundary condition (SDBC) at the metal walls. The SDBC allows use of real optical properties of metals with limited reliance on numerical techniques.

We demonstrate two applications of this solution method by calculating the dispersion relation for a square aperture embedded in a gold film. Furthermore, we determine the cutoff frequency's dependence on the cavity dimensions, and support our findings with finite element simulations.

8255-27, Session 6

Tunable surface plasmon band-gap in an index-perturbed double-electrode waveguide structure

Y. Zhou, A*STAR Singapore Institute of Manufacturing Technology (Singapore)

A double-electrode planar waveguide structure, which is a stack of insulator (I) and metal (M) layers arranged in the order of IMIMI, usually supports four surface plasmon modes: two long-ranging and two short-ranging. It is found that when cover index of the double-electrode structure differs from the index of other insulator layers, a spectral band-gap exists for one of the hybridized long-range plasmon mode. Such mode is associated with lower loss as compared to the other bound modes excited, enabling the hybridized long-range mode to be separated from the system and applied for plasmonic filtering devices.

The standard Transfer Matrix Theory (TMT) is used to obtain the modal solutions of the waveguide structure and we use Reflection Pole Method (RPM) to search for the roots. The hybridized long-range plasmon mode is found to cut off at a certain wavelength, and later reappears at a longer wavelength. This leaves a spectral band-gap for a range of wavelengths in the long-range mode propagation. Dispersion relations show that the hybridized long-range mode results from the coupling of one long-range mode of a symmetric IMI substructure and one short-range mode of an asymmetric IMI substructure. The band-gap width can also be tuned by index difference between cover and the other insulator layers. By tuning the cover index, minimum band-gap width is found to be several nanometers.

8255-28, Session 7

Metamaterials based on polaritonic composites for THz and mid-IR

S. Foteinopoulou, The Univ. of Exeter (United Kingdom)

[Invited] The THz and mid-IR part of the electromagnetic (EM) spectrum is of key importance for chemical/bio sensing applications. Emerging technologies, such as Quantum Cascade Lasers, made sources at such frequencies possible. This underlines the dire need to construct highly transmissive novel materials at this regime, with extra-ordinary capabilities to divert light and manipulate its polarization. Here we discuss hyperbolic metamaterials made of polaritonic constituents that can show an extra-ordinary polarization filtering behaviour. We analyze how this behaviour emanates from the hyperbolic type of EM dispersion, and further show that this can enable a high transmission even when the individual constituent materials of the structural meta-atom do not themselves transmit.

8255-29, Session 7

Design of Bragg gratings having negative group time delay for continuum generation

G. A. Iordachescu, J. Jacquet, Supélec (France)

In this paper we present the simulation results of two different methods of grating engineering (Genetic Algorithm and Discrete Layer Peeling) used for the synthesis of Bragg Gratings with a negative Group Time Delay. The physical structures of the resulting gratings, as well as their reflection spectra, are displayed for different initial parameters. The efficiency for each one of the two algorithms is also discussed in relation to the proposed problem. There are also physical limitations forbidding the group time delay to go under a certain limit. The reason for this is found by appealing to the theory of digital signal processing, from which the Discrete Layer Peeling algorithm is derived. The purpose for creating negative group time delay gratings is for the widening of the resonant modes of a Fabry-Perot cavity. It is demonstrated that when the group time delay of the gratings (used as cavity reflectors) opposes the group time delay of the round-trip through the cavity, the Fabry-Perot modes are canceled and the resonant modes are extended indefinitely. If an active medium is added to such a cavity the emission spectrum becomes continuum, similarly to a white laser source. Because of the limitations on the group time delay value, the ideal continuum case is not yet reached. The differences between the ideal continuum emission and physical realizable one are displayed at the end of the paper.

8255-31, Session 7

Optimization of nanophotonic devices with adjoint FDTD

P. Hansen, Y. Zheng, L. Hesselink, Stanford Univ. (United States)

Surface plasmons around metal nanostructures can enhance the intensity of light fields many thousands of times and confine optical modes to a volume far smaller than a cubic wavelength. The high field intensity enhances many processes that rely on coupling of light to electrons in media. Consequently metal-optics is increasingly a tool of choice for electro-optic devices such as photodetectors, solar cells and LEDs. A practical barrier to the adoption of metal optics is the difficulty of obtaining good device designs. At the sub-wavelength level, enabling approximations such as the scalar wave approximation are no longer valid and device behavior can only be predicted by full vectorial solutions of Maxwell's equations, incorporating the appropriate material behaviors of both dielectric and metallic components. This can be done through numerical means such as FDTD at considerable computational expense. However, the inverse problem of obtaining an optimal design requires the intelligent adjustment of many dimensional and shape parameters, and it is very difficult to prove that a design is in fact locally optimal in its parameter space.

We present a gradient-based optimization technique, based on adjoint design sensitivity analysis, for design of nanophotonic structures that rapidly converges on a locally optimal design. We obtain the sensitivity of a design to changes in all of its structural parameters at the cost of one additional FDTD simulation. By iteratively calculating the sensitivities and adjusting the structural parameters we can improve a device design until it converges on a locally optimal configuration.

8255-32, Session 7

Efficient 3D FDTD analysis of arbitrary birefringent and dichroic media with obliquely incident sources

M. N. Miskiewicz, P. T. Bowen, M. J. Escuti, North Carolina State Univ. (United States)

We have developed a 3D Finite Difference Time Domain (FDTD) algorithm to model obliquely incident waves through arbitrary birefringent and dichroic media with either finite or periodic boundaries. Beginning with arbitrary conductivity and permittivity tensors, we employed the Split-Field Method (SFM) to enable broadband (pulsed) and monochromatic sources with oblique incidence. In order to simulate structures with finite dimensions, we employ absorbing boundary conditions in all directions. To this end, we derive the general equations for a 3D uniaxial perfectly-matched-layer using the SFM. In other cases, we apply periodic boundaries in one or two dimensions. The algorithm is validated via several case studies: a finite rectangular aperture, isotropic binary diffraction grating, birefringent waveplates, polarizer pairs, and a twisted nematic LCD mode. The results are compared against analytic solutions and another FDTD solver. We analyze the stability of the algorithm and an empirical description of the stability factor is found. Using our 3D FDTD algorithm, for the first time we simulate polarization gratings, and begin to rigorously study oblique incidence effects on efficiency and polarization. Our FDTD code is open-source under the name WOLFSIM and available online.

8255-33, Session 7

Scattered light by refracting and reflecting surfaces

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Prior to the development of high quality, low loss optical material for optical communications, researchers believed that reflecting components produced less scattering and were therefore more suitable for building spectrometers than refractive elements. In the past, when the quality of optical materials was low, this belief was to a large degree, justified. However, demand for high quality optical materials generated by the needs of the fiber optics industry led to dramatic improvements in this field, resulting in material virtually free of internal defects. As a result scattered light from the surface of materials becomes the major contributor to photometric noise.

In this paper it is shown that in the present situation application of refracting optical components might have significant advantage over reflecting elements.

A scalar theory, verified by the Rigorous Coupled Wave Analysis (RCWA), is used to compare the performance of optical surfaces with a specified roughness. It is shown that for surfaces with identical micro roughness structures, backward scattered light level for a reflecting surface is much higher than the forward scattered light produced by the surface of a refractive optical element made from typical optical glass. This implies that application of refractive component (such as transmission gratings and lenses) in spectrometers with high dynamic range may be advantageous over reflective components such as reflection gratings and mirrors.

8255-34, Session 8

Advances in quantum dot lasers for silicon photonics application

Y. Arakawa, The Univ. of Tokyo (Japan)

Advances in quantum dot lasers
for silicon photonics application

8255-35, Session 8

Realization of a photonic crystal surface emitting laser through GaAs based overgrowth

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Recently, there has been much interest in a novel type of device, the 2D photonic crystal surface emitting laser (PCSEL). The periodic change of the refractive index in a photonic crystal forms a band structure for photons in a similar fashion to the electronic band structure. In PCSELs the group velocity of light becomes zero at the band-edge and we exploit this phenomenon to form large and stable two-dimensional single-cavity modes. PCSELs have a collection of unique and attractive properties such as coherent emission over large areas, beam steering, very low divergence angles and high single mode powers. To commercialize these devices a robust and high reliability manufacturing method is required. Previous techniques with GaAs based PCSELs have relied upon wafer fusion techniques which exploit voids within the photonic crystal. Re-grown GaN based PCSELs have resulted in devices that exploit similar voids within the structure. We demonstrate a GaAs based PCSEL structure that relies upon epitaxial overgrowth to completely infill the deeply etched structure with semiconductor, to provide a robust manufacturing method.We discuss the design of the photonic crystal by modelling the band structure, coupling coefficients, and highlight the key fabrication points in optimising the overgrowth epitaxy. We report on the angular dependent emission characteristics, and the temperature dependence of the operating characteristics as we vary the photonic crystal period.

8255-36, Session 8

Thermo-optical simulation of high-power diode lasers

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Numerical simulations are an important tool for the design of opto-electronical components and devices. In order to obtain realistic results, a multitude of physical effects and theories have to be included, e.g., Maxwell's equations for lasing mode computations, heat transfer in active devices, and electronic transport. In our contribution we perform coupled electro-thermal simulations of high power diode lasers. Analyzing the temperature dependence of the mode profile and far field characteristics, especially the degradation of beam quality due to the appearance of higher order modes at higher injection currents lie in our focus. Therefore, we compute the temperature distribution in dependence on the injection current and perform optical simulations according to the corresponding refractive index change. We show that the effect of thermal lensing is the dominant waveguiding mechanism. The increasing far field angle, i.e., the effect of thermal blooming will show very good quantitative agreement to experimental measurements of broad area lasers.

8255-37, Session 8

Bending losses and modal properties of serpentine and bent waveguides

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In the design of photonic integrated circuits, the resonance properties of microrings are utilized to achieve various active and passive functionalities such as laser sources and filters, respectively. Also, bent waveguides and couplers are indispensable for the minimization the overall chip size. Thus the characterization of bending losses and modal properties inside the microrings and along the bending section of waveguides is an integral part of the design process.

For these purposes, we have designed and fabricated Fabry-Perot lasers with the middle sections of the cavities consisting of different bent and serpentine structures with arc lengths equivalent to a ring with the same curvature. Here, we present the experimental results and the FDTD simulations of these novel structures, as well as a discussion of the implication and application in the designs of microring-based photonic circuits. The emphasis is on the impact of the measured properties on microring lasers since, as in any laser system, the threshold current of a microring laser is determined by the total cavity loss, which in a ring configuration is contributed largely by the bending losses.

8255-38, Session 8

Thermally tunable DFB dual mode laser diode by an external platinum thin-film heater for THz generation

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The thermal investigations of tunable laser diodes i.e., distributed feedback (DFB) and distrusted Bragg reflector (DBR) semiconductor have been study in order to get terahertz frequency sources based. The dual-mode DFB Lasers is used for tunable continuous-wave THz generation (N. Kim et al., Optics Express, vol.17, 2009). The thermally tunable DFB laser diode fabrication is easy and the wide range of injected current to corresponded heater is main requirement to produce a wide range of temperature (Todt et al., Applied Physics Letters, vol. 87, 2005). This method can be considered for many applications such as THz spectroscopy. The various generated temperatures will affect on the difference temperatures in grating layer of the DFB laser and the effective refractive index of grating will directly be changed (R. Kashyap, 2009 and J. E. Carroll, et al., 1998). Sakano et al. presented the continuous tunability over 4nm at the output power of 20mW (Photonics Technology Letters, vol. 4, 1992.). In this paper, we will study a wide thermally tunable compact DFB laser using an external platinum thin-film. This study will investigate a thermally tuning DFB laser with platinum as a heater which is mounted on its top surface. The relation between injection current into the heater and tuning wavelength will be demonstrated. The results show that by increasing injection current, the tuning range is exponentially increased. The aim of this research is the realization of a potential and tunable source in the THz frequency range.

This work is supported by MITEPHO project (www.uc3m.es/portal/page/portal/grupos_ investigacion/optoelectronics/european projects/mitepho) which is coordinated by GOTL research group in Carlos III de Madrid University with foundation grant agreement number 238393 (EU-FP7) in order to develop compact tunable dual-mode diode lasers and terahertz spectroscopy in sensing and biomedical applications.

8255-39, Session 8

Comparison of linewidth enhanancement factor for compressively strained AlGaInAs and InGaAsP quantum well lasers

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Low-chirped lasing operation in semiconductor lasers is desirable for high-speed high-bit-rate optical transmission. We have compared and analyzed this issue with a theoretical investigation for the possibility of extreme reductions in the linewidth enhancement (α-factor) in strained layer quantum-well (QW) lasers between AlGaInAs and InGaAsP material. Valence band structure and optical gain in both types of QWs under compressive strain have been calculated using 4×4 Luttinger-Kohn Hamiltonian. The Luttinger parameters of these quaternary materials were determined from the linear interpolation between the values of their respective binaries. Hydrostatic deformation potential (a), shear deformation potential (b), and elastic stiffness constants (C11and C12) were also determined from the same method. The α-factor have been calculated as the ratio of the change in real component of the complex refractive index with a change in carrier density to the change in imaginary component of the refractive index with a change in carrier density. We have used Kramers-Kronig relations to calculate the refractive index change due to carrier induced. The α-factor was up to 1.64 times smaller in AlGaInAs QW than in InGaAsP QW lasers. The modal material differential gain and material carrier induced refractive index change is found to be approximately 1.38 times larger and 1.16 times smaller, respectively in the former material than the latter. We also compared our results to the revealed reported results for both QWs lasers. Thus we concluded that, the QW lasers of aluminum quaternary are superior to those of phosphorus for high speed direct modulation QW lasers.

8255-40, Session 9

The solar cell physics required to approach the Shockley-Queisser efficiency limit

E. Yablonovitch, Univ. of California, Berkeley (United States)

The Solar Cell Physics Required To Approach The Shockley-Queisser Efficiency Limit

8255-41, Session 9

Semiconductor nanowire solar cells: high efficiency concepts

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Nanowire arrays synthesized from III-V materials on silicon have the potential to fit the concept of third generation photovoltaics, namely highest efficiencies at moderate cost. In this talk, the efficiency potential for nanowire array solar cells is investigated by means of detailed simulation. Electromagnetic analysis of the absorption properties is based on the three-dimensional solution of Maxwell's equations, for the electronic part, microscopic transport equations are utilized. It is shown that the dispersion properties of nanowire arrays can be used to reach the Shockley Queisser limit of a bulk solar cell with low density arrays. This is due to an electromagnetic microconcentration effect. Furthermore, nanowire arrays have unique spectral absorption properties to design novel multi-junction solar cells. Core-shell multi-junction solar cells will be presented and analyzed in detail.

8255-42, Session 9

Carrier dynamics and defects in MOVPE-grown bulk InGaAs layers with metamorphic InGaAs and InGaPSb buffer layers for solar cells

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Bulk-InGaAs layers with a 1eV band-gap grown on GaAs-substrates are attractive for high-efficiency multi-junction solar cells. However, a large amount of lattice-mismatch between bulk-InGaAs layer and GaAs-substrate necessitates development of novel metamorphic-buffer-layers (MBL). In this study, we report carrier dynamics and defects in MOVPE-grown bulk-InGaAs layers grown on ~2um thick step-graded MBLs on GaAs-(100)-substrates. Two different types of MBLs were studied including InGaAs and InGaPSb. About 2um thick InGaAs layers were clad on both sides by 100nm thick In(0.75-0.85)GaP layers to form double hetero-structures (DH). Sample A was an In0.17Ga0.83As DH on InGaAs MBLs. Sample B was an In0.28Ga0.72As DH on InGaAs MBLs. Sample C had the same In0.28Ga0.72As DH structure, but chemical-mechanical-polishing was employed to remove a portion of InGaAs MBLs, followed by MOVPE-regrowth of the DH on top of the MBL. Time-decay curves were measured using a streak camera. Sample A showed a faster component of 304ps and a slower component of 0.9ns. Samples B and C showed comparable faster components of 342-481ps, but Sample C showed a significantly improved slower component of 9.6ns compared to 2.1ns for Sample B. Sample C also showed improved PL intensities. Time-resolved PL results clearly indicate that Sample C improved optical properties, but further investigation including HR-TEM and HR-XRD analyses were employed to fully understand the origin of the improvements. We will report our TEM analysis and investigate correlations between carrier lifetimes and defects among various structures, as well as results on bulk-InGaAs layers grown on other MBL structures including InGaPSb.

8255-43, Session 9

Study of silicon solar cell double-triangular nano-gratings

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This study concentrates on the solar light extraction power in a silicon solar cell using double diffraction triangular nano-grating. The first grating is located on top of the solar cell and the second lattice is located on the bottom of the solar cell right above a reflective metallic substrate of AR (Si3N4) with refractive index of 2.01, assuming the air is the surrounding surface around the solar cell with a refractive index of 1. We simulate the solar cell behavior as it absorbs sun light through the its structure in various cases and compare the average power output extracted from the center of the solar cell in each case. Each case simulates a period (At) that varies from 100nm to 800nm with a 100nm interval for the top lattice while maintaining the bottom lattice at a constant period (Ab). We repeat this procedure for the bottom lattice, again changing the lattice period from 100nm to 800nm with a 100nm interval in order to find the optimized case. We also consider the solar spectrum irradiation under wavelength ranges from 300nm to 1100nm with a 50nm interval between each case. Results show an increase of the weighted power extraction of 132% with a top grating period (At) that varies from 300nm to 800nm and a bottom grating period (Ab) at 500nm. We also observed a maximum power extracted (134%) at the solar irradiation wavelength of 900nm solar spectrum for the 100nm period top diffraction grating.

8255-45, Session 10

Multi-helix chiral fiber gratings

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Recently, it has been demonstrated by Victor I. Kopp et al. that the polarization sensitivity of chiral fiber gratings depends on the gratings symmetry: double-helix fibers are polarization sensitive while single-helix fibers are not. In this study, we proposed new structures of chiral fiber gratings with multi-helical symmetry-three-helix and four-helix. Using the finite difference time domain (FDTD) method, we systematically simulated the features of the transmission spectrum of the multi-helix chiral fiber gratings. The results show that the three-helix fibers are polarization sensitive while the four-helix fibers are not. In addition, we explain the polarization properties of the multi-helix chiral fiber gratings through the coupled-mode perturbation theory. In the end, a summary of circular dichroism of the helical chiral fiber gratings is presented.

8255-46, Session 10

Modeling of a 2x2 multimode interference switch for wider optical window operation

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With this work, we have elaborated the design and detailed performance analysis of a 2×2 MMI–switch based on self–imaging principle by defining the partial refractive index regions. The channel waveguide are assumed with a profile of Ti-indiffused Lithium Niobate (Ti-LN). The channel waveguides and image modulated regions are optimized theoretically to reduce overall device area coverage with enhanced switching performance. Whole device is 516μm long and 8μm wide including all sections, which are in accordance to the integral multiple of the characteristic imaging length. Finite difference beam propagating method is used to investigate lightwave propagation in axially varying waveguides with perfectly matched layer boundary conditions. Initially the switch remains in cross state and possesses a CT level better than -24dB and -14dB, for centre wavelengths 1.3μm and 1.55μm respectively for either case of polarization. In its 3-dB state, the optical losses have been maintained less than 0.06dB and 0.3dB, for centre test wavelengths of 1.3μm and 1.55μm respectively with a CT level ≥ -15dB in all cases. The extinction ratio is observed higher than 25 dB for either case of considered range. Similarly the device has shown satisfactory performance in terms of its switching states (cross and bar) and exhibited very low insertion loss, excess loss and acceptable CT levels.

8255-47, Session 10

Estimation of coupling power parameters of 1x3 directional fused fiber coupler

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The coupling characteristics of 1X3 directional fiber coupler is reported. Power distribution in coupling region has been calculated by using Transfer Matrix Method (TMM) based on coupling mode theory. It has shown that if the three fibers are electromagnetically isolated, propagation constant, and separation between the fibers are maintained constant, power distribution among three fibers are periodically normalized. By launching 1mW input power to the fiber 1, it will be transferred gradually to the fiber two then fiber three. Although, the input power will be symmetrically distributed to the two others fiber by launching power to the center fiber 2. However, the power exchange between the fibers in coupling region significantly depends on the coupling length and coupling coefficient between them. It has been shown in 3D that the coupling coefficient describes how strong the coupling can transfer its power to the others. In another hand, the higher coupling coefficient, the shorter coupling length is required to transfer power.

8255-48, Session 10

Parametrization of optical constants of anisotropic materials

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Optical characterization of anisotropic materials requires parametrization of optical constants in directions of the principal axes. Thus, two pairs and three pairs of the optical constants for the uniaxial and biaxial materials, respectively, must be parametrized. This leads to increase the number of parameters needed for expressing the dispersion models of the optical constants if the optical constants corresponding to the individual directions are independent. It will be shown that Thomas-Reiche-Kuhn sum rule implies that these optical constants are not independent which reduces the number of independent parameters. The theoretical results achieved will be demonstrated to the modeling of optical constants of the symmetric materials such as graphene and also for disordered materials such as P3HT organic polymers.

8255-49, Session 11

From an exciton laser to a polariton laser in a ZnO microcavity

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ZnO is a wide bandgap semiconductor with strong excitonic properties, in particular a large oscillator strength and a large exciton binding energy. It therefore raises a strong interest for the demonstration of polariton lasing up to room temperature with microcavities in the strong exciton-photon coupling regime.

The strong coupling regime has recently been demonstrated for planar ZnO microcavities fabricated by various approaches. In this work, the investigated cavities consist in a ZnO active layer grown by molecular beam epitaxy embedded between an AlGaN/AlN distributed Bragg reflector (DBR) and a SiO2/SiN DBR.

Coherent non-linear emission under non-resonant optical pumping is demonstrated in two different regimes as a function of the exciton-cavity detuning.

At large negative detuning, from T=80 K to 300 K, the cavity switches at threshold from the strong coupling to the weak coupling regime. A gain-related transition, which appears while still observing polariton branches and, thus, with stable excitons, is observed below 240K. This shows that exciton scattering processes, typical of II-VI semiconductors, are involved in the gain process, and that we realized an exciton laser [Guillet et al., APL 98, 211105 (2011)].

At small negative detuning, and at T=120 K, the cavity persists in the strong coupling regime at threshold with negligible blue shift. Angle-resolved μPL experiments demonstrate the spectral narrowing at threshold, as well as a competition between multiple lasing polariton modes. Those results are compared with macroPL experiments. The far-from-equilibrium behavior of the system is typical of a polariton laser in a cavity presenting photonic disorder.

8255-50, Session 11

VECSEL action and strong exciton-photon coupling in all-monolythic ZnO-based microcavities

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We report laser action and strong exciton-photon coupling as a function of temperature in microcavities formed by ZnMgO-based DBRs and containing ZnO/ZnMgO quantum well structures as active parts, all grown by molecular beam epitaxy.

8255-51, Session 11

Exciton-polaritons study in ZnO-based hybrid microcavities

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The characteristics of exciton-polaritons in ZnO-based microcavities (MCs) at room temperature (RT) are demonstrated with a large vacuum Rabi splitting of 72 meV due to large exciton binding energy and oscillator strength. The lower polariton branches (LPBs) can be clearly observed. Relatively, the upper polariton branches (UPBs) are pushed into the ZnO scattering absorption states resulting from the large vacuum Rabi splitting. In addition, the polariton relaxation bottleneck in bulk ZnO-based MCs has been observed in angle-resolved photoluminescence measurements from 100 to 300 K at different cavity-exciton detunings. For low temperature and large negative detuning conditions, a clear polariton relaxation bottleneck is found. The bottleneck is strongly suppressed with increasing the temperature and reducing detuning. This observed results supposed to be due to more efficient phonon-assisted relaxation and a longer radiative lifetime of the polaritons.

8255-52, Session 11

Universality in the quantum to classical transition of the one-atom laser

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Hanbury Brown and Twiss astonished the scientific community with their discovery that photons from a thermal source are correlated. A few years later, Glauber laid down his theory of optical coherence, showing how correlation between photon detection provide a general and rigorous framework for quantum coherence. The laser is the most famous example of a quantum coherent source. In addition of generating uncorrelated photons, it also has more famous properties such as a narrow linewidth, a focused beam and large intensity of its output. All these features proved extremely useful, but are not intrinsic to lasing. A narrow linewidth, for instance, can be obtained by filtering a thermal source, which can also be intense.

Cavity QED brings new insights into light-matter interaction. We revisit the one-atom laser where optical coherence grows thanks to a single emitter in strong-coupling with the cavity field. We identify a new regime where the emission of uncorrelated photons is retained even without stimulated emission. We provide the conditions for this and prove analytically that a field coherent to all orders is generated even for small and vanishing intensities, bringing a new light to thresholdless lasing. We analyse the crossover between this regime and the one established by stimulated emission and show that a universal transition--independent of the energy scales--occurs when going from the quantum to the classical regime, where the quantization picture breaks down, giving rise to a new type of Mollow triplet.

8255-53, Session 11

Narrow band high transmission mode in nanocavity self-assembly structure

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Strong coupling of light via a nanovoid lattice is demonstrated with numerical simulations. Transmission is facilitated via strong localized plasmonic resonances of the spherical nanocavities. Metallic nanovoids can be fabricated by electrochemical deposition through a template of closely packed latex spheres. Self-assembly methods with their low cost and low weight, are promising prospects for wavelength filters and biological and chemical sensors. These self-assembled structures are capable of enhancing light transmission in a narrow band.

We present a design consisting of a metal film with an array of truncated spherical nanovoids. The narrow band and high transmission is produced by the coupling of the localized and extended surface plasmon modes and the cavity modes within the nanovoids and on the metal/dielectric surface of the transmitting side of the structure. This effect scales with the period and diameter of the nanovoids. We show agreement with theoretical work by N. Stefanou, et al. [sol. St. comm.. 118 (2001)].

The structures were optimized for the efficiency of the transmission mode by using a commercial finite element software (Ansoft HFSS). A single unit cell was simulated with appropriate boundary conditions, i.e. periodic symmetry. Field profiles demonstrate the noted resonant interaction between the localized void plasmons and the propagating surface plasmon-polaritons.

8255-65, Poster Session

Application of anti-reflection structures on curved surfaces

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Conventional lens manufacturing is accomplished by injection molding followed by application of a thin film anti-reflection coating. This requires several production steps, each with the associated constraints. Here we report a technique for production of injection molded lenses with conical sub-wavelength grating anti-reflection structures. While similar structures have been made in the past, our technique allows the sub-wavelength structure to be created on curved surfaces during the injection molding process, reducing the number of steps in the manufacturing process.

8255-66, Poster Session

A novel single-transistor APS and its comparison with 3T CMOS image sensor

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In this paper, a novel single-transistor active pixel image sensor (1T-APS) based on a Floating-Junction-Gate structure is proposed and fabricated using 0.18 μm dual-poly technology. The proposed 1T-APS has a similar fabrication process to EEPROM. However, the tunnel window oxide of conventional EEPROM is omitted and the photo-diode is connected to the floating gate of a floating-gate (FG) MOSFET. The floating gate is p++-type doped. Because it is connected to the anode of the photodiode (PD) through a tiny contacting window, the potential change caused by incident light will impact the threshold voltage of the floating-gate (FG) MOSFET directly. Thus the read-out current through this FG-MOSFET is changed under different exposure conditions. Different to the conventional 3T-APS, the floating-gate MOSFET in this 1T-APS is a multi-functional transistor. It can realize the functions of the reset transistor and the source follower. This 1T-APS simplifies the cell operation and array configuration. It can be arranged in a DRAM-like array configuration without extra reset and source following transistors. Therefore, the fill actor of the photo-diode can be improved remarkably. Considering a photo-diode of 1 μm × 1 μm size, the PD fill factor of this 1T-APS is 45% for 0.18 μm technology node and 72.5% for 65-nm technology node. TCAD simulation is also carried out to investigate the working principle and performance of this device. The non-destructive read operation is investigated. The dependency of floating gate potential on the light intensity, the dynamic range, sensitivity and further improvements will be discussed.

8255-67, Poster Session

Two-dimensional cell parameters measurement of a twisted nematic liquid crystal device by using imaging ellipsometer

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Based on the equivalence theorem of a unitary optical system. We proposed an analytical approach to characterize the cell parameters of a twisted nematic liquid crystal device (TNLCD) with full field resolution. The spatial distribution of three characteristic parameters of a TNLCD were measured by using an imaging polarizer-sample-analyzer ellipsometer, thus the untwisted phase retardation, cell thickness and twisted angle of a TNLCD can be directly calculated through the explicit expressions as function of its characteristic parameters. The measured results are very close to the design values provided by TNLCD manufacture. This method shows that both the system setup and parameters calculating process are quite simple. It would be more practical for characterization of a TNLCD in the manufacturing process.

8255-68, Poster Session

Non-equilibrium QW populations and internal efficiency of polar and nonpolar III-nitride light emitters

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III-nitride QW light-emitting diode structures are characterized by deep QWs and strongly asymmetrical carrier injection. As a result, multiple-QW active region of the device suffers from inhomogeneous carrier injection and large residual charges of optically active QWs. Electrical non-uniformity of the active region unfavorably affect the structure efficiency. In this work, we show that injected QW carrier concentrations strongly deviate from their equilibrium values and should be simulated self-consistently with overall injection and light generation processes in the structure. We have performed comparative modeling of polar and nonpolar/semipolar multi-QW light emitting structures taking full account of band mixing and strain effects in QWs of different polarity and corresponding modifications of QW radiative characteristics. Self-consistent modeling of carrier transport in diode structures reveals different mechanisms of the internal efficiency droop. In polar structures, the droop is dominated by electron leakage and is noticeably affected by the active region ballistic overshoot. Efficiency droop in nonpolar structures is dominated by combined effect of radiative rate saturation and nonradiative Auger recombination in active QWs while the carrier leakage becomes a factor of secondary importance. For device simulation, we use COMSOL-based Optoelectronic Device Modeling Software (ODMS) developed at Ostendo Technology Inc.

8255-69, Poster Session

Linewidth influenced by phase modulation and frequency modulation in optical feedback diode laser

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Unlike electronic method for reducing the linewidth, optical feedback of laser into the laser diode is used for enhancing the qualities of the laser in terms of its spectral linewidth. The optical feedback is achieved by means of extending the laser diode cavity provided by an end external reflector. In this paper, we derive and calculate numerically laser diode linewidth by means of the laser rate equation and vectorial analysis of the reacting components in a compound diode laser cavity. Based on the theoretical analysis, this feedback mechanism to compensate for the spectral linewidth effects is dealt with both phase modulation (PM) and frequency modulation (FM) components for the laser diode. The analysis results are shown that narrow linewidth is closely connected with phase modulation and frequency modulation. The dominance of two mechanisms depends on the original bandwidth and laser frequency change magnitude under the determinate linewidth enhancement factor, reflective coefficient and length of external cavity. A much narrower spectral linewidth can be obtained by use of PM when a wider bandwidth and/or faster frequency change of the laser diodes is introduced. The FM component is predominant mechanism to the linewidth reduction for a smaller spectral bandwidth and/or slower frequency change of the laser diodes. This analysis will be the significant reference value for exploring new practical approaches to achieve a much narrower linewidth laser diodes which could be used for many fields eg metrology, spectroscopy etc.

8255-70, Poster Session

Effect of reversed polarization on characteristics of N-face InGaN/GaN p-i-n solar cells

Y. Kuo, J. Chang, National Changhua Univ. of Education (Taiwan)

The III-N materials have attracted increasing interest in photovoltaics (PVs) due to their tunable energy band gaps (covering almost the whole range of solar spectrum) and many other superior photovoltaic properties (direct energy band gap in the entire alloy range, high absorption coefficient, low effective mass, high mobility, and radiation resistance). Despite the superior properties, there are still many problems that need to be solved to develop high-efficiency III-nitride PV devices. The most important challenge is presumably the difficulty in growing high-quality InGaN layers with high indium composition. However, besides this issue, it has been reported quite recently that the polarization effect also plays an important role on the performance of nitride-based solar cells in the conventional orientation of Ga face. In GaN-face solar cells, the carrier collection efficiency is seriously degraded by the polarization-induced electric field whose direction is against that of the normal built-in field. This unfavorable effect needs to be overcome for future development. In this study, the influence of reversed polarization on the performance of (0001) face GaN/InGaN p-i-n solar cells with N-face orientation is investigated numerically. In contrast to the detrimental effect of normal polarization, the internal electric field induced by reversed polarization may enhance the efficiency of carrier collection by enlarging the energy band tilting to the favorable direction in the InGaN absorption layer. In addition, this beneficial effect becomes more remarkable when the indium composition of the InGaN absorption layer is high.

8255-71, Poster Session

Enhancement in carrier-collection efficiency of Ga-face InGaN/GaN p-i-n solar cells by polarization-reduced InGaN interlayer

S. Chang, J. Chang, National Changhua Univ. of Education (Taiwan)

The nitride-based devices grown on c-plane are well-known to have significant interface charges induced by spontaneous and piezoelectric polarizations. In Ga-face solar cells, it was investigated recently that the carrier collection efficiency is seriously reduced due to polarization-induced electric field whose direction is opposite to that of the normal built-in field in the p-i-n structures. This detrimental effect becomes more remarkable in fabricating a GaN-based solar cell that contains an InGaN absorption layer of high indium composition, which is desired if we were to extend the absorption spectrum to longer wavelength. Thus, novel techniques such as the usage of non-polar substrates, N-face templates, and polarization-matched AlGaInN layers might be beneficial for obtaining GaN/InGaN p-i-n solar cells of high device performance. These novel techniques can fully solve the detrimental influences of polarization effect; however, they suffer from the problems in fabrication, i.e., the difficulty in crystal growth. In this study, the impact of polarization-reduced InGaN interlayer, which is easy to be fabricated, between the hetero-layers of Ga-face InGaN/GaN p-i-n solar cells is investigated numerically. Simulation results show that the conversion efficiency is improved markedly due to the enhancement of carrier-collection efficiency, which can be ascribed to both the reduction of polarization-induced electric field in the InGaN absorption layer and the mitigation of potential barriers at heterojunctions. This beneficial effect is more remarkable in the situations with higher polarization, such as the devices with lower degree of relaxation or the devices with higher indium composition in the InGaN absorption layer.

8255-72, Poster Session

The effects of temperature and stress on the spectrum broadening in high power semiconductor laser arrays

P. Zhang, Xi'an Institute of Optics and Precision Mechanics (China); J. Wang, Xi'an Focuslight Technologies Co., Ltd. (China); L. Xiong, Xi'an Institute of Optics and Precision Mechanics (China); X. Li, X. Ding, Xi'an Jiaotong Univ. (China); Z. Wang, X. Liu, Xi'an Institute of Optics and Precision Mechanics (China)

The spectrum broadening of 60W conduction cooled semiconductor laser arrays was studied. As shown in figure 1, the laser diode array with 19 emitters, 150μm stripe width and a pitch of 350μm is demonstrated. We studied three typical cases of spectrum broadening: 'left shoulder', 'right shoulder' and 'double peaks'. The corresponding spectrum of each emitter was also measured. The central wavelengths of 19 emitters are different from each other, which induced the broadening of the total spectrum. The wavelength differences of 19 emitters are mainly induced by the non-uniform of temperature and stress at each emitter. We performed simulations using finite element method to analyze the effects of solder voids on the temperature and stress in active region. The thermal behavior of semiconductor laser with voids in the solder layer was studied and the relationship between temperature and voids sizes was analyzed. It was found that the emitter temperature increase with the size of void, e.g., the temperature rise is 30K when the size of void is 290μm. The temperature rise will cause the emitter wavelength red shift at 0.28nm/K, hence the 'right shoulder' shown in figure 2 is mainly induced by thermal effect.We created a model describing the correlations between the spectrum shape and the distribution of temperature and stress. Based on our model, the distributions of temperature and stress could be deduced from the measured spectrum of diode laser array. On the other hand, we also deduce the spectrum shape according to the distributions of temperature and stress. The detailed results will be presented in the manuscript.

8255-73, Poster Session

Optical 90-degree hybrids based on silicon-on-insulator multimode interference couplers

T. Hong, W. Yang, Peking Univ. (China)

In multilevel coherent transmission systems, quadrature phase shift keyed (QPSK) modulation is considered as one of the efficient methods to maximize spectral efficiencies and receiver sensitivities. Working as a demodulator of the QPSK modulated signals, an optical 90° hybrid is one of the prerequisite components in coherent detection systems. In consideration of monolithic integration with photodetectors (PDs) in coherent systems, a 4×4 Multimode interference coupler (MMI) is an efficient waveguide-based structure to realize the function of optical 90 ° hybrid. Due to its inherent quadrature phase relationship, a 4×4 MMI coupler is easy to achieve good IQ balance.

In this paper, we demonstrate an optical 90° hybrid using 4×4 MMI couplers on silicon-on-insulator (SOI) platform. Simulations results of 4×4 MMI couplers show that the 4×4 MMI couplers act as 6dB couplers with only one launching light from one input waveguide. Besides, phase deviation of 4×4 MMI couplers, the most important indicator of an optical hybrid, is below 2.2° across C-band for TE mode, well satisfying the typical systems requirements. 4×4 MMI couplers are fabricated in SOI strip waveguide with 340-nm top silicon using E-Beam technology. The optical transmission powers from port to port have been measured by two lens fibers coupling to the devices, which show that the devices function well as a 6dB coupler with excess loss around 1dB at wavelength λ=1550nm for TE mode. In order to get the phase deviation of the 4×4 MMI couplers, the optical delay lines, with 50GHz free spectral range, was added in front of the couplers. More details of this experiment are carrying out.

8255-74, Poster Session

Biaxial strain effects on the electronic band structure of wurtzite InxGa1-xN alloys using first-principles calculations

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The III-nitride semiconductors have received much attention in the past few years since they have potential applications in light emitting diodes (LEDs) for displays and solid state lighting, short-wavelength laser diodes (LD) for high-density optical storage and high resolution laser printing diodes, and solar cells for high-efficiency photovoltaics. This is due to their relatively wide band gap corresponding to the spectral region from the infrared, visible to the near ultraviolet and high emission efficiency. The lattice match between the semiconductor epilayer and the substrate plays a key role to generate a perfect optoelectronic device. However, the lattice mismatch exists between the III-nitride semiconductor epilayer and the substrate of sapphire or GaAs. The strain generated from the stress, resulting from the lattice mismatch or even the special purpose to change the properties of optoelectronic device, will effect on the electronic band structure and optical properties of materials. The objective of this study is to investigate the effect of biaxial strain on the physical and optical properties, such as the band structure, direct band gap, indirect band gap, width of valence band, and bowing parameter of direct band gap, for ternary wurtzite InxGa1-xN alloys. The electronic band structures were carried out using first-principles calculations based on density functional theory (DFT) in the local density approximation (LDA).

8255-75, Poster Session

Fast random-number generation using a diode laser's frequency noise characteristic

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We show that rapid physical-random number generation, at speeds as high as 40 Gbps, is obtainable from laser diode's frequency noises. We also show possibility of parallel physical-random number generation by using "coherence collapse". Naturally generated physical-random numbers, which have no calculable periodicity, are better-suited to the task of creating a reliable cryptogram, than pseudo-random numbers, which are generated by definite algorithms. The laser diode has a wideband "noise" signal that is believed to have tremendous capacity, and great promise for the rapid generation of physical-random numbers for use in cryptographic applications. We measured a laser diode's output by means of a fast photo detector and generated physical-random numbers, using frequency noises. In the early stages of this experiment, we transformed the frequency fluctuation into the intensity fluctuation through the frequency discriminator and produced physical-random numbers, using a fast photo detector, and then identified and evaluated the binary-number-line's statistical properties. The diode laser's output was directed along separate optical paths, to two different photo detectors, in order to speed up the process. In this method, the optical path length difference between two beams was greater than the laser diode's coherence length. We obtained independent noise signals from two photo detectors and produced two series of physical-random numbers. The two independent two noise signals were evaluated by calculating their correlation.

8255-76, Poster Session

Oscillation wavelength shifts of vertical cavity surface emitting lasers exposed to magnetic fields

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As long ago as the 1960's, scientists understood that diode lasers' oscillation wavelengths showed a significant shift to the shorter wavelength (high frequency) side, when exposed to strong (<4[T]) magnetic fields, at extremely low temperatures (<80[K]). When we exposed Fabry/Perot-type diode lasers oscillating at 780[nm] to weak magnetic fields (<1.4[T]), at room temperature (300[K]), we observed that the oscillation wavelength shifted to the longer (low frequency) wavelength side. In the present work, we tested the oscillation wavelength shift of a vertical-cavity surface-emitting laser (VCSEL) in a magnetic field.

In this work, we focus our attention on the wavelength shift brought about by the change in the VCSEL's current flow, when the device is exposed to a magnetic field. We applied a weak magnetic field to the VCSEL, at room temperature. When aligned with the direction of current flow, carrier-density increases in the active region, producing a shift to the shorter wavelength side; a result that differs significantly, from the one we obtained using the Fabry-Perot type laser, during our previous experiments. These adjustments improve the VCSEL's performance, without altering its structure.

8255-77, Poster Session

Self-pulsation in two-section laser with an air gap

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This study explores the optical field distribution of 1.55μm InGaAsP Fabry-Perot Laser with an air gap in the middle section. We fabricate an air gap with a special width and depth in the middle of the two single-mode lasers side by side with the focus ion beam system. We demonstrate that the air gap can make the monolithic laser two independent lasers , a master laser and a slave laser.One facet is high reflection and the other is anti-reflection one.By means of the optical injection-locking technique,we can improve the laser dynamic characteristics.The optical field distribution was analyzed by different depth and width of an air gap. Besides,the current distribution in the two-section cavity will also differ because of the various depths.Based on the optical injection-locking theory,we demonstrate the improvement of frequency bandwidth and relative intensity noise(RIN)and so forth. We can observe that the resonance frequency increase largely under a external injection light condition. Theoretically if we increase the injection ratio, the resonance frequency can be enhanced, and relative intensity noise can reduce effectively. Data modulation with self-pulsation was enabled by on-chip optical injection locking.With this technique,we can enlarge the laser frequency bandwidth and improve other dynamic characteristics.

8255-78, Poster Session

Reduction of back scattered light in sub-wavelength apertures through coupled cavity effects

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Anomalous transmission through sub-wavelength aperture metamaterials has been a topic of immense interest in the present decade. The ability to manipulate light energy as it propagates through the metamaterial has ushered in an age of sub-wavelength optical devices. Optical devices are prone to harmful back scattering and diffraction effects which inhibit the transmission performance of metamaterial sub-wavelength films. One way to reduce back scattered light is by careful placement of sub-wavelength apertures throughout a metamaterial. The apertures create coupled cavity effects which can reduce back scattering of light. We modeled the coupled cavity effects of sub-wavelength periodic square apertures, using a Rigorous Couple Wave Algorithm (RCWA) to investigate ways to reduce back scattering effects thereby, enhancing the forward transmission of light through the metamaterial film. The RCWA was developed in MATLAB for a periodic array of apertures in a unit cell. Our metamaterial film is patterned with an array of sub-wavelength apertures. This approach, couples cavities in neighboring apertures thereby overcoming the scattering of the light by opening up additional transmission channels that cause light to be transmitted rather than being reflected.

8255-79, Poster Session

A new approach for implementation of associative memory using volume holographic materials

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Associative memory, also known as fault tolerant or content-addressable memory, has gained considerable attention in last few decades. This memory possesses important advantages over the more common random access memories since it provides the capability to correct faults and/or partially missing information in a given input pattern. There is general consensus that optical implementation of connectionist models and parallel processors including associative memory has a better record of success compared to their electronic counterparts. In this article, we describe a novel optical implementation of associative memory which not only has the advantage of all optical learning and recalling capabilities, it can also be realized easily.

We present a new approach, inspired by tomographic imaging techniques, for holographic implementation of associative memories. In this approach, a volume holographic material is sandwiched within a matrix of inputs (optical point sources) and outputs (photodetectors). The memory capacity is realized by the spatial modulation of refractive index of the holographic material. Constructing the spatial distribution of the refractive index from an array of known inputs and outputs is formulated as an inverse problem consisting a set of linear integral equations. We used singular value decomposition technique to solve the inverse problem. As a result, a closed-form equation for calculating spatial distribution of electric permittivity of the material is developed in infinite dimension. To support the theory, computer simulations were performed to solve the forward and inverse problems. Some simulation results of the learning and the recalling for pattern recognitions are presented.

8255-80, Poster Session

Nonlinear pulse reshaping in passive optical fibers towards quasi-parabolic waveforms

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Generation and applications of the optical pulses with a parabolic intensity profile has developed into the area of dynamic research activity over recent years. Parabolic pulses can propagate remaining their parabolic profile. Particularly these pulses resist to the deleterious effect of the optical wave breaking. They are of great interest for a number of applications including the high power pulse generation, and all optical signal processing. Alternative methods of generating parabolic pulses are of especial interest in the context of non-amplification usage, such as optical telecommunications. It is found that Gaussian waveforms provide best quasi-parabolic pulses among others and within shortest distance. There is a range of soliton numbers where the shape of quasi-parabolic pulse is closest to parabolic one.

8255-81, Poster Session

Thermal and optical properties of both ridge and buried structures laser including waveguide layer

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Thermal and optical properties of both Ridge and Buried structures laser are simulated in the case where we include a waveguide layer beneath the Multi Quantum Well's. The role of this waveguide is twofold. On one hand It attracts the optical field on lower side of the active waveguide where the losses are low due to n doped side of the laser. On the other hand, we can improve the coupling coefficient to the fiber by increasing the divergence of the beam together with its waist increase. Finite element software is used to calculate thermal resistance of the structures. Beam Propagation method is use for optical modeling. We optimize active waveguide composition and thickness for various multi-quantum wells number. Optical modeling is used to check the single mode operation of the structure together with beam shape optimization according to the objectives. Waveguide parameters are optimized to reduce the thermal resistance of both structures. Trade of between thermal and optical properties is discussed. P side up and down mountings are considered in both structures.

We investigate the use of diluated waveguide layer made of periods of alternatively InP and InGaAsP quaternary layer of equivalent band gap of 1.18µm which is much easier to fabricate. The ratio of InP and quaternary thickness are investigated and optimization is discussed. Surprisingly, we discover that thermal resistance is lower in the case of diluated structures as compared to uniform material use for the waveguide.

8255-82, Poster Session

Analysis of 1D photonic crystal microcavity sensor using surface plasmon resonance effect

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Recently, sensors using nano-structures have gained much interest in the area of bio-chemical sensing and environmental monitoring. It has many prominent features, such as high sensitivity, real-time detection, label-free, and immunity from electro-magnetic interference. The most widely used commercial system for label-free binding analysis is the surface plasmon resonance (SPR)-based biosensor. Although it allows label-free, real-time analysis, high sensitivity (> 103 nm/RIU), its performance has some important limitations. A number of reports indicate that SPR sensors have detection artifacts in binding constants due to the mass transport problem and low Q-factor. Biosensors using photonic crystal (PhC) structures have also been investigated as optical biosensors for easy fabrications, and high Q-factor. However, the PhC biosensors have a low sensitivity (> 102 nm/RIU) than SPR sensors.

In this paper, we have theoretically analyzed and designed a 1D PhC microcavity sensor with SPR based on the total internal reflection mirror using analytic calculation and FDTD methods. The proposed structure has many advantages. One of that is a high sensitivity using SPR characteristics. Another is a high Q-factor of the characteristics in the PhC microcavity structure. The incident light has double resonance characteristics, because the filtered light by PhC structure is met the thin metal film for SPR effect. We have also observed the change of resonance characteristics according to the variation of effective index on the metal film.

More detailed results on a triangular resonator structure with micro-cavity arrays will be presented.

8255-83, Poster Session

Oscillation frequency stabilization and narrowing of a laser diode by using an external cavity

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External cavity diode laser (ECDL) systems are presently experiencing a surge in popularity as laser light-sources, in advanced optical communications- and measurement-applications. Because such systems require that their external reflectors be precisely controlled, to eliminate low frequency fluctuations (LFF) in optical output, we conducted experiments with a two-cavity version of the ECDL system. This technique brings the added advantages of a narrower linewidth than would be achievable via a single optical feedback. However, the ECDL's oscillation frequency is susceptible to the influences of the driving current, changes in the refractive index, and changes in external-reflector length that result from fluctuations in atmospheric temperature. We made every effort to maintain the length of the ECDL cavity, while evaluating oscillation-frequency stability. We used a Super-Invar board as the platform for our ECDL system, in order to minimize the influence of thermal expansion.

At First, oscillation frequency noise characteristics and narrowing the width of the oscillation of Fabry-perot type laser were evaluated This system makes narrower linewidth down to 250kHz from 20MHz and the reduced oscillation frequency noises.

Next, those of a vertical cavity surface emitting laser (VCSEL) were evaluated using a double optical feedback method, because the VCSEL has many good characteristics but its oscillation linewidth is very wide. We used the square root of the Allan variance, when evaluating oscillation frequency stability, and confirmed that the double optical feedback method improved stability by about one order of magnitude, and narrower linewidth down to 3MHz from 150MHz.

8255-84, Poster Session

Graphene: an exciting two-dimensional material for science and technology

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One atom thick graphene is derived from graphite and is a new material; however, graphite has been a part of human history for centuries. Graphene generates so much excitement in a wide variety of scientific disciplines. In this paper, we emphasize its electronic and mechanical properties with an eye towards applications that may impact our lives sooner, rather than later.

We also review methods to make this wonder material, including the famous 'scotch-tape' technique that led to the Nobel-Prize winning research Nan science researchers working on problem how do electrons flow differently when they are confined to flow through structures that are only about 10nm in one of their dimensions In computer processor, the electrons flow through the devices and interconnects in a manner very similar to water flowing through the pipes in the plumbing system of a typical home Sp2 hybridization leads to a hexagonal symmetry as seen in graphite, grapheme, carbon Nanotubes and C60. Carbon nanotubes (CNT) with single walls consist of a single atom thick

sheet of graphite also called grapheme rolled into a seamless cylinder The lattice structure of grapheme has hexagonal symmetry.This class of lattice is not a Brava's lattice but can be constructed from two interpenetrating lattices of equilateral triangles. It is the half filled shell of unhybridized pz that gives the state its unique electrical property due to the overlap with nearest neighbours to form pi orbital. In order to better understand the electronic properties of any material it is important to understandthe energy energy (E)and momementum relationship for different k also known as band structures of the material The optical properties and the fact that it can transmit close to 97%of light makes it a good candidate for electrodes for solar cells. Graphene has very unique chemical properties and the fact that it is chemically very stable makes it a very good candidate for chemically resistant coatings. The inherent flexiblility of the material makes it a flexible displays

8255-86, Poster Session

Polarization splitter based on a porous silicon waveguide

Y. Liu, Xinjiang Univ. (China)

Optical communication systems employ polarization splitters in many applications, such as coherent and polarization diversity optical detection.

A prism coupled porous silicon(PS) waveguide has similarity with the suface plasmon resonance(SPR),however PSi is easy fabricate for its advantage of nonpoisioner,label free detection and so on. In this work, the polarization splitter is based on the phenomenon of resonant waveguide. Two pores density PS layer act as waveguide core and cladding, when the component of the incident field wave vector parallel to the surface matches the mode of the PS waveguide core,the resonant happens,the relectance reached the minimum at the same time. Conclusion is drawn,in fixed incident angle of 47.9 degree,s polarization beam has almost zero reflectance,while p-polarization has nearly 100% reflectance at the same wavelength 1.55um.

8255-87, Poster Session

Geometric and material modeling environment for the finite-difference time-domain method

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The simulation of electromagnetic problems using the Finite-Difference Time-Domain method starts with the geometric design of the devices and their surroundings with appropriate materials and boundary conditions. This design stage is one of the most time consuming part in the Finite-Difference Time-Domain (FDTD) simulation of photonics devices. Many FDTD solvers have their own way of providing the design environment which can be burdensome for a new user to learn.

Google SketchUp is one of a freely available three-dimensional modeling environment. Although it only allows surface modeling capabilities, features can be added using its API. In this work, geometric and material modeling features are developed on it allowing users who are fond of its environment to easily model photonics simulations. The resulting environment also provides neutral data format for FDTD simulation inputs which can be adopted by different FDTD solvers. The design and implementation of the modeling environment and its neutral data format are discussed.

8255-54, Session 12

Physics, design, and modeling of passive vertical cavity surface emitting lasers

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We report modeling and design techniques and measured and simulated results for passive vertical cavity surface emitting lasers (VCSELs). In one variation the new device consists of a passive microcavity cavity with a thickness on the order of a half-lambda and a quarter-wavelength active gain region, wherein the gain region resides in one of the VCSEL's distributed Bragg reflectors. We show that our device concept invites extensive opportunities for innovation in the combinations of materials and gain region placements that may be used to construct surface emitting devices.

8255-55, Session 12

Novel modulation approaches for directly and electro-optically modulated vertical-cavity surface-emitting lasers

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Directly-modulated (DM) vertical-cavity surface-emitting lasers (VCSELs) have been the dominant optical sources in short-reach applications at line rates up to 10 Gb/s. Presently, high-speed data channels operating at a line rate of 14 Gb/s are being introduced in storage-area networks and server farms, as a result of the recent 16 Gigabit Fibre Channel standard. Furthermore, 32 Gigabit Fibre Channel is under development, with considerable interest in continuing the use of VCSELs at a line rate of approximately 28 Gb/s. DM VCSELs remain relevant, but it is essential to explore the possibilities offered by advanced modulation formats, since NRZ operation at high line rates presents challenges in terms of device bandwidth, yield and reliability. Therefore, this paper explores the potential of pulse amplitude modulation with four levels (PAM4), carrierless amplitude and phase (CAP) modulation and quadrature amplitude modulation (QAM) to reach line rates in the region of 30 Gb/s, whilst using considerably lower symbol rates. Advanced techniques such as transmitter-based equalization of the VCSEL response are considered. Furthermore, electro-optically-modulated (EOM) VCSELs have been proposed as an alternative to DM VCSELs. A modulator integrated into the VCSEL allows the active region to be operated in continuous mode under low bias thus reducing the effects of high carrier densities and permitting low-power-consumption operation of the device. In this paper, an EOM VCSEL is used to demonstrate, for the first time, transmission of 16 Gb/s data over 100 m of OM3 multimode fibre using quadrature-phase-shift keyed (QPSK) modulation. Error-free operation is reported.

8255-56, Session 12

Novel picosecond optical sources based on gain switched diode lasers and nonlinear pulse reshaping

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Pulsed laser diodes offer an alternative to other sources through its compactness, efficiency, low cost and the high repetition rates they allow to achieve. Among the techniques available, Gain Switching (GS) is the most straightforward, which is based on the direct modulation of the gain of the device through the injected current (or light) and can be applied to any type of laser diode, including commercial or cost of The Shelf (COTS). These advantages are responsible for the renewed interest shown recently in such sources GS. However, the quality of the pulses obtained is generally limited as they present low output power characteristics and pulses limited to the picosecond range (typically 10 ps to 100 ps). Another undesirable feature of these pulses is their asymmetric shape and the presence of high pedestals. The improvement of this pulsed regime will deliver a novel optical source that takes advantage of the benefits of GS while opening its rage of applicability to offer an alternative to other techniques.

This has been achieved using an external compressor based on a Nonlinear Optical Loop Mirror (NOLM) that has been designed to adapt to the characteristics of GS optical sources. The compressor developed is compact, can be applied directly to the GS pulsed source and does not require any previous stages. The assembly formed by the Gain Switching laser diode source and the Nonlinear Loop has led to a novel compact source of improved performance.

8255-57, Session 12

Delay differential equation-based modeling of passively mode-locked quantum dot lasers using measured gain and loss spectra

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Quantum dot mode-locked lasers (QDMLLs) are attractive optical sources for applications requiring pulse trains with low timing jitter and low energy per bit, such as for optical interconnects in multi-processor architectures [1,2]. In order to optimize QDMLLs to excel for these precision applications, it is necessary to accurately predict device operation using realistic parameters characteristic of the underlying semiconductor gain material, under realistic operating conditions. To this end, quantum dot (QD) gain and loss spectra are experimentally measured over wavelength, temperature, gain section current density and absorber section reverse bias using the segmented contact method on a multi-section test structure. This information is then used to seed the numerical model.

The approach presented in this paper builds on our previous analytic approach [3], in which the onset of mode-locking was analyzed as a function of temperature using measured gain and loss characteristics. Using transformation equations derived from the expressions given in [4], the measured physical QD quantities can be inserted into the Delay Differential Equation (DDE) formalism of Vladimirov and Turaev [4]. In addition to accurately predicting the operating regimes where mode-locking can be maintained, the DDE approach allows for accurate predictions of the output pulse characteristics. The results of these numerical simulations are seen to exhibit close agreement with experimental observations on a monolithic passive MLL based on the same QD material system. This is invaluable in realizing devices that not only mode lock, but also maintain good pulse quality over a wide range of operating conditions.

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8255-58, Session 12

THz wave generation using frequency stabilized laser diodes

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Laser diodes (LD) widespread appeal lies in their small size, light weight, economy and durability. On the down-side, their oscillation frequencies are extremely susceptible to changes in atmospheric conditions or injection current.

We have succeeded in stabilizing semiconductor lasers’ frequencies to Rb absorption lines, by means of negative electrical feedback. The Rb absorption line exhibited good stability over the long-term, but its spectrum linewidth broadened, due to the Doppler effect. So, Rb-saturated absorption lines were employed.

Stability was evaluated using a beat note two laser beams. THz-wave generation by means of a stabilized laser diode’s beat note has been the subject of much discussion, of late, and our system accomplishes the task, with a high level of frequency stability, a narrow linewidth, and perfect frequency tunability. In our experiment, a high-speed photo detector was adopted for beat note observation, which resulted in our obtaining a beat note frequency up to 3 GHz.

8255-59, Session 13

Potentials and challenges for the optoelectronic oscillator

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We will review our experimental and simulation studies of optoelectronic oscillators (OEOs). A necessary condition to produce ultra-low phase noise microwave signals is a high intrinsic quality factor, Q, of the oscillator. The OEO can have an intrinsic Q produced by a long optical fiber that is an order of magnitude higher than that of the best electronic oscillators (i.e. the Poseidon). However, our experimental results show that the OEO’s current phase noise level is still worse than the Poseidon at certain offset-frequencies. That is caused by many noise sources in the OEO system that reduce the “loaded-Q” in the loop system. In order to mitigate these noises, we have made a systematic study of these noise sources, including laser RIN, Brillouin and Rayleigh scattering in the fiber, temperature variation, and vibration, etc. These noise sources in both the optical and electrical domains, are convoluted in the system by many different physical effects, so that it is difficult to experimentally separate them and only the dominant phase noise is observed in each offset-frequency. Therefore, we are developing a computational model to simulate our experimental injection-locked dual-OEO system. By validating the model with our experimental results from both individual components and OEO loops, we can start to trace the individual phase noise sources. The goal is to use the validated model to guide our experiments to identify the dominant phase noise under different operation condition, which should alow us to mitigate these noise sources so that the OEO can reach the full potential its intrinsic Q.

8255-60, Session 13

System modeling of passive millimeter wave imager based on optical up-conversion

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In this paper we present an end-to-end system model of passive millimeter wave (mmW) imaging system by utilizing an optical up-conversion process. The system leverages our high-speed Lithium Niobate (LiNbO3) electro-optic (EO) phase modulators to efficiently upconvert received millimeter-wave fields onto an optical carrier, such fields can be readily captured, routed, and processed using optical techniques, thereby providing significant advantages over traditional heterodyne imagers. Such a system, however, involves tremendous integrated devices and subsystems ranging from RF to optical domains, including receiving antennas, RF amplifiers, RF transitions, EO modulators, RF and optical couplers and filters, optical imaging system, fiber routing, phase feedback loop and focal plane detector array. Due to the complicated nature of the system, accurate and efficient modeling of such system becomes extremely challenging. To this end, start with radiometric phenomena, we establish a mathematical model to bridge all component and subsystem models together to complete the system performance evaluation, therefore, it is capable of taking the component-level design parameters into account. The subsystem models through theoretical simulation and experimental measurement provide accurate input to system evaluation. The theoretical framework developed here has demonstrated its ability to model, evaluate, and predict the overall system performance. The modeling tools have been used for the validation our First-Ever demonstrated optical based passive mmW imager at 35 GHz. Optimization can be followed to tune the system into a better operation mode. Besides this, more importantly, these tools are also employed for the development of our targeted 77 GHz imaging system.

8255-61, Session 13

Speckle noise reduction of a dual-frequency laser Doppler velocimeter based on an optically injected semiconductor laser

C. Cheng, J. Lee, T. Lin, F. Lin, National Tsing Hua Univ. (Taiwan)

We develop and investigate a dual-frequency Laser Doppler Velocimeter (DF-LDV) based on an optically injected semiconductor laser. By operating the laser in a period-one oscillation (P1) state, the laser can emit light with two coherent frequency components separated by about 10 GHz. Through optical heterodyning, the velocity of the target can be determined from the Doppler shift of the beat signal of the dual-frequency light. While the DF-LDV has the same advantages of good directionality and high intensity as in the conventional single-frequency LDV (SF-LDV), having an effective wavelength in the range of microwave in the beat signal greatly reduces the speckle noise caused by the random phase modulation from the rough surface of the moving target. To demonstrate the speckle noise reduction, the Doppler shifted signals from a moving target covered by the plain paper are measured both from the SF-LDV and the DF-LDV. The target is rotated to provide a transverse velocity, where the speckle noise increases as the transverse velocity increases. The bandwidth of the Doppler signal obtained from the SF-LDV is increased from 4.7 kHz to 9.4 kHz as the transverse velocity increases from 0 m/s to 5 m/s. In contrast, the bandwidth obtained from the DF-LDV maintains at 0.09 Hz with or without the rotation limited by the linewidth of the P1 state used. By phase-locking the laser with a RF current modulation, the linewidth of the P1 state can be much reduced to further improve the velocity resolution and extend the detection range.

8255-62, Session 13

Simulation of the evolution of spectrum-managed optical pulse propagation in active fibers with programmable gain spectral profile

T. Yang, Z. Wang, D. Yang, D. Jia, M. Sang, Tianjin Univ. (China)

Erbium-doped fiber (EDF) lasers have become a reliable source of sub-100 fs pulses at 1550 nm; however dispersion and nonlinearities in the optical fiber make the generation of multi-nano Joule pulses difficult. Most research groups have focused on reshaping or compressing the pulses by adding extra anomalous dispersion in-cavity or out-cavity fiber lasers. However it was found recently that the spectral filtering in an all-normal-dispersion mode-locking fiber oscillator plays a dominant role in pulse shaping by cutting the edges of the spectrum profile of the pulse that is characteristic of dissipative solitons. On the other hand in fiber amplifiers, self-similar propagation of parabolic pulses in a normal-dispersion fiber seems to be a perfect solution to mitigate or possibly eliminate the difficulties due to the nonlinearities in optical fiber if the gain bandwidth in an active fiber is larger than the spectral bandwidth of amplified pulses. Unfortunately the bandwidth of a very flat gain of EDF is limited to about 20 nm which is much less than that needed to generate sub-100 fs pulses based on previous soliton mode-locking mechanism. In this paper, a spectral filter is introduced in an EDF amplifier for reshaping the spectral profile and modifying the chirp condition of the amplified pulse at the end of active fiber in the time and frequency domain, respectively. A segment of single-mode fiber (SMF) with high nonlinearity and anomalous dispersion following the EDF is used for further compressing the pulse duration. The evolution of the optical pulse propagation is simulated based on a modified Ginzburg-Landau equation and by modeling the filter transfer function. The results show how the combination of the programmable gain spectral profile and nonlinearity in a SMF affect the amplified pulse. A new pulse narrowing mechanism is proposed for designing high power fiber amplifiers.

Conference 8256: Physics, Simulation, and Photonic Engineering of Photovoltaic Devices

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8256-01, Session 1

Increasing upconversion by metal and dielectric nanostructures

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Upconversion (UC) of sub-bandgap photons has potential to increase solar cell efficiencies. Until now, the achieved upconversion efficiencies are too low, to make UC relevant in photovoltaics. Therefore, additional means of increasing UC efficiency are necessary. In this paper, we investigate different photonic structures for this purpose. The theoretical analysis is based on a rate equation model that describes the UC dynamics in β_4-$NaYF_4$: 20% Er^{3+}. The model considers ground state and excited state absorption, spontaneous and stimulated emission, energy transfer, and multi-phonon relaxation. The model uses Einstein coefficients derived from measured reflection spectra by Kubelka-Munk and Judd-Ofelt theory and reproduces the observed dependence of the luminescence on the irradiance very well. For one, this model is coupled with results of Mie theory and exact electrodynamic theory calculations of plasmon resonance in gold nanoparticles of various sizes. The effects of the gold nanoparticles on the local field density and on the transition rates within in the upconverter, and energy transfer to the nanoparticle are considered. Calculations are performed at high resolution for a three dimensional simulation volume. Especially the local field enhancement by the plasmon resonance positively influences UC efficiency because of the non-linear nature of upconversion. Furthermore, the effect of a changed local field in the proximity of dielectric nanostructures is investigated. For this purpose RCWA and FDTD simulation models of such structures are coupled with the rate equation model of the upconverter. The results suggest that both metal nanoparticles and dielectric nanostructures can increase UC efficiency.

8256-02, Session 1

Simulations of solar cell enhancement using whispering-gallery modes of dielectric nanospheres

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Dielectric texturing is a viable method to induce light trapping, but thin film device quality often suffers upon direct texturing of the semiconductor active material. We propose here an approach for coupling light into smooth untextured thin film solar cells of uniform thickness using periodic arrangements of resonant dielectric nanospheres deposited as a continuous film on top of a thin cell. We show an enhancement of more than 10% for a thin film solar cell. Freely propagating sunlight can be diffractively coupled and transformed into several guided modes within the array of wavelength scale dielectric spheres. Spheres can be mono or multi sized. Incident optical power is then transferred to the thin film cell by leaky mode coupling into the cell thin absorber layer. It is shown that guided whispering gallery modes in the spheres can be coupled into particular modes of the solar cell and significantly enhance its efficiency by increasing the fraction of incident light absorbed. After analytically analyzing the resonant modes of a dielectric nanosphere in vacuum, we numerically demonstrate this enhancement using 3D full field finite difference time domain (FDTD) simulations of a SiO2 nanosphere array above a thin film amorphous silicon solar cell and a gallium arsenide (GaAs) solar cell structure featuring back reflector and double anti-reflection coating. We use the nonuniform generation rates calculated from the FDTD results in two and three dimensional device physics simulations to investigate the effects of nonuniform generation. We show results at normal incidence and at different angles.

8256-03, Session 1

Inverse design for enhanced light management in photovoltaic cells

S. Faruque, Stanford Univ. (United States); B. Armbruster, Northwestern Univ. (United States); P. Peumans, IMEC (Belgium); S. Fan, M. L. Brongersma, Stanford Univ. (United States)

Inverse design is a powerful and well-established tool for the development of complex photonic devices. In this talk, we discuss how inverse design can be used to optimize the power conversion efficiency of photovoltaic cells. We will demonstrate how our method efficiently obtains the appropriate choice of materials and geometry for optimal light management across the solar spectrum.

We first illustrate how this design methodology can be applied to the optimization of single and multilayer dielectric stacks that can serve as a broadband anti-reflection coating on top of a solar cell. Using these examples, we explain and quantify the advantages of inverse design over computationally intensive, brute-force numerical simulations.

We continue by discussing the potential use of this technique for the optimization of more complex light trapping layers, such as non-periodic gratings. It is by now well established that a certain degree of non-periodicity can enhance broadband light trapping, but effective optimization strategies to develop these are lacking.

Finally, we present the applicability of our method to an arbitrary photovoltaic cell structure, indicating its value for efficiently optimizing cells with many functional components, such as advanced multi-junction geometries.

8256-04, Session 1

Exact field solution to guided wave propagation in lossy thin films

J. R. Nagel, S. Blair, M. Scarpulla, The Univ. of Utah (United States)

We derive the full-field solution for electromagnetic wave propagation in a symmetric dielectric slab with finite conductivity. The functional form of the resultant eigenvalue equation is identical to the lossless case, except the propagation constants take on complex values. The solution must therefore be found through the use of nonlinear inversion methods, which we demonstrate by applying the steepest descent method with linear line search. We find that extra eigenmode solutions exist for the lossy case which do not normally exist in a purely lossless system. We also demonstrate a special case of wave guidance that occurs in a lossy slab with lower real index than the surrounding medium. An approximate solution for the longitudinal attenuation coefficient is derived from geometric optics and shows excellent agreement with the exact value. Lossy mode propagation is then explored in the context of thin-film photovoltaics.

8256-05, Session 2

Plasmonic photovoltaics: combination of electromagnetic and carrier-transport modeling reveals performance windows for nanoplasmonics (Keynote Presentation)

S. A. Maier, Imperial College London (United Kingdom)

We report three-dimensional modeling of plasmonic solar cells in which electromagnetic simulations are directly linked to carrier transport calculations. Previous descriptions of plasmonic solar cells have only involved electromagnetic modeling without realistic assumptions about carrier transport, which leads to discrepancies in behaviour particularly for devices based on materials with low carrier mobility. Enhanced light absorption and improved electronic response arising from plasmonic nanoparticle arrays are observed, in good agreement with previous experiments. Complete modeling provides design criteria with a thorough understanding of the plasmonic interaction with a photovoltaic device. Implementations for the III/V system will be presented and critically assessed.

8256-06, Session 2

Plasmonic enhancement of up-conversion in ultrathin Y2O3: Er layers

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In most solar cells, 30 to 50% of the solar spectrum incident power is lost because it is not absorbed by the solar cell. Combining IR photons by up-conversion could in principle reduce this loss significantly and provide for a concept appendable to any existing device [1]. The concept has been proved with composite materials of Y2O3 and an improvement of the system with very thin Er-doped Y2O3 layers growth at moderate temperatures (below 300°C) by ALD and deposited plasmonic structures on top of them will be described.

These films have been characterized, and their upconversion efficiency were measured. The films display upconversion with values comparable to those obtained from films prepared at high temperature by other thin film methods.

A strong enhancement, by a factor 5, of the upconversion efficiency by plasmonic periodic structures is demonstrated and discussed.

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8256-07, Session 2

Improved efficiency for nanopillar array of c-Si photovoltaic by down-conversion and anti-reflection of quantum dots

C. Lin, H. Chen, H. W. Han, Y. L. Tsai, C. H. Chang, M. Tsai, H. Kuo, P. Yu, National Chiao Tung Univ. (Taiwan)

Improvement of efficiency for crystalline silicon (c-Si) with nanopillar arrays (NPAs) solar cell was demonstrated by deployment of CdS quantum dots (QDs). The NPAs was fabricated by colloidal lithography of self-assembled polystyrene (PS) nanospheres with a 600 nm in size and reactive-ion etching techniques, and then a colloidal CdS QDs with a concentration of 5 mg/mL was spun on the surface of c-Si with NPAs solar cell. Under a simulated one-sun condition, the device with CdS QDs shows a 33% improvement of power conversion efficiency, compared with the one without QDs. Additionally, we also found that the device with CdS QDs shows a 32% reduction in electrical resistance, compared with the one without QDs solar cell, under an ultraviolet (UV) light of 355nm illumination. This reduced electrical resistance can directly contribute to our fill-factor (FF) enhancement. For further investigation, the excitation spectrum of photoluminescence (PL), absorbance spectrum, current-voltage (I-V) characteristics, reflectance and external quantum efficiency (EQE) of the device were measured and analyzed. It is noteworthy that the introduction of our QD layer also reduce the reflectance at longer wavelength. Based on the spectral response and optical measurement, we believe that CdS QDs not only have the capability for photon down-conversion in ultraviolet region, but also provide extra antireflection capability and current conductivity for the improvement of Si-based solar cell efficiency.

8256-08, Session 2

Scattering analysis of the indium-tin-oxide (ITO) nanowhiskers on ITO film substrate for a-Si solar cell

H. Liu, C. Chang, C. Lin, P. Yu, National Chiao Tung Univ. (Taiwan)

Light trapping techniques such as textured surfaces and highly reflective back contacts enhance the optical absorption in thin film solar cells by increasing the light path due to scattering. Such a scattering capability at rough interfaces inside a solar cell is generally characterized by haze ratio. In this work, we demonstrate the measured haze characteristics of novel indium tin oxide (ITO) nano-whiskers deposited on ITO-coated glass substrate. The ITO nanowhiskers for scattering layer have shown superior properties for both antireflection and scattering efficiency. Moreover, as ITO is a widely used transparent conductive oxide material, it is very appealing to employ nano-whiskers in thin-film solar cells as light trapping textures.

Next, we construct two theoretical models to analyze the scattering capability, namely, the relationship between haze ratio and the distribution of the structure size and shape. First, an equivalent spheres model based on a classical Mie theory is developed. The radius and the space distribution of spheres are used for the curve-fitting of the measured haze ratio for various nanowhisker structures. The result shows the haze-ratio of an ITO whisker layer matches the measurement closely. However, there still exists slight discrepancy in the long wavelength region as the arbitrarily-oriented nanowhisker structures do not resemble spheres but rather look like a collection of cylinders. Therefore, a scattering model based on cylinder particles is under development to investigate the scattering property of nano-whiskers in more detail. The studies are crucial to the development of novel light trapping structures for thin film solar cells.

8256-09, Session 3

Improving photo-generated carrier escape in quantum well solar cells

A. Alemu, A. Freundlich, Univ. of Houston (United States)

Solar cell devices incorporating quantum wells are expected to lead to better performances. Nonetheless, the smooth vertical transport of carriers to the contacts could be hindered if care is not taken in the specific choice of the material system and energy band design, leading to device performance degradation. The study of carrier escape in conventional quantum well solar cells (i.e. InP/InAsP, GaAs/InGaAs) displaying distributed band offsets shows the presence of a sequential carrier escape mode where carries transfer to higher laying energy levels before their eventual escape. The order at which various carriers escape their confining potential also affects device performance. These insights offer practical pointers towards a better choice of materials in order to implement device designs that fasten the escape of all carriers. Using material systems displaying a band offset only on the conduction (GaAs/(In)GaAsN) or valence (GaAs/GaAsSb(N)) band, we offer device designs that rely on intra-subband thermal transitions accompanied by resonant tunneling to adjacent wells, which greatly accelerates the carrier escape process. Typically, photo-excited carriers in the well regions need about several nanoseconds to make their way out of deep wells (>250 meV), but a proper design of energy states in successive quantum wells can reduce this escape time to few picoseconds, leading to reduced recombination and higher carrier collection. Using a solar cell modeling program based on the drift-diffusion framework, we show that quantum well solar cells displaying such thermo-tunneling carrier escape process can substantially surpass the efficiency limit of their bulk counterpart.

8256-10, Session 3

Exploring the radiative limits of InGaAs quantum well solar cells

R. E. Welser, Magnolia Solar, Inc. (United States)

High-voltage InGaAs quantum well devices are demonstrated and shown to operate in a regime of suppressed radiative recombination. A novel extended heterojunction structure is employed to reduce non-radiative recombination and expose the limiting n=1 component of the diode current. Short circuit current versus open circuit voltage curves derived from illuminated current-voltage measurements on several sets of InGaAs quantum well solar cells are analyzed, and the underlying saturation current densities extracted. Diode currents lower than those expected from detailed balance theory are observed, and possible mechanisms for the apparent suppression in radiative recombination are discussed.

8256-11, Session 3

Exploring the potential of quantum wells for efficiency enhancement in photovoltaic cells

M. Sugiyama, The Univ. ot Tokyo (Japan); Y. Wang, Y. Wen, K. Watanabe, Y. Nakano, The Univ. of Tokyo (Japan)

There has been controversy whether or not inclusion of quantum wells (QWs) is beneficial for conversion efficiency of photovoltaic cells. Narrowed effective bandgap by QWs usually imposes a trade-off relationship: enhancement in short-circuit current (Isc) by the extended range of absorption to shorter wavelengths, and reduction in open-circuit voltage (Voc) due to carrier population in the energy states that exist between the band edges of a host material. According to this discussion, if carrier escape is fast enough to make quasi-Fermi-level splitting wider than the effective bandgap of the QWs, a cell including QWs should be able to gain efficiency over a simple p-i-n cell of a host material.

Although the discussion above has long been developed, no definite experimental evidence has been presented to draw a conclusion. For example, everyone can assume that a superlattice is beneficial for enhanced carrier transport, but a strain-balanced InGaAs/GaAsP superlattice, which can be inserted in a GaAs p-i-n cell, has been demonstrated quite recently with an elaborate hetero-interface management in MOVPE. The implemented superlattice cell indeed exhibited a substantial increment in Isc and only a small drop in Voc, making the efficiency of a QW cell equivalent to, or a bit larger than, the value of a bulk p-i-n cell. Combining it with a stepped potential structure further accelerates carrier escape from the potential bottom of quantum wells. Such an elaborate band-gap engineering is implementable only for quantum wells at the present stage of growth technology.

In addition, the superlattice cell exhibited photocurrent enhancement by two-step photon absorption, suggesting a possibility of an intermediate-band photovoltaic cell using QWs. The QW structure can also slow-down thermalization of hot carriers, and can open a way to a hot-carrier cell.

Elaborate design and growth of QWs, therefore, will still boost efficiency of photovoltaic cells.

8256-12, Session 3

Minority carrier contacts for high efficiency tandem solar cells

C. B. Honsberg, S. M. Goodnick, Arizona State Univ. (United States)

The efficiency potential of the tandem solar cells depends on the number of solar cells in the solar cell stack; how close the band gaps are to the thermodynamic optimum band gap; and the fraction of the thermodynamic efficiency achieved by each of the solar cells in the stack. The dominant focus of existing tandem research is on increasing efficiency by developing or optimizing materials and growth processes to address the trade-offs between material quality and optimum band gaps. This fundamental trade-off accounts for the approximately 3% percentage points in efficiency between the different approaches.

We present how a minority carrier contact can provide the same efficiency impact as new materials and growth approaches, with the additional advantages of simpler and/or thinner layer structures, reduced losses such as those due to temperature, and enabling greater flexibility in materials, allowing between 4-6% percentage points for 3J materials, 6-10% percentage points for 4J tandems.

A minority carrier collecting contact consists of a superlattice or quantum well region which collects minority carriers without the need for a conventional junction. This implements the thermodynamic ideal, eliminating the inherent difference in open circuit voltage between a pn junction (which are limited by the built-in voltage and hence doping) and thermodynamic calculations. Because such effects are larger for smaller band gap devices, this approach greatly benefits advanced tandem structures which used 4 junction (4J) approaches (and hence two lower band gaps) or improved 3J concepts using lower band gap (targeting 1 eV) middle solar cells

8256-13, Session 4

Efficiency improvement of InAs/GaAs quantum dot solar cells through VOC loss mitigation

C. G. Bailey, D. V. Forbes, R. P. Raffaelle, S. M. Hubbard, Rochester Institute of Technology (United States)

Same.

8256-14, Session 4

Photovoltaic properties of silicon quantum dots in dielectric matrices

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Silicon nanocrystals (Si NC) embedded in dielectric matrices provide a band gap higher than that of bulk Si but still based on and compatible with Si technology. A combination of the bulk Si (1.12eV) with the Si QD (1.8eV) band gaps in an all-Silicon dual junction solar cell results in a theoretical efficiency limit of 42.5% compared to 29% of bulk Si.

In this paper, the photovoltaic properties of Si NC in SiO2 and SiC are investigated.

Si NC superlattices were fabricated by the deposition of alternating stochiometric SiC or SiO2 layers and the respective Si rich layers, followed by thermal annealing and hydrogen passivation. The material synthesis is described in detail in [1,2] for the oxide, and in [3] for the carbide material system. The bandgap was determined by photoluminescence and a blue shift from 1.3 eV for 6 nm to 1.6 eV for 2 nm QDs was observed. In order to investigate current transport and to measure the quasi Fermi level splitting electronically, PIN structures with an intrinsic Si QD absorber layer were fabricated. Selective contacts for electrons and holes were realized by p and n doped amorphous silicon. Very first devices with an intrinsic layer of Si NC in SiC show open circuit voltages of 300 mV under 1 sun illumination.

1 M. Zacharias et. al., Appl. Phys. Lett. 80 (2002) 661

2 A. M. Hartel et al., Thin Solid Films, 2011, doi:10.1016/j.tsf.2011.06.084

3 M. Kuenle, Proceedings of the MRS, San Francisco, 2010

8256-15, Session 4

Achieve more than 5% PbS quantum dot solar cells

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Quantum dot solar cells(QDSCs) attract intense attention in the past few years due to their low fabrication costs and simple processing methods compared to other solar cells of thin film materials such as a-Si, CdTe, copper indium gallium selenide (CIGS). Also, QDSCs employing multiple-exciton generation effect potentially further boost device efficiency. We recently reported an NREL certified ~3% efficient device with structure of ITO/ZnO/PbS QD/Au. The device is remarkably stable in air without encapsulation for more than 1000 hours. However, we discovered the existence of two opposing diodes in this type device structure: a desirable forward diode at the heterojunction formed between a ZnO nanocrystal (NC) layer and the PbS QD layer, while a Schottky barrier forms between the PbS QD layer and the anode in the opposite direction, which reduce device power conversion efficiency.

In this study, we focus on devices with structure of ITO/ZnO/PbS QD/metal fabricated in air. By introducing hole extraction layer and optimize intrinsic PbS QD film electrical transport property, more than 5% PbS QDSC can be achieved.

8256-16, Session 4

Numerical simulation of QD-intermediate band solar cells: effect of dot size on performance

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In this work, we present a Quantum Dot Intermediate Band Solar Cell (QD-IBSC) photogeneration model that is based on detailed balance principles. The 3D Schrödinger equation is solved for a regimented array of cubic quantum dots known as a Quantum Dot Crystal (QDC). Energy levels used in the simulation are derived from the dispersion relation. We consider only the dispersion relation along the [100] quasi-crystallographic direction. Absorption coefficients used were assumed to be constant and non-overlapping for each energy transition. Various JV curves were simulated for different dot sizes for the InAs0.9N0.1/GaAs0.98Sb0.02 dot/host system. This material system was chosen due to its property of a negligible valance band offset. The negligible valance band offset offers more feasibility for the isolation of the intermediate band. Simulations were done under a non-concentrated 6000K black body spectrum at a cell temperature of 300K. Performance parameters for each IV curve were calculated in order to ascertain the effect of dot size on performance from a fundamental level. Results show that for a fixed dot separation of 2nm, cell efficiency increases to 36.7% as the dot size is increased to 3.5 nm, but begins decrease for larger dot sizes.

8256-17, Session 5

Screening of next-generation thin film PV absorbers from thousands of candidates (Keynote Presentation)

A. Zunger, Univ. of Colorado, Boulder (United States); L. Yu, National Renewable Energy Lab. (United States)

Thin film PV absorbing materials need to satisfy a multitude of material properties to reach high efficiency. But one class of critical target properties is the strength of the absorption at solar photons. Not all direct gap materials with band gap values of 1-1.5 eV are strong absorbers. Data bases of inorganic compounds such as the ICSD contain ~ 10 **5 compounds ,but currently we are lacking simple “selection principle” for preliminary screening of good absorbers. We have constructed a quantity called “Spectroscopic Limited Maximum Efficiency” (SLME) which is a predictor of absorption quality and can be calculated for each material given its band structure and calculated absorption spectra. It replaces the Schockley-Queisser criteria in that it takes into account the actual absorption (calculated quantum-mechanically by the GW method) and a model for non radiative relaxation. By applying it to ~ 300 “generalized chalcopyrites” IpIIIqVIr materials where p,q,r are not restricted to 1,1,2 and the element III is not restricted to have their common oxidation state III, r ,we identified a few candidates that have a significantly higher SLME than CuInSe2, opening the possibility that (all other things being equal) they can be better absorbers. This opens a practical strategy for future selection of materials from large data bases.

8256-18, Session 5

Thin Cu(In,Ga)Se2 photovoltaic microcells: high efficiency with reduced material usage

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In order to develop photovoltaic devices with increased efficiency using less rare semiconductor materials, microcells made of Cu(In,Ga)Se2, down to a few micrometers wide were fabricated. They show, at around x120 suns, an absolute increase in efficiency of 4%, that is more than 30% relative compared to 1 sun efficiency, thanks to concentrated illumination (532 nm laser). This is a breakthrough concerning concentration on this type of devices, which were previously limited to the low concentration range (about 10 suns). Due to light concentration, the open circuit voltage increases up to several thousand suns equivalent, to reach over 850 mV. The temperature increase is limited to less than 20°C over the ambient at concentration around x1000. New measurements, made under concentrated full solar flux illumination, will be presented to confirm the conclusions of our previous laser experiments.

We have also pushed our approach to another level, using ultrathin Cu(In,Ga)Se2 layers (from 1.5µm down to 0.5 µm). This further reduces the volume of generating semiconductor compared to standard 2.5µm thick devices. Contrary to thin film solar cells of conventional size, where the window layer sheet resistance is limiting under concentration, microcells are limited by absorber and contact resistances. Therefore the use of thinner absorber reduces resistive losses significantly, and better efficiencies can be measured.

Cu(In,Ga)Se2 thin films prove to be appropriate for a use under concentration, leading significant gains in terms of efficiency and material usage. Due to an advance architecture, microcells present highly efficient resistive and thermal management.

8256-19, Session 5

Highly surface textured tin oxide thin films fabricated by nozzle spraying process in photovoltaic devices

L. Chou, Y. Lin, A. T. Wu, National Central Univ. (Taiwan)

Surface texture of transparent conducting oxide (TCO) enhances the optical properties of the films. The fabrication technique to modify the surface morphology was improved by a novel and simple nozzle spraying process followed by thin film deposition. The SnO2 nanoparticles were synthesized by reverse micelle (RM) method using tin tetrachloride pentahydrate (SnCl4. 5H2O) and ammonia (NH3) as precursors, and the particles crystallized after calcinations at 700 oC for 2 hrs. A layer of SnO2 nano-particles were sprayed on glass substrates. Atmosphere pressure chemical vapor deposition (APCVD) was employed to deposit continuous SnO2 thin films on the glass substrates. The surface morphology of the film was pyramid-like texture without the particles beneath, and it changed to cauliflower-like texture when deposited on the nano-particles. The transmittance and haze of the films revealed that the irregular morphology of the SnO2 films could enhance the light scattering without losing the transmittance.

8256-20, Session 5

Optimal optical designs for GaAs single-junction solar cells

S. Liu, D. Ding, S. R. Johnson, Y. Zhang, Arizona State Univ. (United States)

Much effort has been devoted to the improvement of the performance of single-junction solar cells. Recently, conversion efficiencies as high as 28.2% have been reported for a GaAs cell with the substrate removed. To further improve the device performance, it is critical to thoroughly understand the impact of solar cell design parameters on performance. In this work, high performance planar solar cells are investigated using a semi-analytical model, where combinations of smooth, textured, reflective, and absorbing surfaces/interfaces are explored. These combinations cover almost all the possible planar structures for a single-junction solar cell. Using the ray tracing method, detailed calculations are carried out of the absorptance, emittance, photon density, and photon recycling and extraction factors. The impact of above parameters and effects, together with material quality (in terms of carrier lifetime) and solar concentration on the device performance is analyzed. Our results show that a combination of textured and reflective surfaces greatly enhances device performance by effectively increasing the photon and carrier densities, which leads to higher open-circuit voltages and conversion efficiencies. It is expected that the GaAs single-junction cell can practically achieve 30% conversion efficiency under one sun AM1.5G with properly designed structures and the state-of-art best material quality. Detailed results will be reported at the conference.

8256-21, Session 6

Impurities versus quantum dots for the intermediate band solar cell

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The intermediate band solar cell (IBSC) model proposes an efficient way of exploiting sub-bandgap absorption in a photovoltaic device. The IBSC as described theoretically is a cell with enhanced photocurrent due to the absorption of low energy photons, and high operation voltage due to the high energy gap of the materials and the device structure. Other photovoltaic devices absorbing sub-bandgap light can present enhanced photocurrent, but at the cost of lowering the voltage. Different material approaches are being investigated to realize in practice the IBSC concept. They can be divided in two branches: approaches using bulk intermediate band materials, i.e. materials doped with a high concentration of deep level impurities, and quantum dot material systems. In this paper we will compare both paths, discussing their respective strengths and weaknesses. We will present a systematic review of the most remarkable results, focusing on the limitations found to date for both kinds of IBSCs, such as the sub-bandgap absorption strength, the presence of strain in QD materials or the impurity contamination of devices in the bulk approach. We will try to discriminate which limitations are fundamental and which are susceptible to be improved technologically in the short term. We will pay special attention to the voltage loss, which is probably the most serious obstacle to be fought in all cases.

8256-22, Session 6

Demonstration of a multiband solar cell

N. López Martínez, Lawrence Berkeley National Lab. (United States); L. A. Reichertz, Lawrence Berkeley National Lab. (United States) and RoseStreet Labs. Energy (United States); K. M. Yu, Lawrence Berkeley National Lab. (United States); K. Campman, Sumika Electronic Materials, Inc. (United States); W. Walukiewicz, Lawrence Berkeley National Lab. (United States) and RoseStreet Labs. Energy (United States)

Efficient utilization of the full solar spectrum extending from near infrared to ultraviolet is one of the primary challenges for solar power conversion technologies. Using the unique features of the electronic band structure of highly mismatched GaNxAs1-x alloys we have designed, fabricated and tested a single junction multiband photovoltaic device. Such a device has an energy band separated from the conduction band as a result of the incorporation of a small amount of N into GaAs. The device demonstrates an optical activity of three energy bands that absorb the crucial part of the solar spectrum and convert it into electrical current. The performance of the device and measurements of the electroluminescence, quantum efficiency and photomodulated reflectivity are analyzed and related to the band anticrossing model of the electronic structure of highly mismatched alloys. The results are in a good agreement with the predictions of the model for the electronic band structure of GaNxAs1-x with x=0.024. The results of the solar cell characteristic curve demonstrated that the open circuit voltage of the devices is limited by the largest band gap of the material. The results accentuate the importance of the blocking layers eliminating the charge transport in the narrow intermediate band and assuring that the band acts only as a “stepping stone” enabling efficient use of low energy solar photons. In addition, we have also analyzed the band gaps in this material at different temperature and show, for the first time in this intermediate band solar cell structure the experimental temperature evolution of the three energy bands.

8256-23, Session 6

Device simulation of intermediate band solar cells

K. Yoshida, Y. Okada, The Univ. of Tokyo (Japan); N. Sano, Univ. of Tsukuba (Japan)

To realize high efficiency solar cells, new concepts beyond the Shockley-Queisser limit are widely investigated. The intermediate band solar cell (IBSC) is one of the candidate concepts. From the importance of device physics, we have developed a device simulator for IBSCs. For device simulation of IBSC, the Poisson equation, carrier continuity equations of electrons in the conduction band (CB) and the valance band (VB) and balanced equation of IB state electrons must be solved self-consistently. The simulation methods can clarify the intrinsic device behavior of IBSCs which cannot be investigated by the detailed balance model. For example, by the existence of electrons trapped in IB states, electrostatic potential along the depth direction of the solar cells is strongly modified from the equilibrium under illumination of sunlight. This potential change is strongly related to its absorption property of sunlight. And the doping to IB region can enhance short circuit current density via IB states. Under larger concentration, this doping effect is decreased by the photo-filling effects in the radiative limit. Absorption coefficients of each band-to-band transition are decided by the semiconductor materials and fundamental physics. These limitations make the different spectra and values from ideal treatments and decide the maximum efficiency of the IBSC. In this work, we present the fundamental properties and suggestions to approach the high efficiency IBSC operations as a device.

8256-28, Session 6

The Therdomymic Limits of Tandem Photovoltaic Devices with Intermediate Band

J. Lee, C. B. Honsberg, Arizona State Univ. (United States)

The thermodynamic limits of multijunction solar cells are based on splitting wide range of solar spectrum and finding maximum efficiency and well-matched optimum bandgaps. And, its maximum efficiency is 86% under infinite number of stacks. But, multijuncton solar cells have own limitation because of materials defects between interfaces and optimum materials. To overcome such drawbacks, using quantum dots or nano structure materials inside multijunction solar cells will be promising technologies. There are lots of quantum researches related with intermediate band solar cells. Because of the multiple transitions, the actual behavior of intermediate band solar cells is the nearly same as three stacks of multijunction solar cells. So, we can expect that each stack of hybrid solar cells have three stacks of conventional multijunction solar cells. For instance, three stacks of hybrid solar cell can show the nearly 9 stacks of conventional multijunction solar cells. To setup the novel model of hybrid multijunction photovoltaic devices, we have used two conventional detailed balance models from both multijunction and intermediate band solar cells. To do further research of hybrid solar cells, we have to consider about overlapping of spectrum. Because, the transitions from intermediate band to conduction band is lower than that of valence band to intermediate band. So, we have modified the detailed balance equations of intermediate band and combined with multijunction solar cells. Under maximum concentration, we have obtained about 71% maximum efficiencies and its value is closed to 4 ot 5 stacks of multijunction solar cells.

8256-25, Session 7

Spectrum-optimized Si-based III-V multijunction photovoltaics

S. A. Ringel, T. Grassman, J. Grandal, A. Carlin, C. Ratcliff, L. Yang, M. Mills, The Ohio State Univ. (United States)

The optical partitioning of the solar spectrum by multijunction (MJ) solar cells is traditionally constrained by available substrate lattice constants, but with the advantage of outstanding material quality. However, in spite of lattice-matched III-V/Ge MJs achieving efficiencies beyond 40%, higher performance at much lower cost is desired. This presentation focuses on an approach that can merge the low cost, large area and proven efficiency of Si photovoltaics with metamorphic III-V epitaxial cells whose bandgaps are engineered to create ideal multijunction bandgap combinations when combined with active Si wafer/subcells, such that the lattice matching constraint is removed. We focus on the metamorphic epitaxy of GaAsyP1-y on Si as enabling in this context since its comparatively large bandgap provides optical access to the Si cell/substrate while capturing an unusual range of direct bandgap Ga-rich GaInP and also GaAsP alloys through compositional grading. A multi-step growth temperature profile covering atypical growth conditions by molecular beam epitaxy, coupled with controlled GaP/Si nucleation chemistry, leads to high quality metamorphic GaAsyP1-y layers on Si spanning from GaP to GaAs. Total suppression of coalescence-driven defects over the entire alloy range on Si is demonstrated. Internally lattice-matched GaAsP and Ga-rich GaInP subcell materials and GaInP/GaAsP/Si structures are achieved which possess ideal bandgap combinations of ~ 2.0 eV/1.55 eV with the underlying 1.1 eV Si. Excellent optical properties throughout the entire bandgap range of 1.5 - 2.2 eV on Si are observed, correlating with low trap concentrations, low dislocation densities and heterovalent defect-free interfaces. Early device results will be shown.

8256-26, Session 7

Simulation of novel InAlAsSb solar cells

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Triple-junction solar cells lattice matched to InP are a promising route to achieving extremely high efficiencies, due to the availability of lattice matched materials close to the ideal bandgaps for terrestrial and extra-terrestrial solar energy conversion. A good candidate for the top cell of the 3J is the lattice matched quaternary InAlAsSb, which is encompasses the 1.7-1.8eV bandgap range required for high efficiency 3J cell architectures. In this work, we describe the results of modeling work to aid the design of InAlAsSb solar cells. Using a drift-diffusion model developed at NRL, we are able to make predictions of device performance for a wide variety of InAlAsSb cell designs. In order to produce realistic predictions for the performance of the material, we have investigated and characterized the optical constants, minority carrier transport and recombination properties of MBE grown samples of the material, using a range of experimental techniques. This information is then coupled with k.p bandstructure calculations and the drift diffusion model to model the solar cell performance, including quantum efficiency, light IV and dark IV properties. We have designed antireflection coatings using a transfer matrix model to maximize the energy conversion efficiency of the cells, and discuss an efficient approach to interpolating the optical constants of quaternary films from the constituent end-point binary materials. Finally, we discuss the performance predictions for triple junction cells incorporating the InAlAsSb material based on realistic material parameters.

8256-27, Session 7

Two-dimensional modeling of CdZnTe/Si based dual and triple junction solar cells

Y. Xiao, Z. Li, M. Lestrade, Z. S. Li, Crosslight Software Inc. (Canada)

There is intensive interest to develop high efficiency multi-junction solar cells including the exploration of using Si substrate. Consistent growth of laterally uniform CdTe on Si substrate by molecular beam epitaxy has been reported, which indicates that II-VI semiconductor alloys based on CdTe and grown on Si substrates may give good cell performance. In this work, using Crosslight software APSYS, we have made two-dimensional simulation of dual and triple junction solar cells based on CdZnTe/Si structure and material system with tunnel junctions. The basic physical quantities like band diagram, optic absorption and generation for the modeled solar cells, and external quantum efficiency for individual subcell junctions are obtained. Current matching analyses and multi-sun concentration simulation are performed. The modeling results are also discussed versus issues for efficiency enhancement. The presented results indicate that triple junctions with II-VI CdZnTe and CdTe on Si can achieve efficiency comparable to those III-V based compound on Ge substrate.

8256-29, Session 8

Electron confinement and phonon effects in semiconductor quantum dots

R. Ferreira, Ecole Normale Supérieure (France)

We review the large confinement effects in self-assembled quantum dots (QDs) with emphasis on two effects: (i) capture of free charges into and escape of trapped charges from the QD and (ii) the specific effects related to the couplings of bound carriers with the lattice vibrations. Such topics, of large fundamental and applicative interests, are yet not fully understood in QDs.

8256-30, Session 8

Modeling carrier relaxation in hot carrier solar cells

S. M. Goodnick, C. B. Honsberg, Arizona State Univ. (United States)

Hot carrier solar cells consist of an absorber in which the photon energy above the band gap of the semiconductor is not lost to thermalization with the lattice. Recently, it has been proposed that that nonequilibrium 'hot' phonons play a critical role in reducing carrier energy loss. Typical optical phonon decay times are much longer than the electron optical phonon emission rate. Whether this time is long enough to slow the energy loss rate and realize hot carrier temperatures sufficient for efficient hot carrier solar cell operation is not well understood.

We present first a simplified energy balance approach to examine hot photons in a hot carrier solar cell, in which the optical energy entering the system is balance by the energy loss through photon loss and extraction/recombination of carriers which allows examination of the effective carrier temperature as a function of carrier extraction and band gap. Ensemble Monte Carlo modeling allows more detailed examination of carrier temperatures, taking into account a broader range of scattering mechanisms.

Based on an energy model approach, it is theoretically possible to realize high carrier temperatures, but only for long and not experimentally demonstrated LO phonon lifetimes. Ensemble Monte Carlo simulation shows that a nonequilbrium carrier population exists, but questions remain about the ability to achieve these even under solar intensity from concentrating systems and about the impact of large phonon lifetimes.

8256-31, Session 8

InGaAs/GaAsP quantum wells for hot carrier solar cells

L. C. Hirst, M. Furher, D. J. Farrell, Imperial College London (United Kingdom); A. Le Bris, J. Guillemoles, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France); M. J. Y. Tayebjee, R. Clady, T. W. Schmidt, The Univ. of Sydney (Australia); M. Sugiyama, Y. Wang, The Univ. of Tokyo (Japan); N. J. Ekins-Daukes, Imperial College London (United Kingdom)

In hot carrier solar cells the steady-state carrier population does not fully thermally equilibrate with the lattice phonon population, allowing the carrier distribution to be described by a higher temperature than that of the semiconductor lattice. In an ideal single junction device ~30% of total incident solar radiation is dissipated as heat to the surrounding material. In an optimal hot carrier device this loss mechanism is eliminated, leading to fundamental efficiency enhancement over single junction devices. Despite clear efficiency advantages, no real world device has been demonstrated. One of the key challenges to developing a hot carrier solar cell is creating an absorber material which exhibits sufficiently slow carrier cooling to maintain a hot carrier population under realistic levels of solar concentration.

Slowed carrier cooling has recently been demonstrated in strain-balanced InGaAs/GaAsP quantum wells (QWs) under high photon flux density [1]. We will present our latest continuous-wave and ultra-fast spectroscopy results of InGaAs/GaAsP single QW, multiple QW and SL structures under a range of operating conditions. We will use these results to calculate carrier cooling rates, allowing comparison with other proposed material systems. The paper will also combine these experimental results with device modelling to comprehensively evaluate the viability of this material system as a hot carrier absorber, and outline a roadmap for developing the first proof of concept hot carrier device.

[1]Hirst et al. "Hot Carrier Dynamics in InGaAs/GaAsP Quantum Well Solar Cells" Proceedings of the 37th IEEE Photovoltaic Specialists' Conference, 2011

8256-32, Session 8

Anitmonide based heterostructures for hot carrier solar cells

A. Le Bris, M. M. Mannan, L. Lombez, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France); P. Christol, G. Boissier, J. Perez, Univ. Montpellier 2 (France); J. Guillemoles, Institut de Recherche et Développement sur l'Energie Photovoltaïque (France)

Single junction III-V heterostructures based devices have the potential of extracting more energy from the solar spectrum than allowed from the Shockley-Queisser limit if thermalisation of photogenerated carrier can be harnessed to some extent as in the hot carrier solar cell concept [1]. Previous modelling [2] and experiments [3] have shown the interest of Multiple Quantum Well heterostructures in the antimonide system and the importance of very thin structures [3]. In this paper we report new data on the thermalisation rates in antimonide heterostructures and compare them to extremely thin GaSb homojunctions. For the first time optical and electrical measurements of thermalisation rates performed on heterostructures and thin homojunctions devices will be presented.

[1] D. Konig, K.Casalenuovo, Y.Takeda, G.Conibeer, J.F.Guillemoles, R.Patterson, L.M. Huang, M.A.Green, "Hot carrier solar cells: Principles,materials and design", Physica E, 42 (2010) 2862-2866

[2] Arthur LE BRIS and Jean-François GUILLEMOLES , " Hot Carrier Solar cells: achievable efficiencies accounting for main thermalisation paths" Applied Phys. Letters, 97, (2010) 113506

[3] A. Le Bris et al.. Thermalization rate study of GaSbbased heterostructures by continuous wave photoluminescence and their potential as a hot carrier solar cell absorber. Energy and Environmental, Sciences, submitted, 2011.

8256-33, Session 9

Third generation photovoltaics: high efficiency at low cost to drive large scale PV implementation (Keynote Presentation)

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

No abstract available

8256-34, Session 9

Multiple exciton generation in PbSe nanorods

P. D. Cunningham, U.S Naval Research Lab. (United States); J. E. Boercker, E. E. Foos, U.S. Naval Research Lab. (United States); M. P. Lumb, U.S. Naval Research Lab. (United States) and The George Washington Univ. (United States); A. R. Smith, J. G. Tischler, J. S. Melinger, U.S. Naval Research Lab. (United States)

The possibility of generating more than one electron-hole pair per incident photon is of fundamental importance to the improvement of photovoltaic devices. While multiple exciton generation (MEG) is known to occur in semiconductor nanocrystals, the required energy threshold prevents visible photons from being utilized. We report transient absorption measurements demonstrating a two-fold increase in the MEG efficiency of solution samples of PbSe quasi one-dimensional nanorods over zero-dimensional nanocrystals to 0.81, where 1 is the largest efficiency possible. This improvement is accompanied by a reduction of the MEG threshold energy to 2.23Eg, which allows visible photons to participate in MEG. This approaches the theoretical limit for the threshold energy of 2Eg imposed by energy conservation. Detailed balance calculations show that, unlike nanocrystals, photovoltaic cells based on PbSe nanorods could achieve power conversion efficiency above the Shockley-Queisser limit, especially when used in conjunction with solar concentrators.

8256-35, Session 9

Recycling carrier thermalization losses for improving efficiency of dilute nitride multi quantum well solar cells

G. K. Vijaya, A. Alemu, A. Freundlich, Univ. of Houston (United States)

III-V Dilute Nitride multi-quantum well structures are currently promising candidates to achieve 1 sun efficiencies of >40% with multi-junction design (InGaP/ GaAs/ GaAsN/ Ge). In order to improve existing efficiency limits for this design, one possible path is to utilize the substantial portion of the incoming radiation which is lost in the spectral energy region greater than the band-gap. The feasibility of utilizing the thermal loss with the help of thermally assisted transitions from below-bandgap levels to the conduction band is examined by means of modeling its maximum possible efficiency. Some preliminary assumptions made regarding electron transfer are that it is limited only by the availability of electrons in the sub-band gap level and the availability of the required thermal loss energy. The behavior of the GaAsN/GaAs multi-quantum well cell is modeled by using calculated energy levels, where the standard k.p model is used to obtain the energy levels, including effects of strain and spin-orbit interaction. The resulting absorption coefficient calculation has contributions from excitons in addition to the bulk and quantum-well responses. The overall efficiency with this design is optimized with respect to the bandgap of the quantum well region, with the resulting estimated efficiency of ~60% possible for a single junction solar cell under one sun with a band-gap of GaAs (1.4eV)/MQW (0.95-1 eV). Suggestions for the practical realization of such a design are provided.

8256-36, Session 9

The use of nanostructures for meeting the terawatt photovoltaic challenge

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The rapid growth rates of photovoltaics over the last decades - averaging 40% compound annual growth (CAGR) -demonstrates the ability of photovoltaics to be installed and used on a large scale. Nanostructured photovoltaics offers the twin advantages for providing a route to high efficiency as well as a means to overcome the conventional trade-off between high quality, novel materials and expensive fabrication. The use of nanostructures in high efficiency often involves increasing the efficiency of a single solar cell via new physical processes, such as intermediate band or multiple excition approaches. However, a growing yet underutilized use of nanostructures is to incorporate them into existing solar cell structures to minimize loss mechanisms or achieve a closer match to the ideal efficiency. For example, quantum wells in tandem solar cells can alter the effective band gap of the material, allowing improved efficiencies. Such nanostructured approaches are an important element in the ultimate realization of high efficiency solar cells, since they provide an entry point for nanostructures in existing solar cells.

The paper focuses on demonstrating approaches to the use of nanostructured in existing solar cells which can lead to higher performance, lower cost devices. Further, such devices provide a path for the inclusion of new physical concepts, which allow efficiencies similar to today's triple junction solar cells in a single solar cell. Finally, new approaches using a combination of different physical concepts provides a route to a single solar cell with a theoretical efficiency equal to the thermodynamic limit.

8256-37, Session 10

Spectroscopic ellipsometry: metrology for photovoltaics from the nano to the giga

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Non-destructive, non-invasive measurement and monitoring tools are needed at all stages of photovoltaic devices development - from the nano-scale in research laboratories to the giga-scale of mass production. Optical probes based on polarized light spectroscopy, such as spectroscopic ellipsometry, have been applied in such cases and examples will be presented there for the three major thin film photovoltaics (PV) technologies including thin film hydrogenated silicon (Si:H), cadmium telluride (CdTe), and copper indium-gallium diselenide (CuIn1-xGaxSe2). At the same time, real time SE during materials fabrication has provided insights into the nucleation, coalescence, and phase evolution of the thin films. These insights in turn can lead to guiding principles for PV performance optimization, as well as future directions for real time control of processes. The thickness as well as the spectral dependence of the index of refraction and extinction coefficient (n, k) can be deduced in real time from these in situ SE measurements. Further analysis of the deduced (n, k) spectra can also yield more fundamental optical parameters of critical point (CP) amplitudes, CP energies or band gaps, and CP widths. These can provide information on material density, temperature, composition, strain, grain size, and defect density, assuming that appropriate databases exist. Here we will present analysis of such parameters for the growth of nanoparticles of metals or semiconductors, as well as for high efficiency thin films solar cells, notably for I-III-VI solar cells with various compositions (Cu content, Ga content).

8256-38, Session 10

Quantitative luminescence imaging of solar cells using hyperspectral imager

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Photoluminescence (PL) and electroluminescence (EL) are important characterization methods for solar cells, from which we can derive several physical properties such as the open circuit voltage from PL [1] or the external quantum efficiency (EQE) from EL [2]. Our work takes profit of a hyperspectral imager that records spectrally resolved luminescence images [3].

Thanks to the absolute calibration of the system, we investigate the reciprocity relations between Solar Cell and LED. The first relation links the EQE of a solar cell with the EL spectra [2]. The second relation links the QE of a LED to the open circuit voltage of the cell and the open circuit voltage calculated in the radiative limit [2]. Analysing GaAs solar cells, we obtain local EQE as well as radiative efficiency of the device. Measurements at high forward voltage allow to estimate the local value of the series resistance. These effects are observed on PL and EL images as a variation of the electric potential with the distance from the contact [4]. This effect is also quantified when comparing I(V) curves and integrated EL in absolute values and enable to obtain a local measurements of the photovoltaic efficiency of the solar cell.

When we analyse more complex structures such as polycrystalline thin film solar cells, we observe strong inhomogeneities at different scales. For instance, PL images exhibit fluctuations related to quasi Fermi level splitting variations. We show that the hyperspectral imager is a powerful tool to quantify these fluctuations.

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8256-39, Session 10

Spectroscopic analysis of InAs quantum dot solar cells

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The incorporation of InAs quantum dots (QD) into GaAs solar cells has become a proven method for enhancing short circuit current density through sub-bandgap absorption. Recently, a cell design incorporating 40 layers of QDs exceeded the efficiency of a control GaAs device under AM0, despite the small voltage loss typical of the addition of these quantum structures. One end for QD devices is the intermediate band solar cell, which requires two-photon absorption through a transition from valence-to-intermediate band followed by a transition intermediate-to-conduction band. In this study, an infrared-pumped spectral responsivity technique will be used to compare two-photon absorption from QD solar cells with varying inter-dot barrier thicknesses, as well as QD cells incorporating delta-doping, to control GaAs cells. The use of differential voltage and differential temperature measurements will also be discussed as a means of isolating the two-photon process from thermal assisted carrier extraction and tunneling. Finally, carrier lifetime measurements of QD enhanced solar cells using time-resolved photoluminescence will be discussed, and compared to light-IV and spectral responsivity.

8256-40, Session 10

A novel method to eliminate the artifacts in external quantum efficiency measurements on multi-junction solar cell

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The external quantum efficiency (EQE) is critical for the design and performance evaluation of multi-junction solar cells. However, the electrical and optical coupling of monolithically integrated subcells makes it difficult to obtain the true EQE. The measurement artifacts due to the shunt and luminescence coupling effects are analyzed using DC equivalent circuits of triple-junction solar cells under the DC light and voltage biases, and small signal equivalent circuits under the AC monochromatic light scan. Use a conventional InGaP/InGaAs/Ge triple-junction cell as an example, our previous studyhas shown that the voltage bias predominantly controls the operating points of reverse-biased Ge subcell and hence the measurement artifacts due to its low shunt resistance, while the light bias on the InGaAs subcell predominantly controls the operating points of the forward-biased InGaAs subcell and hence the measurement artifact due to luminescence coupling from the InGaAs to the Ge subcell. However, even at the optimal light and voltage bias conditions, the measurement artifacts cannot be eliminated completely for subcells with strong luminescence coupling and low shunt resistance. It makes it impossible to obtain the true EQE under the DC bias conditions.

In this paper, we propose a new method to use specially designed light or voltage biases in EQE measurements to eliminate the measurement artifacts. By using the specially modulated light or voltage biases, the operating points of subcells are precisely controlled to reveal the true photocurrents.

8256-41, Session 11

Toward high efficiency ultra-thin CIGSe based solar cells using light management techniques

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Reducing the thickness of the Cu(In,Ga)Se2 absorber (CIGSe) is a strategic issue in the CIGSe technology associated with the minimization of indium utilization. Within the frame of the UltraCIS project, we have started to explore the possibility of reducing down the thickness of the Cu(In,Ga)Se2 (CIGSe) layer to the sub-micron level (0.1µm) while maintaining a high efficiency performance of solar cells. Although the absorption coefficient is high for the CIGSe material, we observed that a decreased thickness will reduce the absorption and thereby the short circuit current (Jsc). In this case, the application of advanced light management techniques and light trapping is of great importance to improve the photocurrent of solar cells (Jsc). In this work we emphasize the possibility to improve the Jsc of thin absorber cells down to 0.2 µm just by minimizing the optical losses in supporting front window layers and by replacing the back contact by the "lift-off" of CIGSe layer from the Mo layer and deposition of a new reflective back contact. The combination of these steps can lead to efficiencies higher than 13 % for an absorber thickness of 0.5 µm. Moreover, for very ultra-thin (0.1 µm) CIGSe solar cells, an original plasmonic structure is proposed leading to a highly improved Jsc.

8256-42, Session 11

Trackfree planar solar concentrator system

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Solar concentrator systems rely on focusing a large collecting aperture onto a small high efficiency solar cell. The main drawback of concentrator systems is the need to track the direction of the sun. Planar luminescent solar concentrator is a class that does not require sun-tracking, however this type suffers from a poor light collection efficiency of a few percent. We report on the development of a new class of trackfree planar solar concentrator that offers the potential to achieve high light collection efficiency. An array of parabolic mirrors reflects and focuses sun light with a high numerical aperture, effectively trapping an array of reflective particles dispensed in a liquid waveguide at the focus. The trapped particles follow the focal spots and hence the direction of the sun without external motion of the concentrator device. The particles reflect the array of incoming light cones, which are then guided by total internal reflection in the waveguide, towards a solar cell placed at the side of the device. We experimentally demonstrate a proof of concept trackfree planar solar concentrator device with reflective particles of varying sizes, effective reflectivity and their impact on light collection efficiency. Future work will be aimed at advancing this device to a larger scale.

8256-43, Session 11

A cascadable circular concentrator with confocal structure for increasing the energy density

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In traditional concentrators, their designs belong to static concentrative devices with diamond structure. Basically, the concept is allowing the planar light source to transform to the linear light source, and then finally transform to a point source. Such kind of design will guide the light into the optical guiding system, and then into an inner space in order to save power. We, in this paper, propose a novel design including disk-type concentrative lens with confocal curved module. With this design, we can let the input surface and output surface be confocal. By co-focus design, we make the input light and output light become co-focus in the proposed optical structure. Under such design, the parallel light will pass by the first curved interface and then focus on the assigned focus. Afterwards, it will reflect from the co-focus and pass by the second curved interface; meantime, it transforms to parallel light again via light compression. In addition, we can use this disk-type structure to increase the area of light absorption. In this way, we can increase the ratio about light compression, and get better efficiency in illumination. By the definition of "KPI" as a performance indicator about light density as following: lm/(mm)2, the simulation results show that the proposed Concentrator is 500 KPI much better than the 30 KPI measured from the traditional ones. Such a new design obviously has increased the performance of previous concentrators.

8256-44, Session 11

Minimizing solar cell reflection loss through surface texturing and implementation of 1D and 2D subwavelength dielectric gratings

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In this work we did simulation of reflection losses, for both TE and TM mode, on 1D and 2D subwavelength dielectric gratings and surface texturing, comparing reflection losses with various incident angles for photovoltaic materials like Si and GaAs. Transfer matrix formalism is modeled by treating grating's effective refractive index as composed of several layers of varying refractive indexes. Discrete parameterization on intervals with different profiles like 1D triangle, rectangle, 2D pyramid and hemisphere is used to minimize power reflected for AM 1.5G spectrum. This simulation treats each layer to be uniform, which requires the texturing to be in subwavelength region. We compared the reflection loss and incident angle dependence for dielectric layers, dielectric gratings and the combination of both dielectric layers and gratings, and found that with gratings, reflection losses are less dependent on incident angle. It is shown that the TM polarization compared to TE polarization is less dependent on the incident angle for all textures. These gratings can be made by laser holography, which have better transmission and less incident angle dependent than conventional dielectric layers. Spin coating polymer hemisphere is a better technique to obtain hemisphere morphology. By optimizing the texturing and design parameters, we can obtain reflection losses much less than 1% for spectral range of solar cell.

8256-58, Poster Session

Sub-ns luminescence lifetime measurements and imaging for characterization and quality control of thin film solar cells

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Luminescence lifetimes of semiconductor samples cover a broad range from microseconds for Si-wafers down to sub-nanoseconds for III/V and II/VI based thin film materials. The lifetime of a given wafer sample is, however, not constant, but can be affected by several parameters. A typical example is the influence of surface defects [1], which therefore makes the lifetime a possible indicator for wafer quality. On dye-sensitized solar cells, lifetime measurements are also useful to characterize the energy transfer process from the sensitizer to the conduction band [2].

We have developed a setup for time-resolved photoluminescence measurements (TRPL) based on pulsed diode lasers and time-correlated single photon counting with highly sensitive single photon avalanche detectors (SPADs). The instrument response function (IRF) can be as short as 100 ps and the laser pulse rate can be adapted to the luminescence lifetime of the material. The setup can be used to resolve luminescence lifetimes from approx. 50 ps up to several hundred microseconds. Spatially resolved lifetime imaging can also be performed with a microscope based setup which can be configured to cover lateral resolutions down to sub-μm and scan ranges from 100 microns to several centimeters [3].

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8256-59, Poster Session

Energy conversion materials for photovoltaic application

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The efficiency of a solar cell can be increased significantly with a process, in which infrared photons are converted to visible photons. Second harmonic generation or two-photon absorption upconversion can fulfill this condition. In the upconversion process two or more IR photons are converted to a visible or NIR photons, which can be absorbed by a solar cell. Shockley-Queisser calculated the theoretical limit of a single junction solar cell to be 30.9 % but after using additional up-converting material as an optically active center, Trupke et al. has shown theoretically that over-all external quantum efficiency can be increased to 47.6 %. It is known that intermediate excited states with long lifetimes are needed for fulfilling these requirements. Rare earth ions are known for discrete energy levels and relatively long excited state lifetimes. When doped in a low phonon matrix such as glass, glass ceramics, phosphor etc non-radiative losses can be reduced and increase the fluorescence efficiency. In this work, we are interested to investigate the highly efficient IR upconverting material with an intense fluorescence and use them as a upconverting layer for solar cell to enhance the solar cell efficiency.

8256-60, Poster Session

Low surface recombination velocity on p-type B-Si by atmosphere pressure metal-organic chemical vapor deposition grown aluminum oxide

S. C. Hung, National Central Univ. (Taiwan); C. F. Lin, Chung-Yuan Christian Univ. (Taiwan); S. M. Lan, Chung Yuan Christian Univ. (Taiwan); T. N. Yang, Institute of Nuclear Energy Atomic Energy Council (Taiwan); G. Chi, National Chiao Tung Univ. (Taiwan)

Aluminum oxide layers can provide excellent passivation for lowly and highly doped p-type silicon surface. Fixed negative charges induce an accumulation layer at the p-type silicon interface, resulting in very effective field-effect passivation. In this work, we demonstrate highly negatively charged aluminum oxide layers grown by atmosphere pressured metal-organic chemical vapor deposition, leading to very low effective recombination velocities 35cms-1 on low-resistivity p-type substrate. Further detail will shown in the conference.

8256-61, Poster Session

Near-field optical beam induced current (NOBIC) characteristics of a GaAs solar cell with biomimetic antireflective structures

C. Yang, M. Tsai, P. Yu, National Chiao Tung Univ. (Taiwan)

Sub-wavelength structure (SWS) used as the antireflective layer has offered a new possibility in suppression of the Fresnel reflection. Due to the spatially graded structural profile in a single layer, a SWS antireflective coating exhibits not only broadband and omnidirectional antireflective characteristics, but also polarization insensitivity. The power conversion efficiency of a solar cell is affected by the SWS antireflective coating. However, the nanoscale photovoltaic effect related to SWS under light illumination has not yet been investigated in detail.In this work, scanning near-field microscopy (SNOM) with a near-field optical beam induced current (NOBIC) technique is introduced to investigate the nanoscale photovoltaic effect of SWS. the system provides a 2D mapping of both topographic and optical/ photovoltaic information simultaneously. The setup has been employed to investigate the photoelectric conversion characteristics of single and triple-junction solar cells with biomimetic antireflective nanostructures. The mappings of the topography and photocurrent induced by incident light with different wavelengths are obtained simultaneously for three different laser wavelengths: 472nm, 532nm, and 632 nm. Based on the measured data from SNOM, the photocurrent is mostly harvested near the valley of the nanostructures, which serve as light guides for incident light. The observation is also consistent with simulation results using a rigorous coupled wave analysis. The studies prompt the deployment of nanostructures with graded structural profiles and wide valleys.

8256-62, Poster Session

Efficiency prediction and interface effects of organic/crystalline silicon hybrid solar cells

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Organic/inorganic hybrid solar cells are cheap alternative to conventional silicon solar cells. Due to the composition of both organic and inorganic materials, the devices take the advantages of inorganic semiconductors, such as high optical absorption and high carrier mobility, while maintaining the easy processing attributes of polymers and other soft materials. However, the interface characteristic has become a major technical barrier to advance the development of such novel devices. In this study, we employed a self-consistent drift-diffusion and Poisson solver to theoretically investigate the interface effects on the device performance using P3HT and Si as the hypothetical material system. A very thin interface layer with a large number of defect states distributed within the silicon bandgap is assumed and inserted in the model. Moreover, the ultimate power conversion efficiencies (PCEs) of hybrid solar cells based on n- and p-type silicon are also predicted for different band gaps and band alignment with respect to the crystalline silicon. For n-type silicon, an organic material with a bandgap of 1.2-2eV and an electron affinity of 3-3.5eV achieves a PCE of 16% efficiency. For p-type silicon, an organic material with a bandgap of 1.2-1.6eV and an electron affinity of 4.5-5eV achieves a PCE of 12%. Then, the simulated PCEs with different thickness of organic layer show that the thinner organic layer we have, the better PCEs it will be. We also observe a decreased PCE when the interface density of states increases, mainly resulting from open-circuit voltage decreasing.

8256-63, Poster Session

Theoretical study of solar cells based on a semiconductor with spatially varying band-gap

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The paper theoretically investigates the main features of solar cells based on a semiconductor whose energy gap linearly decreases towards the p-n junction metallurgical edge. Calculation of dark and light current-voltage characteristic of such p-n junction shows that it possesses a number advantages over the solar cell with uniform base and the band-gap corresponding to the metallurgical edge of the structure under consideration. It has been shown that the reverse current can be much less than that in the case of p-n junction in a semiconductor with the homogeneous gap structure. This is caused, firstly, by decreasing the thermal carrier generation under moving away from the metallurgical edge and, secondly, by presence of the quasielectric fields connected with the spatial dependence of conduction and valence band edges which deflect non-equilibrium carriers from Ohmic contacts what gives rise to the decrease in carrier recombination loss at the contacts. Reduction of the dark reverse current gives rise to increasing open circuit photovoltage. At the expense of quasielectric fields the drift-diffusion length of non-equilibrium carrier is enlarged what allows to increase the collection coefficient of photocarries. The range of spectral sensitivity has been shown to can be substantially widened due to the energy gap drop in base regions of the p-n structure. The numerical estimations have been made for the case of a solar cell based of GaAlAs solid solution with spatially varying composition.

8256-64, Poster Session

Optimum concentration factor analysis using dynamic thermal model for a concentrated photovoltaic system

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A new dynamic thermal model of a concentrated photovoltaic (PV) system is presented in order to better understand high temperature effects on semiconductor material properties, and hence electrical properties of these systems. While certain areas of research in concentrated PV technology have focued on temperature effects, and a singificant amount of research has been devoted to the solid state physics of these devices, few models currently in the literature have incorporated both the high temperature material effects with the solid state physical changes associated with increased illumination rate and resulting temperature increase. This research begins with the mathematical derivation of the diode current of the semiconductor solar cell, using the fundamental assumption of expoenentially decaying generation rate, rather than constant generation rate accounted for by the majority of solar cell models in the literature. The resulting differential equation yields a complicated boundary value problem, but once solved lends to a more accurate description of the total current through the cell as a function of illumination and temperature. Furthermore, the boundary conditions used to solve the differential equation for exponentially decaying generation reveals a fundamental relationship between the majority carrier diffusion length and photon penetration depth. The resulting expression for total solar cell current is then used to determine a portion of the heat generated in the cell as a function of illumination, and hence current. The resulting thermal model used to quantify this effect dynamically is then used to predict the optimum concentration factor for a variety of illumination conditions.

8256-65, Poster Session

First principle investigation of optoelectronic properties of (S-Ta)-doped TiO2: an approach for solar energy harvesting

S. Arab, R. K. Lake, Univ. of California, Riverside (United States)

TiO2 as an inexpensive, chemically stable and environmentally friendly metal oxide that has been nominated for various applications including: photoelectrochemical water electrolysis (solar hydrogen), water/air purification and photovoltaic. TiO2 has been widely used for dye-synthesized solar cells and hydrogen generation. However, wide band gap of TiO2 (3-3.2 eV) limit its absorption to the Ultra Visible (UV) spectrum which is only 5% of the solar spectrum. One of the methods for band gap reduction of TiO2 is doping (anion and/or cation). Antion-cation co-doping of TiO2 is one of the most effective approaches for solar absorption improvement without suppressing its photocatalytic properties. Here, we present the effects of (Sulfur-Tantalum) co-doping on the electronic structure and optical absorption of TiO2 by using density functional theory. We use Perdue Burke Ernzerhof (PBE) pseudopotentials which are implemented in Vienna ab initio simulator (VASP). The effects of dopant positioning and concentrations are investigated through calculation of Density of State (DOS), E-k diagrams and band composition. Substitution of titanium atoms with tantalum and oxygen atoms with sulfur shows band gap reduction and formation of continues band structure which avoids trapping of photo generated electrons and holes. The band gap reduction is attributed to the corporation mixture of 2p and 3p orbitals of oxygen and sulfur in valence band and 3d and 5d orbitals of tantalum and titanium in conductance band.

8256-66, Poster Session

Analysis of radiation hardness and subcell I-V characteristics of GaInP/GaInAs/Ge solar cells using electroluminescence measurements

R. Hoheisel, George Washington Univ. (United States)

Monolithically stacked multi-junction photovoltaic cells made of group III-V semiconductor compounds yield the highest conversion efficiencies among today's solar cell technologies. Apart from the deployment in terrestrial concentrator systems (CPV), multi-junction solar cells are the primary choice for the electrical powering of satellite systems.

When space applications are considered, the development of novel solar cell structures is not only motivated by achieving superior initial solar cell efficiency but also has to consider the influence of highly energetic cosmic particles, which, in general, lead to semiconductor material dependent minority and majority carrier degradation effects during the mission lifetime. In order to understand and master the particle-induced degradation and to further improve the device efficiency, a detailed characterization of the solar cell is of crucial importance. This holds in particular for the individual subcells of which the multi-junction cell is composed and which define the overall device performance characteristics. This aspect is especially important since the subcells may demonstrate different degradation mechanisms as a result of their different semiconductor material composition.

However, the access to the respective current density voltage (J-V) characteristics of all individual subcells is not directly possible which often complicates the device characterization and optimization. To overcome these restrictions, we discuss the employment of the reciprocity relation, i.e., the analysis of the injection dependent electroluminescence emission characteristics (EL) of all individual subcells. It is shown that this technique permits to derive the J V curves of all individual subcells and their underlying saturation current densities (J01, J02) for both begin-of-life (BOL) and end-of-life (EOL) conditions. Comparison to component cells is provided. Finally, the applicability and the accuracy of the presented method is discussed for very high particle irradiation conditions.

8256-67, Poster Session

Performance analysis of acid texturization for multi-crystalline silicon solar cells

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A maskless acid texturization based on HF: HNO3: H2O-mixture ratio has been demonstrated. This texturization is not dependent on crystal orientation so that it is suitable for texturing the mc-Si substrate. It eliminates a damaged layer texturized in few seconds. For a theoretical approach to get lower reflectance, we calculate the reflectance considering a texture as an oval-pit spherical structure. In the mean time, the measured reflectance is in good agreement with the simulation. Comparing the electrical characteristics of the non-etching, alkali and acid textured mc-Si solar-cell applications, the overall efficiencies (η and IQE) of acid texturization is higher than the others.

8256-69, Poster Session

Numerical analysis of triangular micro-optical array for enhancement of incident power of photovoltaic panels

R. Dey, E. V. Bordatchev, M. Tauhiduzzaman, H. W. Reshef, National Research Council Canada (Canada)

The solar industry strives to make the collection, generation and distribution of solar energy more efficient, more cost effective, and more scalable. Integration of specific micro/nano optical structures on the top surface of the solar panels is one of the efficient ways to enhance their performance. In this study, an array of elongated micro-optical elements in ploymethyl methacrylate (PMMA) with a triangular cross-section was numerically simulated and optimized using LightTools software. The goal of this study is to enhance the ability of solar panels to convert maximum obtainable amount of solar energy by increasing the optical path length. With this approach, the incoming sunlight is captured and reflected back onto the photovoltaic material for a second or more chances for absorption and conversion into electricity. The light trapping and redirection is achieved through the use of total internal reflection phenomenon. Simulation results have shown that a photovoltaic panel without enhancement using micro-optical structures exhibits an incident power of 0.353 W for an orientation of the light source of 90°. By adding an array of elongated micro-optical elements with optimized triangular cross-section, the incident power of photovoltaic panel power improved to 0.541 W (a relative improvement of 53.3%). In addition, the optical performance of optimized micro optical array is studied with respect to the acceptance angles across the 180° horizon by creating acceptance angles more favorable to light transmission into the glass cover sheet and underlying PV materials. Functional prototypes of elongated micro-optical elements are fabricated with optical surface quality and analysis of their geometry and surface quality is presented. The simulation results allow understanding how the overall daytime photovoltaic performance of solar panels can be improved by adding an array of micro-optical elements.

8256-45, Session 12

Interface quality enhancement of the epitaxial regrowth process for nipi photovoltaic devices

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The nipi photovoltaic device is a doping superlattice-based device, that uses iterative n type / intrinsic / p type / intrinsically doped GaAs layers to minimize the effect of minority carrier diffusion length. Following photon absorption, carriers are quickly swept vertically by drift into majority doped layers. Carriers are collected in the lateral contacts via diffusion through the doped superlattice layers. Epitaxial regrowth is used to form selective lateral contacts in V-grooves that are etched into the superlattice layers. Devices have been simulated and fabricated, where simulation shows the potential of AM0 non anti-reflective coated Jsc of 24.02 mA/cm2 and Voc of 0.83 V. Fabricated devices however have a degraded measured Voc of 0.35 V predominantly due to low shunt resistance of 2.3 kΩ resulting from leakage at the epitaxial regrowth interface. In this study, interface quality of the epitaxial regrowth is explored by varying the conditions in which the growth is performed. Factors to be evaluated include chemical pre-treatments of the substrate, the oxygen desorption process utilized in the MOCVD growth chamber, and growth temperature. Regrowth quality is evaluated on test structures, and the best results will be demonstrated on nipi device wafers. Furthermore, test results show that quantum confinement in the doping superlattice results in a 3.3% increase in current. The fundamentals behind this increase will be evaluated in CrossLight, a simulation program. A clearer understanding of the relationship between device design and quantum confined levels generated will be gained.

8256-47, Session 12

Characteristics of bulk InGaAsN and InGaAsSbN material grown by metal organic vapor phase epitaxy (MOVPE) for solar cell application

T. Kim, T. J. Garrod, L. J. Mawst, T. F. Kuech, Univ. of Wisconsin-Madison (United States)

Bulk, lattice-matched InGaAsSbN material has been grown by metal organic vapor phase epitaxy (MOVPE) for applications in concentrated multi-junction solar cells. High background carbon concentrations generally observed in MOVPE-grown InGaAsN material have been correlated with poor minority carrier diffusion lengths. There are few reports on MOVPE-grown InGaAsSbN [1].

In the MOVPE growth of dilute-nitride materials, the intrinsic hole concentration is sensitive to the gas-phase growth conditions, including the partial pressure of the group V materials. We find the background hole concentration of InGaAsN is an order of magnitude lower than that of InGaAsSbN for as-grown material with similar growth conditions [1]. However, the PL intensity of InGaAsSbN is significantly higher than that of InGaAsN. Variable temperature PL measurements in the range 40K-300K indicate that below room temperature, multiple spectral features are observed, possibly an indication of compositional phase separation. Below 200K, the (high energy) PL spectral peak from the InGaAsSbN exhibits an inverted S-shape dependence with temperature, similar to that previously reported for InGaAsN materials. By optimizing the growth conditions for high Sb and As partial pressures, we achieved background hole concentrations as low as 2×10^18 cm-3. After thermal annealing, the background hole concentration increases from 2x10^18 cm-3 to 2×10^19 cm-3, although PL intensity increases by 7x.

We have recently grown single junction (1eV) solar cells incorporating dilute-nitride materials and devices will be fabricated and characterized to further assess these materials for solar cell application.

[1] T.J. Garrod, J. Kirch, P. Dudley, S. Kim, L.J. Mawst, T.F. Kuech, J. Cryst. Growth 315 (2011) 68-73

8256-48, Session 12

Dilute nitride GaInNAs and GaInNAsSb for solar cell applications

S. L. Tan, W. M. Soong, The Univ. of Sheffield (United Kingdom); M. J. Steer, Univ. of Glasgow (United Kingdom); S. Zhang, J. S. Ng, J. P. David, The Univ. of Sheffield (United Kingdom)

The dilute nitride GaInNAs(Sb) alloy system is challenging to grow and defects can cause short diffusion lengths and high background doping densities. Despite these difficulties, a new world record for cell efficiency has recently been achieved in multi-junction solar cells utilising 1 eV GaInNAs absorber layers. This study aims to highlight the electrical and optical characteristics related to the performance of GaInNAs(Sb) diode structures grown by molecular beam epitaxy , with band gaps ranging from 0.97 to 1.28 eV. Post-growth annealing was necessary in some instances to reduce the background doping and dark current densities. The incorporation of Sb into GaInNAs has enabled the possibility of producing a dilute nitride cell with a band gap lower than 0.85 eV, although with an increased dark current.

8256-49, Session 12

Intersubband and intrasubband transition in InGaN quantum dot for solar cell application

K. Wang, Y. Wu, National Taiwan Univ. (Taiwan)

In recent years, the fabrication techniques of GaN/InGaN self-assembled quantum dot have become feasible. The quantum confinement effects in quantum dots modify the electronic band structures properties as well as their optical properties. For the third generation solar cell, the concept of intermediate band solar cell is proposed and the quantum dots array plays a very important role in designing the intermediate band solar cell. As we know, the band gap of InGaN alloy covers most of the solar spectrum, which is a very good candidate for the solar cell application. The strong strain in the system makes the formation of quantum dot much easier. In this paper, we will study the band structure properties of InGaN quantum dot and calculate their inter-subband and intra-subband transition rates. By deriving the light absorption coefficient and recombination coefficient, we propose that InGaN quantum dot structure with In composition 0.7, height 3.12 nm, and width 7.65 nm be the best configuration for solar cell applications.

To understand its optical properties, we first obtain the strain-tensor distribution in the InGaN quantum dot by valence force field model which minimize total energy consisting of bond bending terms and bond stretching term. Second, the strain induced piezoelectric field and potential in the quantum dot are calculated. Third, wave functions are found by eight-band kp model. Finally we apply Fermi golden rule to calculate the transition rate between subbands including stimulated and spontaneous transmission rate. Since different dot sizes induce different strain tensor, which in turn alters transition rate between different bands. The transition rates are therefore altered. In our simulation, we set different dot sizes and base to height ratios. The parameter of dot size changes the absorption spectra of quantum dot and an optimization can be found with solar spectra.

In this work, we propose that InGaN quantum dot to be a possible structure for Intermediate band solar cell by calculating their transmission rates. However, with high spontaneous emission rate, recombination may impair light absorption. A concentrator solar cell shall be solution to solve that problem. For future works, a rate equation can be derived combining our transition rate and some carrier transmission rules. Then the internal quantum efficiency will be derived. Our calculation of each subband transition rate provides a more practical estimation of quantum dot efficiency, which would be very important information for explaining the experimental result.

8256-68, Session 12

The role of Sb compositions on the properties of InAs/GaAsSb quantum dots

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InAs quantum dots (QDs) structure has attracted great attention as a candidate of intermediate band solar cells (IBSCs). The InAs QDs have drawbacks such as low absorption cross-section and the sufficient introduction of valence band offset (VBO) which can reduce open circuit voltage (Voc). InAs QDs embedded in GaAsSb barriers give better QD properties such as high uniformity and density due to Sb surfactant effect. In addition, varying Sb content in GaAsSb barriers can allow one to minimize the VBO of InAs/GaAsSb. Therefore, the InAs/GaAsSb has been identified as a promising candidate for the IBSC since it has the negligible VBO and good QD properties.

QD uniformity and density in InAs/GaAsSb for increasing Sb content are studied using Atomic Force Microscopy (AFM). AFM results show that QD density and uniformity improve with Sb content increase. The improvement of QD uniformity is ensured by the narrowing of photoluminescence (PL) spectra. Additionally, the PL spectra are compared with the band calculation of the InAs/GaAsSb.

To obtain minimum VBO, InAs/GaAsSb with various Sb compositions is investigated by PL and TRPL measurements. PL data shows a blue-shift as excitation power increases as evidence of a type II band structure. Since the PL peak of 8 and 13 % Sb samples did not shift while that of 15 % Sb sample is blue-shifted with increasing the excitation power it is concluded that InAs QDs/GaAs0.86Sb0.14 would have minimum valence band offset. This tendency is supported by the change of a carrier lifetime estimated from TRPL data.

8256-50, Session 13

Advanced photovoltaic development at Air Force Research Laboratory (Keynote Presentation)

D. Wilt, Air Force Research Lab. (United States)

Photovoltaics continue to be the primary source of electric power for space missions. The desire to enhance or enable new space missions through higher power, increased specific power, areal power density, and radiation resistance, along with decreased costs, continues to push development of novel solar cell and array technologies. To meet present and future space power requirements, GaAs based solar cells, thin-film solar cells based on amorphous silicon and CIGS, and more novel technologies such as intermediate bandgap devices are being pursued. In the near to mid-term, solar cell devices based on Inverted Metamorphic (IMM) structures with 3 to 6 junctions are expected to be productized and qualified for space use. Efforts so far have demonstrated >34% AM0 solar cell efficiencies. Modeling indicates that practical efficiencies for IMM devices could reach >37. For thin-film solar cells, significant progress has been made in moving to lightweight polymer substrates, pushing cell level specific powers over 1800 W/kg. Efficiencies continue to increase through better process control and post process treatments. Incorporation of new materials and tandem structures promises to further increase thin-film solar cell efficiencies. For the longer term, novel material systems and nanotechnologies are being investigated. While significant challenges exist, these technologies have the promise of breaking the 40% (AM0, 1-sun) efficiency barrier. To take full advantage of these new solar cell technologies, novel module and array structures are also being developed. These array structures have the potential to significantly increase the power that can be stowed in a launch volume and subsequently the power available on orbit. Efforts by the Advanced Space Power Program (as part of the Air Force Research Laboratory's Space Vehicles Directorate), to develop the aforementioned and related technologies will be discussed.

8256-51, Session 13

Modeling of defect-tolerant thin multi-junction solar cells for space application

A. Mehrotra, A. Alemu, A. Freundlich, Univ. of Houston (United States)

Using drift-diffusion model and considering experimental III-V material parameters, AM0 efficiencies of lattice-matched and metamorphic multijunction solar cells have been calculated and the effects of dislocations and radiation damage have been analyzed. Ultrathin multi-junction devices perform better in presence of dislocations or/and radiation harsh environment compared to conventional thick multijunction devices. Our results show that device design optimization, for hetero epitaxial Ga0.51In0.49P/GaAs multijunction devices with high dislocation density, leads to an improvement in EOL efficiency from 5.4%, for the conventional thick device design, to 16.4%, for the EOL optimized thin devices. In addition, an optimized defect free lattice matched Ga0.51In0.49P/GaAs solar cell under 5x1015cm-2 1Mev equivalent electron fluence is shown to give an EOL efficiency of 15.2%; while a Ga0.51In0.49P/GaAs solar cell with 108 cm-2 dislocation density under 5x1015cm-2 electron fluence gives an EOL efficiency of 14.8%. The results suggest that by optimizing the device design, we can obtain nearly the same EOL efficiencies for high dislocation metamorphic solar cells and defect filtered metamorphic multijunction solar cells. Metamorphic III-V solar cells (GaInP/InGaAs/Ge) with thin emitter thickness show similar improvement in efficiency. The findings relax the need for thick or graded buffer used for defect filtering in metamorphic devices. It is found that device design optimization allows highly dislocated devices to be nearly as efficient as defect free devices for space applications.

8256-52, Session 13

Radiation effects on quantum dot enhanced solar cells

C. Kerestes, S. M. Hubbard, Rochester Institute of Technology (United States)

Radiation tolerance of quantum dot (QD) enhanced solar cells has been measured and modeled. GaAs solar cells enhanced with 10 layers of strain compensated QDs show only 3% absolute degradation in sub-bandgap response, at 910 nm, when the power output has been degraded by 50%. Although sub-bandgap response is robust current-voltage measurements reveal a higher degree of shunting in the QD solar cells. Modeling the IQE reveals (1) the base material incurs degradation first and throughout the lifetime of the study and (2) the onset of emitter degradation coincided with decreasing shunt resistance. Increasing the number of QD layer between 20-100 allows for a larger crosssectional area of radiation absorption, to give a larger magnitude of damage to the QD region. Results of increased number of QD layers and that of an Emcore triple junction solar cell with QDs in the middle junction will be presented.

8256-53, Session 13

High efficiency laser power converters for space-based laser power transfer applications

J. Mukherjee, S. Sweeney, Univ. of Surrey (United Kingdom); M. Perren, EADS Astrium (France)

We report on the design, fabrication and characterization of III-V based photovoltaic convertors optimised for converting laser radiation at an eye-safe wavelength of 1.55µm into electrical power. A key application for laser power convertors (LPCs) is the conversion of beamed laser power into electrical energy. In particular, controlled delivery of monochromatic radiation on to the earth's surface via a high power laser on-board a geostationary satellite and subsequent conversion to electrical energy using LPCs, offers a source of an "green" energy which can be made available continuously anywhere on the planet to the user on demand. In addition, these LPCs are also useful for applications such as optical fibre power delivery, remote powering of subcutaneous electrical devices for medical diagnostics and line-of-sight wireless powering of electronic equipments. Monochromatic radiation at wavelengths >1.4µm is both eye- and skin-safe up to a power density of 1 kW/m2. 1.55µm radiation also offers maximum transmission through the earth's atmosphere. It is well known that a photovoltaic cell demonstrates maximum optical to electrical conversion efficiency when illuminated by monochromatic light with a wavelength closely corresponding to the absorbing material band-gap energy. Our LPC design is based on lattice-matched InGaAsP/InP and incorporates a pn-homojunction together with elements for photon-recycling and efficient carrier extraction. We compare results from self-consistent electro-optical design simulations with experimental results from fabricated devices. An experimental conversion efficiency of 41.2 % is obtained from prototype 5mmx5mm square LPCs under an illumination intensity of 1kW/m2 at 1.55µm at ambient temperature.

8256-54, Session 14

Photonic crystals for improving light absorption in organic solar cells

L. Escoubas, D. Duché, J. Simon, Institut Matériaux Microélectronique Nanosciences de Provence (France); C. Gourgon, C. Masclaux, CEA-LETI (France); P. Torchio, J. Le Rouzo, F. Flory, Institut Matériaux Microélectronique Nanosciences de Provence (France)

Organic solar cells (OSC) may prove useful to deliver electrical power to portable electronics such as mobile phones, PDAs, etc... Main drawbacks are due to the still low conversion efficiency of OSC with a record efficiency on small areas devices (<1mm^2) of 8.3% only. The efficiency of OSC is limited by several parameters, one of them being the weak optical absorption of organic materials at long wavelengths, thus leading to relatively low current densities. In that context, we have investigated the use of photonic crystals to trap the light inside the OSCs. The aim is to couple Bloch modes with very low group velocities, also called Slow Bloch Modes (SBM), into the active layer. In this presentation, we will explain, using optical dispersion curves of photonic crystals, how SBM can be excited. Then, using a Finite Difference Time Domain method, we will theoretically study photonic crystals made of organic semiconductors and their incorporation into the stack of an OSC. We will show that an absorption gain ranging between 4% and 11% is possible according to the band gap of the organic material. Finally, we will present first experimental demonstration performed using nanoimprint to directly pattern the standard organic semiconductor P3HT :PCBM blend in thin film form in the shape of a photonic crystal able to couple SBMs. We will show that the crystalline properties of the blend are conserved during the nanoimprint process. In agreement with the model, optical characterizations will demonstrate significant absorption gains.

8256-55, Session 14

Resonance energy transfer from PbS colloidal quantum dots to bulk silicon: the road to hybrid photovoltaics

P. Andreakou, M. Brossard, Univ. of Southampton (United Kingdom); M. Bernechea, G. Konstantatos, ICFO - Institut de Ciències Fotòniques (Spain); P. G. Lagoudakis, Univ. of Southampton (United Kingdom)

Hybrid photovoltaic devices have received attention as a promising technology for the development of high-efficient and low-cost solar-cell platforms. These hybrid devices employ the advantages arising from the use of semiconductor nanocrystals (SNCs) in a combination with the mature technology of bulk semiconductors. SNCs are characterized not only by the tunable absorption spectrum but also by the generation of multiple charges by a single photon. However a significant drawback of these materials is the lack of methods for the efficient charge extraction and carrier transport. On the other hand, silicon is one of the most well studied and widely used semiconductors for the development of photovoltaics; nevertheless, the indirect band gap of silicon results in a low light absorption and exciton efficiency.

We present an approach which exploits the absorption of solar photons and the creation of excitons from the SNCs to a silicon p-n junction. To demonstrate the concept, lead sulphide (PbS) nanocrystals are placed onto the silicon substrate and the efficiency of Resonance Energy Transfer (RET) from PbS nanoparticles to bulk silicon is investigated. We modulate the efficiency of the RET mechanism between the PbS nanocrystals and silicon by varying the distance between them. The later results undoubtably identify RET from colloidal quantum dots to bulk silicon. Temperature measurements are also presented and show that the RET efficiency remains high across a range of temperatures, with a value of 44% at 290K. Our findings increase the likelihood for further investigations and open the way for hybrid photovoltaics.

8256-56, Session 14

Hybrid graphene with TCO nanorods based dye-sensitized solar cell

S. C. Hung, C. W. Chen, Y. H. Chien, Y. P. Huang, C. Shieh, National Central Univ. (Taiwan); P. Yu, G. Chi, National Chiao Tung Univ. (Taiwan)

A dye-sensitized solar cell (DSSCs) has attracted a lot of attention because of the low cost, non rare and non toxic materials. Unfortunately, the electron hole pair generated by dye will recombined by the grain boundaries caused by high temperature annealed TiO2 nanostructured photoanode or the accumulation of electrons in the semiconductor layer due to the relatively slow electron transfer between the interface of TiO2 nanostructured photoanode and transparent contact layer.

In this study, graphene were grown on Cu film by chemical vapor deposition and ZnO nanorods were grown on graphene/GaN template by chemical vapor deposition. we will focus on the hybrid graphene with TCO Nanorods based dye-sensitized solar cell. The unique conductive characteristics and bandgap engineering of graphene are tailored to maximize the power conversion efficiency of thin-film solar cells.

8256-57, Session 14

Full device analysis of novel metamaterial coated PN and MIS solar cells using numerical methods

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Current silicon solar cell technologies can benefit from advanced optical coatings to increase efficiencies and lower costs. In this work we determine how solar cell efficiencies may be increased using novel frequency selective surfaces and metamaterial coatings optimized for light harvesting on a silicon substrate. Metal metamaterial coatings can serve as both a contact and an antireflective coating and can be designed to have high transmission for light incident at a wide range of angles.

As a proof of concept, we simulate the use of metamaterial contacts on first generation monocrystalline solar cells, comparing device characteristics and efficiencies to standard AR coated grid contact cells. We will also discuss possible benefits to using the metamaterial contact in a MIS configuration instead of a PN junction cell.

We simulate the device using a two step process. First we use HFSS, a software implementing a finite element algorithm, to solve for the field profiles produced by the metamaterial contact coating. We then import the intensity profiles into Atlas, a device characterization software, to determine solar cell efficiencies. The effects of the metamaterial contacts on solar cell efficiencies will be discussed for PN junction and MIS cell structures.

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8257-02, Session 1

Sensitization of erbium through silicon nanocrystals in silicon rich oxide

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The process of erbium sensitization through silicon nanocrystals (Si-nc) in silicon rich oxide host is analyzed through a model involving five levels of Er energy states. Energy coupling processes from Si-nc to Er, and the mechanisms involving deteriorating effects in Er sensitization are studied. It is proposed that Er atoms are excited through quasi-direct processes involving excitonic recombinations in Si-nc. Effect of Si-nc concentration in Er sensitization is analyzed. Based on three dimensional spacial considerations, it is shown that only a fraction of 1.8% of the incorporated Er remains within the excitable range of Si-nc for a typical sensitization range of 1.3 nm. The analysis shows that significant fraction of Si-ncs can experience multiple excitations during the Er lifecycle. The probability of Si-nc being excited at every alternate cycles of excitation increases from small fractions to percentage levels for incident flux levels above 1018/cm2-s. It is shown that, for typical values of Er and Si-nc incorporation, saturating effects in Er luminescence starts at flux levels much lower than that for Si-nc excitation. Occurrence of multiple excitation of Si-nc is correlated with the deteriorating effects in Er sensitization at higher flux incidence. Er luminescence profiles with incident photon flux as reported by different experimental groups in literature are simulated with the developed model.

8257-03, Session 1

Recent advancements in multiband IR sensor windows

S. S. Bayya, J. Sanghera, W. Kim, G. R. Villalobos, I. Aggarwal, U.S. Naval Research Lab. (United States)

This presentation will address the rugged passive optical window needs for various sensors operating in the visible, shortwave, midwave and longwave infrared regions. We are developing rugged optical materials for multiband applications covering the 0.2 - 12 µm wavelength region. These materials cover various parts of this multiband region and have mechanical properties that are superior to existing materials. A heavy metal oxide glass was developed to make very large and conformal windows with transmission in the 0.4-5.0 µm wavelength region. It is about 3x harder and >2x stronger than multispectral ZnS. A polycrystalline spinel ceramic was developed with transmission in the 0.2-5.0 µm region. Spinel is about 10x harder than multispectral ZnS and has ruggedness comparable to sapphire and AlON. Spinel has an advantage over sapphire and AlON with superior 4-5 µm transmission which becomes important for several applications. We are also developing a rugged ceramic with transmission in the 1-12 µm wavelength region. These materials can also be used to build multiband optics for imaging systems.

8257-04, Session 1

Pr3+-doped ZBLA glasses for visible laser emission

M. Olivier, Univ. de Rennes 1 (France); J. Doualan, P. Camy, ENSICAEN (France); H. Lhermite, J. Adam, V. Nazabal, Univ. de Rennes 1 (France)

This study is focused on visible emission of praseodymium in fluorozirconate glasses in order to generate compact solid state laser sources. These devices are nowadays source of great interest, since they cover many lightning applications. Praseodymium has been chosen as luminescent doping because direct pumping in blue range is an easy way to favor a population inversion ($^3H_4 \rightarrow {}^3P_0$) and an emission in the green, orange and red spectral range. By a photolithography process, followed by a chemical exchange process ($F^- \rightarrow Cl^-$), channeled ZBLA waveguide can be fabricated offering the opportunity to develop integrated optic systems with compact laser sources. Exchanged layers from 1 µm to 5 µm can be obtained, depending on experimental parameters set, with a refractive index contrast between the exchanged layer and the glass substrate varying from 0.02 to 0.08. The influence of each parameter on the optogeometrics properties of the waveguide were accurately defined experimentally and modelized using mathematical equations. Spectroscopic measurements and calculation were performed on both bulk and waveguides materials, such as absorption cross section, emission cross section (McCumber and Füchtbauer-Ladenburg methods) and Judd-Ofelt parameters. Fluorescence was easily observed at the output of several fluorozirconate waveguides by pumping using a GaN diode emitting at 442 nm. Gain on/off was measured up to 30% in the red spectral range. Optical losses measurements are currently under progress as well as the modelization of laser effect in Pr3+-doped ZBLA matrix.

8257-05, Session 2

A new vision of photodarkening in Yb3+-doped fibers

R. Peretti, Univ. Claude Bernard Lyon 1 (France); C. Gonnet, Draka (France); A. Jurdyc, Univ. Claude Bernard Lyon 1 (France)

Yb3+-doped fiber is one of the most promising hosts for high-power fiber lasers. However, in the late 1990s, photodarkening effect, i.e., the creation of color centers induced by light, was observed and reported [2]. Like in other rare-earth-doped materials, a broad visible and near infrared absorption band appears during laser operation, which strongly lowers the laser efficiency. We have shown how thulium impurities, present at the parts-per-billion (ppb) level in the raw doping material, can induce UV emission (see figure) which in turn creates defects responsible for photodarkening in ytterbium-doped continuous-wave fiber lasers [3]. We will show how this new interpretation can explain different experimental observations such as the photodarkening dependence on the pump source wavelength and power, the Yb3+ concentration, etc. This new vision is not in contradiction with others but it gives for the first time a possible explanation for UV defect creation by an infrared beam.

8257-07, Session 2

Calculation of cross-relaxation parameter in highly Tm-doped glasses

M. Taher, H. Gebavi, S. Taccheo, Swansea Univ. (United Kingdom); D. Milanese, Politecnico di Torino (Italy); R. Balda, Univ. del País Vasco (Spain)

In this paper we develop a mathematical methods to calculate cross-section parameter in highly Tm-doped glasses. We measured several tellurite glasses with concentration ranging from 0.35wt% to 10wt%. We show a linear increase of the cross-relaxation parameter with concentrations.

We compared our results with results using more standard methods and we find a good agreement. We therefore calculate, for the first time to our knowledge, the cross-relaxation parameter over a such wide range of concentrations.

8257-08, Session 2

One- and two-photon pumped random laser action in rhodamine B doped di-ureasil hybrids

S. Garcia-Revilla, Univ. del Pais Vasco (Spain); E. Pecoraro, Univ. de Aveiro (Portugal); R. Balda, Univ. del País Vasco (Spain); L. D. Carlos, Univ. de Aveiro (Portugal); J. M. Fernandez, Univ. del Pais Vasco (Spain)

Linear and nonlinear optical phenomena in fully disordered organic and inorganic systems have received considerable attention due to their important scientific and technological implications. In particular, investigations devoted to light amplification in random structures have lead to the development of a new field of physical optics which gathers various topics such as diffusion, localization or nonlinear optics.

Here, we explore the spectral and temporal dynamics of the random laser action found in disordered microstructures of a new active organic-inorganic hybrid material based on Rhodamine B incorporated into a di-ureasil matrix which exhibits light emission either under one- or two-photon excitation in the VIS or NIR range. Note that due to the covalent linkage between its organic and inorganic parts, a higher efficiency of the dye emission is expected if compared to hybrid materials based on silica gels where the dye molecules are only entangled in the porous silica network [1].

A comparison between the random laser-like effects following one- and two-photon excitations was recently performed by these authors in a dye-doped silica gel powder by pumping with picosecond- and femtosecond-lasing pulses, respectively [2]. In contrast, in this work, one- and two-photon pumped random lasing are studied in Rhodamine B doped di-ureasil hybrids by using a picosecond pump laser emitting either at 532 nm or 1064 nm under controlled experimental conditions. In this case, we use one diffusive medium with identical spatial disorder, the same time-width and temporal profile for the pump pulse, as well as equal pump spot sizes. Only under these conditions, reliable comparisons about localization, statistics, and dynamics of the involved modes following both pumping schemes are possible. Finally, the dye concentration dependence of the corresponding onsets of laser-like emission and slope efficiencies is also investigated.

[1] Pecoraro, E., García-Revilla, S., Ferreira, R. A. S., Balda, R. Carlos, L. D. and Fernández, J. “Real time random laser properties of Rhodamine-doped di-ureasil hybrids,” Opt. Express 18(7), 7470-7478 (2010).

[2] García-Revilla, S., Sola, I., Balda, R., Roso, L., Levy, D., Zayat, M. and Fernández, J. “Two-photon pumped random laser action in a dye-doped silica gel powder,” Proc. of SPIE, 7598, 759804-1 (2010).

8257-37, Session 2

Spectroscopic study of Nd3+ ions in 0.8CaSiO3-0.2Ca3(PO4)2 eutectic glass ceramics

D. Sola, Centro de Física de Materiales (Spain); R. Balda, Univ. del Pais Vasco (Spain); J. I. Peña, Univ. de Zaragoza (Spain); J. M. Fernández, Univ. del Pais Vasco (Spain)

The search for developing new solid state lasers based on rare earth doped glass matrices is a field of great interest. High power lasers for industrial applications or inertial confinement fusion research, glass fiber lasers and amplifiers for telecommunications as well as for biomedical environment purposes, laser cooling, optical sensors, ultrafast spectroscopy, among other applications, are nowadays the subject of an intense research.

In this work we present a detailed study about the influence of the host matrix in the spectroscopic properties of Nd3+ in 0.8CaSiO3-0.2Ca3(PO4)2 eutectic glass-ceramics doped with 1 and 2 wt% of Nd2O3. Site-selective spectroscopy in the 4I9/2→4F3/2 transition has been used to investigate the crystal field changes felt by the Nd3+ ion as a consequence of the sample crystallization stage. The eutectic samples have been grown at 50, 100, 250 and 500 mm/h by the laser floating zone technique, LFZ, with a diameter between 2.5 and 4.5 mm. This technique permits the control of the solidification rate providing high axial and radial thermal gradients in the liquid-solid interface and allows for a microstructure selection of the growing sample, for example, the possibility of fabricating either eutectic glasses and/or glass-ceramics materials.

Site-selective spectroscopy performed at low temperature shows the existence of a very complex crystal field site distribution for Nd3+ ions. In particular, the peak position of the 4F3/2 →4I11/2 transition narrows and red shifts up to 11 nm in these glass-ceramics as a function of the excitation wavelength. The lifetimes have also been characterized and correlated with the glass-ceramic microstructure.

8257-09, Session 3

Advances in modeling of photonic structures for glass lasers

F. Prudenzano, L. Mescia, P. Bia, A. Di Tommaso, M. De Sario, Politecnico di Bari (Italy)

A few models for designing lasers and amplifiers based on rare earth doped glasses are illustrated. As example, different design strategies followed to enhance the pump absorption in the rare earth doped core of microstructured fiber lasers, by employing suitable cascade of multiple long-period gratings (MLPGs) inscribed in the fiber core region are illustrated. Moreover, global search methods, as genetic algorithms (GA) and particle swarm optimization (PSO), for the design and characterization of lasers and amplifiers are illustrated. These algorithms allow to perform a “global optimization,” exhibiting high effectiveness. Because of their stochastic nature, they are not dependent on the initial conditions and are practically uncoupled to the solution domain. This aspect distinguishes them from the conventional local optimization techniques, for which the solution domain can affect the method convergence. Finally, the design of novel chalcogenide glass lasers and amplifier, in both fiber and microsphere configurations, allowing Mid-IR emission, is reported.

8257-10, Session 3

~2.1 um Tm3+-Ho3+ co-doped tungsten tellurite single mode fiber laser

K. Li, G. Zhang, L. Hu, M. Wang, D. Chen, Shanghai Institute of Optics and Fine Mechanics (China)

We investigate the spectroscopic and lasing performance of Tm3+-Ho3+ co-doped tungsten tellurite single mode fiber operating around 2.1 μm with a commercial 800 nm diode laser pump source. The optimum doping concentration of Tm2O3 and Ho2O3 in Tm3+-Ho3+ co-doped TeO2-WO3-La2O3 (TWL) glass is 1 mol% and 0.5 mol%, respectively. The lifetime of Ho3+:5I7 level is 3.3 ms in the bulk glass. The maximum stimulated emission cross-section of Ho3+ in TWL glass is 10.0×10-21cm2. The tungsten tellurite single mode fibers are prepared by using rod-in-tube method. The infrared emission spectra are compared with varying fiber lengths. Tm3+-Ho3+ co-doped fiber shows weak emission at ~1.9 μm and very strong emission at ~2.1 μm, which indicates efficient energy transfer from Tm3+ to Ho3+ in the fiber. The 1.47 μm emission increases with the increment of the fiber length, which means a back energy transfer from Ho3+ to Tm3+. A 106 mW continuous wave laser emission at ~2.1 μm is demonstrated from a 16 cm length of this fiber, the slope efficiency is 23%, corresponding to a 17% optical to optical efficiency. Lasing has also been achieved in <5 cm length of this fiber making this material a promising candidate for single frequency ~2.1 μm laser sources.

8257-11, Session 3

Er3+-doped micro-structured tellurite fiber: laser generation and optical gain

L. C. Barbosa, E. F. Chillcce, Univ. Estadual de Campinas (Brazil)

Optical results concerning the generation of laser and optical gain by using an Er3+-doped micro-structured tellurite fiber are reported for the first time. For this purpose a scheme that consist of two 980 nm diode pump lasers (simultaneously in the co-propagating and the counter-propagating directions) and short Er3+-doped micro-structured tellurite fibers (fabricated by using the stack-and-draw technique and a soft glass drawing tower) was used. The laser produced here was obtained within the range 1530 to 1565 nm, and the maximum optical gain obtained was higher than 8 dB.

8257-13, Session 4

Recent advances in very highly nonlinear chalcogenide photonic crystal fibers and their applications

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Chalcogenide glasses are based on a mixture of chalcogen elements (sulphur, selenium, and tellurium) and other elements such as arsenic, germanium, antimony, or gallium. Compared to silica glasses, they offer several distinctive optical properties such as a transmission window that extends far into the infrared spectral region. Chalcogenide glasses also exhibit an extremely high nonlinear refractive-index coefficient that can be two or three orders of magnitude greater than silica at 1.55 μm. These nonlinear properties can be further enhanced by drawing chalcogenide glasses into photonic crystal fibers (PCFs) due to the possibility of designing such fibers with a very small core diameter. PCFs also exhibit several other interesting properties including endlessly single-mode operation and widely tunable chromatic dispersion that can be extended into the mid-IR by using Chalcogenide PCFs (CPCFs).

Perfos and the laboratory Glasses and Ceramics Group of Rennes University have worked together to develop a new fabrication technique for chalcogenide preforms based on the glass-casting process. Various fiber profiles have been designed by the Fresnel Institute and fiber losses have been significantly improved, approaching those of the material losses. Using this technology, we have manufactured a AsSe CPCF exhibiting a nonlinear coefficient γ of 46000 W-1km-1. Self-phase modulation, Raman effect, Brillouin effect, Four-Wave Mixing have been observed leading to the demonstration of various optical functions such as an efficient nonlinear optical gate at 1.55 μm by FOTON and the generation of a mid-IR supercontinuum source by ONERA.

8257-15, Session 4

Chalcogenide-tellurite composite microstructured optical fibre

T. Kohoutek, Z. Duan, X. Yan, T. Suzuki, Toyota Technological Institute (Japan); M. Matsumoto, T. Misumi, The Furukawa Electric Co., Ltd. (Japan); Y. Ohishi, Toyota Technological Institute (Japan)

We report on fabrication of composite microstructured optical fibre (CMOF) composed of chalcogenide Ge-Ga-Sb-S glass core and tellurite TZLB glass clad. The glass compositions were optimized to be mutually compatible enabling the composite fibre to be drawn at temperature near 320 °C. We employed the rod in tube method to fabricate a CMOF with the diameter of chalcogenide core ~1.3 μm, determined by using a scanning electron microscopy observation. Calculation of the chromatic dispersion showed the zero dispersion wavelength (ZDW) of the fabricated tellurite-chalcogenide CMOF to be near 1.59 μm. Using a tellurite clad, the ZDW value of the CMOF is significantly lower than in fibres achievable by similar design but using a chalcogenide glass only. The fabricated chalcogenide-tellurite CMOF exhibited supercontinuum light generation in the spectral range of 1.3 to 2.2 μm under the fs-laser pumping at λ = 1.6 μm and P = 38 mW. Chalcogenide-tellurite CMOFs bring new options for designing of infrared photonic fibres proposed for highly non-linear applications since they possess large refractive index, high optical non-linearity, wide infrared transmission and strong light confinement of a chalcogenide glass core and well developed fibre drawing processing, tunable chromatic dispersion and large refractive index contrast provided by a tellurite glass clad. Moreover, a composite chalcogenide-tellurite photonic fibres is assumed to have higher thermal and mechanical durability in comparison with chalcogenide glass fibres.

8257-16, Poster Session

Quantum-correlated photon pair generation in tellurite microstructured optical fibers

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Entangled photon pairs are a critical resource for realizing the various quantum information processing protocols such as quantum teleportation and quantum cryptography. Correlated photon pair generation through spontaneous four-wave mixing (SFWM) process in optical fibers focuses much attention as a promising way to realize efficient correlated photon pair source in silica fibers. Recently, more attention has been paid to non-silica glasses with longer infrared transmission windows, such as tellurite, fluoride and chalcogenide glasses. Tellurite and chalcogenide possess high nonlinear refractive indices which are much higher than that of fluoride or silica. Furthermore, tellurite glass has better chemical and thermal stability compared to fluoride and chalcogenide glasses. Therefore, tellurite glass is a highly suitable fiber material for infrared nonlinear applications. However, accompanying with photon pair generation, noise photons would be generated by spontaneous Raman scattering (SpRS), leading to severe deterioration on the performance of correlated photon pair generation in fibers. Hence, how to reduce the SpRS noise photons is the key for realizing high quality fiber based correlated photon pair sources. In this paper, we theoretically investigated the generation of quantum-correlated photon pair through SFWM in tellurite MOF. We evaluated the performance of photon pair generation in tellurite fibers based on Raman gain coefficient spectra. It was shown that the TBSN16P6W tellurite fiber provided a low Raman noise on correlation photon generation over a wide pump-idler detuning range. We can choose proper tellurite composition to obtain a low Raman gain window over wide range for correlated photon pair generation.

8257-17, Poster Session

Enhanced upconversion in rare-earth doped chalcogenide photonic crystals

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Gallium lanthanum oxysulphide (GLSO) is a promising host material for observing strong upconversion emission from trivalent rare-earth ions such as erbium (Er3+). Its attractive properties include high rare-earth solubility due to the lanthanum content of the glass former, a high refractive index (n=2.4) for high radiative efficiency, and a low maximum phonon energy of approximately 425cm-1. Photonic crystals (PhCs) meanwhile can provide controlled light extraction, and may be capable of suppressing unwanted IR emission from lower lying metastable states. Here, we compare the visible upconversion emission spectrum from thermally-annealed sputtered films of Er3+ doped GLSO both with and without PhCs etched into their surface by a focused ion beam. Samples were pumped by an 808nm laser diode focused by a 100x microscope objective and the visible emission collected and dispersed by a spectrometer across a TEC-cooled silicon CCD. The emission intensity is found to increase monotonically with the lattice period, although for periods less than 400nm the excess etch of the host material leads to suppressed emission. For periods greater than 400nm, the emission is enhanced by more than 4x in the larger PhCs at 525nm. The step-like change in enhancement between 525nm and 550nm cannot be explained by a simple linear scattering picture, suggesting alternative mechanisms are the cause.

8257-19, Poster Session

The passively mode-locked and Q-switched operation in a fiber laser cavity with normal dispersion

W. Gao, M. Liao, X. Yan, T. Suzuki, Y. Ohishi, Toyota Technological Institute (Japan)

We demonstrate passively mode-locked and Q-switched operation in the same fiber laser cavity with normal dispersion. The passively mode-locked pulse works in the stretched-pulse mode-locking mechanism, and the spectrum has smooth and broad rectangular shape. The 3 dB bandwidth of the spectrum increases with the pump power addition, and it is also changed by the polarization state in the cavity. The obtained maximum 3 dB bandwidth for the pulse is 34.5 nm. The output pulse width is 2.31 ps with high chirp and is dechirped to 210 fs by standard single-mode fiber, which can be further dechirped to about 110 fs according to the transform-limited time-bandwidth product by compensating the third-order dispersion. The repetition rate of the single pulse operation is 38.3 MHz. With increasing the pump power further, multiple pulses appear and finally six pulses are observed. When the pump power exceeds 180 mW, the mode-locked operation can be switched to the passively Q-switched operation by the polarization state variation. The repetition rate of the Q-switched pulse increases from 162.9 kHz to 348.9 kHz corresponding to the pump power from 180 mW to 643 mW, and the pulse width decreases from 1122 ns to 382 ns simultaneously. The Q-switched pulse can be tunable in the spectral range of 8.45 nm from 1558.50 to 1566.95 nm. The operation between the passively mode-locking and the Q-switching can be switched by adjusting the polarization controllers in the cavity. This fiber laser can be used as mode-locked or Q-switched laser according to the different applications.

8257-36, Poster Session

Optical power control filters: from laser dazzling to damage protection

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With the development of more powerful lasers for applications, optical limiters and blockers are required for providing human eye and optical sensors protection. In some scenarios, laser radiation may seriously interrupt the signal, from transient saturation and can lead to permanent damage, where the problem exists in any imaging sensors in the visible and the IR range. Some commercially available lasers are powerful enough to cause dazzling or damage to the eye. There are several stories regarding dazzling of pilots due to laser pointed at the aircraft, with variation of wavelengths and powers. Same dazzling effect can cause temporary blindness of imaging systems in the battlefield, including also the human eye of the common soldier. Same stories are concerning policemen, soldiers either directly or when looking through any binocular or sight.

We present a passive, solid-state threshold-triggered wideband filters that either limit or block the transmission only if the power exceeds a certain threshold. As opposed to fixed spectral filters, which permanently block only specific wavelengths, the wideband filter is clear at all wavelengths until it is hit by damaging light. At input power below threshold, the filter has high transmission over the whole spectral band. However, when the input power exceeds the threshold power, transmission is decreased dramatically.

Based on this concept we present our Dazzling Protection Filters and Wideband Protection Filters (WPF) ready for use for VIS and NIR detectors, cameras, or eye safety applications. We also discuss a new application of our WPF for FLIR “See-Spot”.

8257-38, Poster Session

A dispersion flattened tellurite composite holey fiber

M. Liao, Z. Duan, W. Gao, X. Yan, T. Suzuki, Y. Ohishi, Toyota Technological Institute (Japan)

Highly nonlinear tellurite holey fiber can be transparent from visible to 5 μm. Its nonlinearity can be higher than highly nonlinear silica fiber by more than one order of magnitude. However, the dispersion of tellurite holey fiber is difficult to tailor because of the difficulties in fabrication. Tellurite glass shows a low viscosity at the fiber drawing temperature. Moreover the viscosity decreases sharply with increasing temperature. Tellurite holey fiber with a complex microstructure could be subject to heavy deformation during fabrication process. So far most tellurite highly nonlinear holey fibers just have a simple structure which results in an unflattened dispersion. It cancels the advantage of high nonlinearity greatly in practical applications.

In this work we try to develop a dispersion flattened tellurite composite holey fiber (TCHF). The holey structure of the TCHF is composed of only one ring of holes, so the heavy deformation, which probably occurs for tellurite complex microstructured fiber during the fabrication process, can be avoided. Since the holey structure is simple, to improve the flexibility in tailoring dispersion, we use two kinds of tellurite glasses which have different refractive-indices to design and fabricate the TCHF. The holes are formed by two tellurite glasses. The fiber can be fabricated by a simple rod-in-tube method. By using this structure the dispersion is engineered to be the most flattened for the highly nonlinear soft glass fiber within 1.5-1.6 μm. More than one octave supercontinuum generation, mainly broadened by self phase modulation, is demonstrated by using the fabricated TCHF.

8257-39, Poster Session

Optimization in Raman+EDFA hybrid amplifiers for WDM systems

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An approximated technique to optimize the gain profile of multi-pump broadband hybrid amplifiers under residual pump recycling in WDM systems is proposed. It is based on the equalization of Erbium-doped fiber's gain spectrum by adjusting the flexible gain profile of a multi-pump Raman amplification stage. In order to increase the pump power efficiency, the Erbium-doped fiber section recycles the residual Raman pump. Multi-channel signal input allowed the gain characterization of the Raman+EDFA hybrid amplifier in terms of global gain, ripple, and noise figure.

For the first time we used the optimization technique in which the EDFA gain profile is offset from the gain profile of Raman amplification stage, adjusting the power and the multiple pumped lasers wavelengths. It uses an analytical approximated model to determine the spectral shaping of the Raman gain stage avoiding the time-consuming process of spectral profile optimization. The optimization has been focused on the global gain and its ripple factor for the hybrid amplifier. The EDFA spectral gain profile is the one to be compensated by the Raman amplification.

In this work we are present the obtained results for 8, 16, 32, 64 and 128 WDM channels, considering the power of each channel equal to - 20 dBm. The increase in the level of input power reduces the overall gain of the amplifier, but the profile remains always similar. Our results also shows that the performance of this configuration presented better results that means high gain, lower ripple, and higher bandwidth than those found in the literature.

8257-40, Poster Session

Numerical simulation of Nd-fluoride and tellurite solar-pumped fiber lasers

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Numerical simulation of Nd-doped fluoride and tellurite fiber lasers pumped directly by sunlight have been performed. Calculations have been done for double clad fibers to achieve both efficient coupling sunlight with a fiber and spatial power condensation. The pumping source was assumed to be initially AM1.5 sunlight and was focused onto a fiber end. The both ends of the fiber were assumed to have AR coating for sunlight and HR coating for laser. It was assumed that the launched sunlight propagate in one longitudinal direction in the inner but the laser light propagate in both longitudinal directions in the core. Propagation equations were solved under boundary conditions determined by the reflectivity of the fiber ends by a boundary value problem solver in MATLAB.

The calculated concentration threshold was about 300 suns for solar pumped fiber lasers with optimized structure. This sunlight concentration can be achieved by conventional optics such as lens, mirrors and so on. The slope efficiency was about 0.5 % for a fluoride fiber and 0.9 % for a tellurite fiber. The sunlight-to-laser power conversion efficiency was about 0.3 % for a ZBLAN fiber and 0.5 % for a tellurite fiber under 1000 suns pumping. These efficiencies are can be improved by farther optimization of fiber parameters and pumping scheme. Solar pumped fiber lasers will be able to provide alternative means to utilize solar power.

8257-41, Poster Session

Novel tellurite-phosphate composite microstructured optical fibers for nonlinear applications

T. H. Tong, X. Yan, T. Suzuki, Y. Ohishi, Toyota Technological Institute (Japan)

For recent years, four wave mixing and supercontinuum from tellurite photonic crystal fibers have been widely researched. Their efficiencies depend mainly on fiber nonlinearity and chromatic dispersion. We have shown that the composite microstructured optical fibers (CMOFs) can have high flexibility on chromatic dispersion control, when refractive index difference between core and cladding becomes larger. Cladding materials with much lower refractive index than tellurite glass are required. We report here a novel tellurite core-phosphate cladding CMOF. Phosphate glasses which thermal expansion coefficient, viscosity, glass transition temperature, softening and crystallization temperature are close to those of tellurite 78TeO2 - 5ZnO - 12Li2O - 5Bi2O3 (mol%) (TZLB) glass are systematically investigated. The phosphate glass we developed has high transparency and broad transmission region up to 3 um in company with a notably low refractive index. Using the phosphate glass doped with mixed alkaline obtained in this work, the refractive index difference between core and cladding becomes as high as 0.5 which is sufficiently high to control the chromatic dispersion with high freedom. Our work shows that tellurite-phosphate CMOFs are promising candidates as highly nonlinear fibers with freely controlled chromatic dispersion for nonlinear applications.

8257-42, Poster Session

Structure light with laser speckle for object contour reconstruction

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Invisible grid-pattern structure light has often been used for being shined on objects for contour reconstruction based on the distortion of grid pattern, for the application of human-machine interaction or vehicle collision prevention etc. However, the structure light can be easily disturbed by surrounding nature light even if infra-red (IR) light source is used because natural light contains quite an amount of IR spectrum. In this paper, it is proposed that the structure light is provided from a highly coherent laser source, so that the structure light pattern reflected from the target object will contain not only the distorted irradiance distribution of grid pattern, but also laser speckle associated with it. The laser speckle pattern depends on the surface roughness of the target object, which provides extra information for extracting the distorted grid pattern from the background irradiance of surrounding natural light. The laser speckle pattern therefore helps to improve the immunity for surrounding light disturbance, and hence the robustness and reliability of contour reconstruction system. Instead of mask or spatial light modulator for generating grid pattern as in traditional structure light techniques, a binary surface relief phase-type diffractive optical element (DOE) has been proposed for generating desired pattern directly at far field when working together with laser light source. The design process is based on iterative Fourier transform algorithm (IFTA) in scalar diffraction theory. The DOE for structure light pattern generation is now being fabricated and the performance on noise immunity will be evaluated.

8257-43, Poster Session

Nonlinear optical testing of electron beam sterilization results

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Secure proof of sterilization processes on packaging materials is an important issue in many economic sectors. Especially in medicine and food industries regulations concerning purity and sterilization are increasingly tightened. Furthermore, the application of high performance product and packaging materials requires new low temperature and dry sterilization techniques. All these demands are efficiently met by electron beam sterilization which exploits the deposition of a certain energy dose on the product or packaging surface. However, nowadays there is no suitable in situ method which allows proving an electron beam treatment.

The following paper reports on an optical, hence fast and contactless approach which gives reliable evidence of a successful e-beam sterilization. The technique is based on placing a suitable marker material (ceramic rare-earth based nanoparticles) inside or as a coating on the packaging material. Upon electron irradiation the marker material changes its luminescent properties as a function of applied energy dose. In particular, the electron beam induces a change in the crystalline structure of the nanoparticles that in turn affects the particles' up- or down-conversion properties. Hence, a change of the luminescence lifetime is observed which can easily be detected by means of a laboratory setup or even a hand-held device.

8257-44, Poster Session

Low losses volume Bragg gratings recorded in photo-thermo-refractive glass

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Volume Bragg gratings (VBGs) recorded in photo-thermo-refractive (PTR) glass have found multiple beneficial applications for spectral filtering, mode selection in laser resonators and both spectral and coherent laser beam combining. The main direction in the development of this technology for high power laser applications is to reduce losses (absorption and scattering) in those diffractive elements.

This presentation summarizes the recent results in development of technology and metrology of PTR glass and VBGs. A technology of PTR glass that enables very low level of impurities having absorption bands in the near IR spectral region is developed. Absorption coefficient of 5×10-5 cm-1 (115 ppm/cm) and scattering of 3×10-3 cm-1 in the range of 1 µm, optical homogeneity better than 10-5 (10 ppm) across the apertures up to 100 mm are demonstrated. A metrology of low absorption based on laser induced interferometry and scattering based on precise photometry is developed. Measurements of absorption and scattering in pristine PTR glass and in VBGs are developed and implemented in the technological process. VBGs which are used for spectral beam combining have demonstrated absorption coefficient of 10-4 cm-1 (230 ppm/cm). These elements can be used in multikilowatt laser systems without forced cooling.

Prospects of further loss reduction and methods of forced cooling for extremely high power applications are discussed.

8257-45, Poster Session

All-fiber optical modulator

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We propose the design and study the performance of a novel all-fiber optical phase modulator based on the electristrictive effect.The modulator employs only a standard telecom fiber tightly clamped with specially designed electrodes. Its working principle is based on the optical-path-length change induced for light guided in the optical fiber subjected to electrostriction. The modulator is driven by a high-voltage electric signal applied to the electrodes. The half-wavelength voltage was measured to be about 60 V. The experimentally proved modulation frequency bandwidth is nearly 100 kHz. As compared with conventional electro-optic modulators based on nonlinear crystals, the proposed modulator exhibits very low insertion loss (<0.5 dB) and polarization insensitivity (polarization dependent loss at the level of measurement accuracy). As compared with earlier reported all-fiber electro-optic modulators based on a specially designed fibers with induced (by thermal/electrical poling) second-order electric susceptibility and internal electrodes (incorporated into the fiber cladding), the proposed modulator has a very simple design which requires no complicated techniques for manufacturing. The described features make this modulator suitable for many practical applications (in particular, for making optical phase locking loops in stabilized fiber laser systems and for active mode locking in long-cavity fiber lasers).

8257-46, Poster Session

Optical humidity sensor using polypyrrole (PPy)

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In previous works it was demonstrated that the electrical resistivity of Polypyrrole (PPY) changes when exposed to different organic solvents which allowed the development of applications in gas sensors. However optical sensors have several advantages over conventional electronic sensors like high sensitivity, reduced signal noise, and immunity to electromagnetic interference.

The optical properties of polymer materials are of great importance in modern optical design of polymer based optical sensors and devices. Thin polymer films appear in a wide spectrum of applications such as photonics, data storage, communications and sensor devices [1]. In this work an optical sensors for the detection of water vapor using as sensitive material Polypyrrole (PPY) is proposed.

Sensor performance for different water vapor concentrations has been measured, and results showed a variation of the refractive indices of the polymer (approximately 0.1 RIU - Refractive Index Units) in the wavelength of 632.8 nm

Based in this characteristic, two different approaches were used. The first approach was through conventional fiber sensing with cladding-stripped optical fiber. The second one was based on integrated optics, where changes in the evanescent field of leaky or curved waveguides were used to produce changes in the propagation losses of the optical modes leading to variations in the output power [2,3].

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8257-47, Poster Session

Refractive-index insensitive long-period fiber gratings point-by-point inscribed by CO2 laser for fiber sensors and lasers

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High refractive index (RI) sensitivity is one of the features that distinguishes long-period fiber gratings (LPFGs) from fiber Bragg gratings (FBG). This feature has been utilized to realize numerous kinds of sensors. However, this feature becomes a disadvantage in certain muti-parameter sensing or laser applications. In the sensing applications, cross-coupling between RI and other parameters such as temperature will decrease the precision of the measurement. While in laser applications where a LPFG can be used as a modulator or filter, the surrounding RI variation of the LPFG can caused stability problems. In this paper, LPFGs fabricated on a double-clad fiber by the CO2 laser point-by-point technique are reported. The LPFGs are tested by measuring the temperature of different liquids. The results show that these LPFGs are very insensitive to the RI of the surroundings. While, the temperature sensitivity is ~0.15 nm/oC, more than 15 times higher than that of the conventional FBG. Such LPFGs can be used as temperature/strain sensors in applications where the surrounding RI is prone to variation, such as the temperature measurement of chemical reactions. They can also be used as modulators in fiber lasers with a high sensitivity to modulation signals and no RI change (such as contact to surrounding materials) induced instabilities.

8257-49, Poster Session

Multi-element superconducting nanowire photon detector for photon-number resolution

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The photon detector with photon-number resolution function is required for many applications, such as linear-optics quantum computing. Traditional superconductor single photon detector is sensitive, high-speed and high time-resolution for photon detecting with low noise, but unable to resolve the photon number in a triggered detecting process. For the purpose of photon number resolution, a novel structure of multi-element superconducting nanowire of superconducting nanowire single photon detector is explored. Multi-element supercodncuting Niobium Nitride (NbN) nanowire is fabricated with electron beam lithography and reactive ion etching. The measurement set up for chips analyzing is also introduced in this presentation. With 4.2 K bath temperature, we analyzed the electrical properties of fabricated supercoducting nanowires. Finally, a primary result of photon resolving is presented with the chips fabricated in this work.

8257-50, Poster Session

Time-of-flight 3D ranging through SPAD arrays with in-pixel time-to-digital conversion

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Combined 2D imaging and 3D ranging sensors can carry useful information for long distance (e.g. 1 km) security applications. To this aim, monolithic imagers based on Single Photon Avalanche Diodes (SPADs), could achieve both the information together. Each pixel must include a SPAD, a quenching circuit (QC), a counter and a Time-to-Digital Converter (TDC), and operate in two different operation modes: photon counting and photon timing. In photon counting the QC quenches the SPAD avalanche and assures a constant and programmable hold-off and the counter counts the photons, thus obtaining 2D intensity images. In photon timing, the duration of the round-trip of a laser pulse (tens of picoseconds width) is measured in order to obtain direct Time-of-Light (dTOF) 3D images. In this case only one photon per integration frame is detected; thus, after the detection of the avalanche, the QC keeps the SPAD quenched until a new integration time starts. The counter performs a coarse time-to-digital conversion (typical resolution 5ns, dynamic range 95m) and the TDC arbiters enhance the overall resolution (down to typically 9 cm). The global electronics manages the readout of the overall array and the generation of the multiphase clocks for TDCs.

8257-51, Poster Session

Impact of threading dislocation density on metamorphic InxGa1-xAs and InzGa1-zP p-i-n photodetectors on GaAs

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Bandgap engineering via metamorphic epitaxy enables the maximization of photodetector performance at target wavelengths. However, an increase in threading dislocation density (TDD), which is inherent for the growth of relaxed, lattice-mismatched layers, could offset this advantage and severely limit detector performance. Hence, it is critical to minimize TDD and study its impact on important photodetector parameters, such as dark current and responsivity. To this end, we are investigating the performance of InxGa1-xAs and InzGa1-zP p-i-n photodetectors, as a function of TDD, by utilizing a variety of InxGa1-xAs buffer designs, grown by MBE on GaAs substrates, to achieve terminal device layers with a range of TDD values. Metamorphic In0.14Ga0.86As, In0.20Ga0.80As, In0.61Ga0.39P and In0.68Ga0.32P p-i-n photodetectors were grown and fabricated in order to study the impact of dislocation density on the device parameters; further extension of the metamorphic platform toward InP is currently in progress. The reverse dark current density was found to be extremely sensitive to TDD for all the photodetectors, with, for example, the In0.20Ga0.80As photodetectors displaying a sharp reduction in dark current density (at -3 V) from 3.3 x 10-7 A/cm2 to 6.8 x 10-8 A/cm2 with a reduction of TDD from low 107 cm-2 to ~106 cm-2, yielding reduced shot noise and a marked improvement in specific detectivity. A comprehensive comparison between the different graded buffer designs used and the resulting metamorphic materials and photodetector characteristics will be presented, along with results related to integration of these detectors to achieve high-performance, monolithic visible/infra-red dual-detectors.

8257-52, Poster Session

Bend loss insensitive all-solid optical fiber

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Conventional core/clad optical fibers composed of all-solid silica material were fabricated using the “stack and draw” method. The optical fiber core is composed of Ge-doped silica glass, and the fiber clad consists of un-doped silica glass. The attenuation and the chromatic dispersion spectra of these optical fibers, with their external diameters of 210, 175, 150 and 125 µm, were characterized by using a PK2500 and a PK2800 instrument respectively. The total loss of these optical fibers, at 1550 nm, was lesser than 5 dB/km and the zero-dispersion-wavelength range from 1000 to 1600 nm. On the other hand, bend loss spectra of these fibers were characterized by using small bend diameter devices (bend diameters from 2 to 10 mm). The bend loss spectra show that these all-solid optical fibers are insensitive to bend effect. In addition we explore the nonlinear properties of these fibers to investigate the potential for supercontinuum generation.

8257-53, Poster Session

Development of nanostructure based antireflection coatings for EO/IR sensor applications

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EO/IR Nanosensors are being developed for a variety of Defense and Commercial Systems Applications. These include UV, Visible, NIR, MWIR and LWIR Nanotechnology based Sensors. The conventional SWIR Sensors use InGaAs based IR Focal Plane Array (FPA) that operate in 1.0-1.8 micron region. Similarly, MWIR Sensors use InSb or HgCdTe based FPA that is sensitive in 3-5 micron region. More recently, there is effort underway to evaluate low cost SiGe visible and near infrared band that covers from 0.4 to 1.6 micron.

In this paper, we will discuss our modeling approach and experimental results for using oblique angle nanowires growth technique for extending the application for UV, Visible and NIR sensors and their utility for longer wavelength application. The AR coating is designed by using a genetic algorithm and fabricated by using oblique angle deposition. The AR coating is designed for the wavelength range of 400 nm to 2500 nm and 0° to 40° angle of incidence. The measured average optical transmittance of an uncoated glass substrate between 1000 nm and 2000 nm is improved from 92.6% to 99.3% at normal incidence by using a two-layer nanostructured AR coating deposited on optical surfaces.

8257-54, Poster Session

Optical switch using polymer functionalized clad etched fiber Bragg grating

S. B. Nanjunda, G. R. Prashanth, S. Asokan, M. M. Varma, Indian Institute of Science (India)

Polyelectrolytes are charged polymer species which can electrostatically adsorb onto surfaces. By sequentially depositing anionic and cationic polyelectrolytes by dip coating or spray coating, one can design multilayer structures for various applications such as bio(chemical) sensors and drug release capsules. As the electrostatic assembly is a self-limiting process, it is possible to get precise thickness control which is necessary for optical applications. It is known that variables such as pH can modify the internal structures of these polyelectrolyte multilayers. We created a multilayer structure (~ 100 nm thick) of cationic polymer Poly-allylamine hydrochloride (PAH) and an anionic polymer Poly-acrylic acid (PAA) on a fiber bragg grating (FBG) structure with the clad completely etched off to increase the interaction of the polymer with the guided optical mode. We observed pH dependent switching of the Bragg wavelength by about 150 pm when the pH of medium surrounding the polyelectrolyte functionalized FBG was switched between acidic and basic states. This switching is expected to be the result of the internal structural change resulting in the polymer film. We are studying the influence of ions on the dynamics of these structural changes and thereby hoping to use this system as an ion sensitive detector. Current switching speed (~ 2 - 3 s) is limited by diffusion times of the pH altering solutions and is large as it is done using a large sample volume (~ 100 mL). By reducing the sample volume using microfluidics it should be possible to reduce the switching speed by orders of magnitude.

8257-55, Poster Session

Middle infrared LEDs: key element for new generation chemical sensors

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Optical chemical sensors are the only ones, which are truly gas specific and therefore reliable. But up to now wide aplication of portable gas sensors is limited by imperfections of currently used heating infrared sources (lamps) with filters.

Qualitative technological break-through in growing of narrow band-gap heterostructures based on GaSb-InAs materials was achieved by technologists of high tech company LED Microsensor NT from St.Petersburg, Russia. Company developed full line high effective LEDs for the spectral range 1600-5000 nm and spectral matched photodiodes. In the LEDs and PDs are used lattice-matched heterostructures with GaInAsSb quaternary solid solutions in the active layer. Commercial production is started.

On the basis of these new LEDs and spectral matched photodiodes it comes possible for the first time to be created gas sensors that meet all demands of the mass market: compactness; low electrical power consumption; high selectivity; high sensitivity; long life-time without additional calibration and low cost in mass production.

Average optical power up to 3.5 mW and peak power up to 170 mW was achieved for 1600-2400 nm LEDs. Optical power of 3000-5000 nm LEDs is still quite low but as far as absorption of CO_2 and CH_4 in this spectral range is very strong, creation of simple design high sensitive gas sensors is possible. Small sizes of the LED and PD chips and low thermal power dissipation give us possibility to design multi-color LED arrays and matrix. This fact gives to the mid-IR LED-PD pairs additional advantages over the thermal infrared sources.

8257-20, Session 5

Broad-band laser emission and optical mode-locking of a Fabry-Perot laser formed between two linearly chirped fiber Bragg gratings

G. A. Iordachescu, X. Wu, J. Jacquet, Supélec (France)

This paper starts with a short exposition of the principles behind the use of Linearly Chirped Fiber Bragg Gratings (LCFBGs) for the spectral widening of laser emission. Then the experimental measurements of light emitted by a novel type of broad-band laser are presented. The laser cavity is realized by placing a Semiconductor Optical Amplifier (SOA) between two LCFBGs. The P-I (power-current) curve of this structure and its spectral distribution of optical power at high currents present similarities with those of continuum lasers, though on a short 10nm-interval. For a better understanding of the processes involved, a superposition of the spectral characteristics of the different elements (gain of the SOA, reflectivities of the gratings) is also presented, in parallel with numerical simulations showing how the lasing bandwidth could be enlarged by LCFBG engineering. The multimodal character of the emission is also discussed here. In spite of the low coherency which would make this laser unusable in OCT (optical coherence tomography) it is hoped it could replace present-day continuums in WDM applications, due to their basic design and cheaper costs of fabrication. In the end, a simple all-optical mode-locking is realized by injecting a tunable master laser inside the cavity. Finally, the efficiency of the mode-locking is studied in both the initial lasing bandwidth and outside of it, respectively.

8257-21, Session 5

Tunable and switchable multi-wavelength fiber laser based on semiconductor optical amplifier and twin-core photonic crystal fiber

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Multi-wavelength fiber lasers have attracted a lot of interest, recently, because of their potential applications in wavelength-division-multiplexing (WDM) systems, optical fiber sensing, and fiber-optics instruments, due to their numerous advantages such as multiple wavelength operation, low cost, and compatibility with the fiber optic systems. Semiconductor optical amplifier (SOA)-based muti-wavelength fiber lasers exhibit stable operation because of the SOA has the property of primarily inhomogeneous broadening and thus can support simultaneous oscillation of multiple lasing wavelengths.

In this letter, we propose and experimentally demonstrate a switchable multi-wavelength fiber laser employing a semiconductor optical amplifier and twin-core photonic crystal fiber (TC-PCF) based in-line interferometer comb filter.

The fabricated two cores are not symmetric due to the associated fiber fabrication process such as non-uniform heat gradient in furnace and asymmetric microstructure expansion during the gas pressurization which results in different silica strut thickness and core size. The induced asymmetry between two cores considerably alter the linear power transfer, by seriously reducing it. These nominal twin cores form effective two optical paths and associated effective refractive index difference. The in-fiber comb filter is effectively constructed by splicing a section of TC-PCF between two single mode fibers (SMFs). The proposed laser can be designed to operate in stable multi-wavelength lasing states by adjusting the states of the polarization controller (PC). The lasing modes are switched by varying the state of PC and the change is reversible. In addition, we demonstrate a tunable multi-wavelength fiber laser operation by applying strain to TC-PCF in the multi-channel filter.

8257-22, Session 6

Recent developments in the fabrication of infrared fiber Bragg gratings

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Fiber Bragg gratings are needed as an enabling technology for infrared fiber lasers. However, fabrication of Bragg gratings in infrared chalcogenide-based fibers has remained elusive, due to difficulties in achieving high reflectivity as well as long term stability. Fabrication is further complicated by the fact that the core and clad glasses of the chalcogenide fibers have similar photosensitivity, unlike silica-based fibers, where the core glass is doped with Germanium. In this paper, we will report on dopant studies to enhance the photosensitivity of the core versus the cladding while maintaining the index of refraction difference to achieve the proper numerical aperture as well as compatible thermal properties (e.g. glass transition temperature and viscosity) to enable fiber drawing. Results for the parameters for grating formation will be presented, including laser writing wavelengths, power and exposure times. We will describe our recent gratings fabrication results, whereby 17 dB reflectivity at 1550 nm was achieved in arsenic sulfide-based fiber, using 633 nm light with a specially designed 0/-1 phasemask. We will also report a study of stability maintained over one year for an IR fiber Bragg grating.

8257-23, Session 6

Temperature stability in silica based fiber Bragg gratings

C. W. Smelser, S. J. Mihailov, D. Grobnic, Communications Research Ctr. Canada (Canada)

Fiber Bragg gratings (FBG) have garnered interest as temperature and strain sensors because they are compact, inexpensive, and can be utilised for distributed and multi-parameter sensing. Traditionally, FBG devices have been fabricated by exploiting the UV photosensitivity mechanism for the inducement of index of refraction changes in Ge-doped silica. The main drawback with UV induced devices for temperature sensing is that the induced index change in the material is not stable at temperatures significantly higher than 500 °C. Some UV induced devices such as Type II damage, chemical composition and regenerated gratings have demonstrated heightened temperature stability, however, have not been shown to simultaneously possess both large induced index change and acceptable spectral quality [1-3]. Recently, researchers have become interested in the use of ultrafast lasers to fabricate FBGs [4]. These devices are likely formed through a multi-photon absorption process for the inducement of index change that does not require germanium doping. Type II gratings produced in this manner proved to have superior spectral quality and large index change [5]. It was also found that, in the case of hydrogen loaded SMF-28 fiber, gratings formed with large initial index change also possessed high temperature stability [6]. The index change in hydrogen loaded fiber can also be controlled so as to tailor the gratings spectral response. In this presentation we will discuss our long-term measurements of these devices (>1000 °C) at elevated temperatures and address their feasibility as sensors at temperatures in excess of 500 °C.

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8257-24, Session 6

Single resonance monolithic Fabry-Perot filters formed by volume Bragg gratings and multilayer dielectric mirrors

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High efficiency reflecting volume Bragg gratings (VBGs) recorded in PTR glass plates have shown un-preceded performances that make them very good candidates for narrowband spectral filtering with sub-nanometer spectral widths. However, decreasing the bandwidth to value below 30-50 pm is very challenging as it requires increasing the thickness of the RBG to more than 15-20 mm. To overcome this limitation, we propose a new approach which is a monolithic Fabry-Perot cavity which consists from a reflecting VBG with a multilayer dielectric mirror (MDM) deposited on its surface. A VBG with a grating vector perpendicular to its surface and a MDM produce a Fabry-Perot resonator with a single transmission band inside of the reflection spectrum of the VBG. We present a theoretical description of this new class of filters that allow achieving a single ultra-narrowband resonance associated with several hundred nanometers rejection band. Then we show the methods for designing and fabricating such filter. Finally, we present the steps that we followed in order to fabricate a first prototype for 852 nm region that demonstrates a 30 pm bandwidth, 90+% transmission at resonance and a good agreement with theoretical simulation.

8257-25, Session 6

High order mode long-period fiber grating refractive index sensor based on intensity measurement

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Long-period fiber gratings have been used for refractive index measurements under different conditions. Normally, this kind of sensor is based on measuring resonance wavelength shift with respect to different refractive index environments. As high order mode long period fiber gratings are attracting more attention, a new methodology based on intensity measurement of turning points is introduced, which involves simple experiment setup and straightforward demodulation process compared with wavelength shift based method. By using CO_2 laser point by point irradiation method, high order mode gratings working at turning point can be easily fabricated. This type of grating has a very high sensitive response to surrounding refractive index, which can be used in chemical, medical and bio applications. In this paper, high sensitive refractive index sensor is demonstrated based on high order mode using intensity measurement. Phase match curve and couple mode theory are combined to analyze the intensity response to refractive index change at turning point of LPFG. This sensor is also demonstrated as an effective refractive index based glucose sensor with a range from 0 to 40 mM concentration of glucose solution, which can fulfill the medical requirement.

8257-26, Session 7

Electro-adaptive multi-layer fluidic lens system of PDMS membranes

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Fluidic lens consisting of a PDMS (polydimethylsiloxane) membrane is a prominent candidate for giving an opportunity to implement an optical zooming system with thin architecture. Compared to the typical zooming system that needs dozen of optical lenses to implement image magnification, the zooming system consisting of a fluid can be implemented by a few liquid lenses with high optical power. The key features made by this multi-layer liquid lens is that it uses the cornea shape of lens consisting of PDMS membrane adhesive to actuating magnet, which moves back and forth in the optical axis. This triplet fluidic lens with a PDMS membrane is suitable for a relatively small system such as a mobile application with a clear aperture. The diameter of the lens is as small as 5 mm, and the lens can be as thin as ~10 mm. The lens structure is designed to make the thickness as thin as it can be while remaining equipped into a mobile device. This structure scheme to stack multiple layers of PDMS membranes was very successfully to makes the lens very thin even with its mechanical frame base. By using actuating force, we were able to slightly adjust the relative position of the each magnet by applying a small amount of electrical power. This research covers the fabrication process and mechanism of multi-layered liquid lens, in which the focal length of each membrane is controlled by voltage-controlled magnetic force which adjusts the relative position of the coupling magnets to the other.

8257-27, Session 7

Flexible fibre-addressable surface-plasmon-polariton chip

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Surface plasmon polariton (SPP) chips are substrates containing metallic surfaces that support transverse-magnetic (TM) polarized surface-bound electromagnetic waves. In the most common configuration, an SPP chip is used with an external light source, optical components to polarize the incident light and guide light to and from the chip, a coupling device to convert free-space light into an SPP wave and back into free-space light, and a light detector. The light source, the optical components, and the light detector are components that are external to the SPP chip, and the coupling structure is often integrated directly with the SPP-sustaining metal surface. The requirement of several external components restricts the miniaturization of devices that incorporate SPP chips. Here, we design, fabricate, and test a new SPP chip architecture that is fibre-addressable, does not require a discrete coupling structure, integrates the light delivery and light polarization control onto the chip, and sustains SPP waves on a flexible plastic surface. Our SPP chip is constructed from a thin gold layer deposited on top of a clear plastic sheet, which is then optically connected from the bottom surface onto a plastic linear polarizer sheet. Two cleaved fibres, one to input light and the other to collect reflected light, are then optically attached to SPP chip. The angles of the input and collection fibres are tuned so that visible light incident onto the gold film from the bottom of the chip couples to SPP waves on the other side of the gold film.

8257-28, Session 7

Optical attenuation across a metal grid

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Metal grids are applied on windows in order to prevent condensation by elevating their temperature relative to the surroundings. This measure, however, degrades the window transmission due to extinction. To minimize the radiation attenuation these grids are made very thin, on the order of micrometers, just about the wavelength of radiation used by many detectors and cameras. It is in this regime that the generation of surface-plasmon-polariton (SPP) is maximized, and in combination with scattered light, bring attenuation to a peak.

Presented in this paper is a study in which a model based on the Mie and Fresnel theories adapted to the case of a grid is used to predict the attenuation of a window. The adaptation of the Mie theory is in applying it to a grid. A method of how to overcome some basic limitations of the Mie series expansion is shown, enabling the present prediction. Then, experimental measurements across the window using a transmission spectrometer in the range of 300 - 2000 nm and a Fourier Transform spectrometer in the range of 1200 - 5000 nm, are conducted. With the parameters of angle-of-incidence, grid density and grid structure we find a good agreement between the data and calculation, revealing the soundness of the theoretical approach.

This study provides a tool for an optical designer to account for the optical grid-loss, minimize it by selecting a suitable mesh, set off the grid losses by applying AR coating and under certain conditions, using a passive, SPP heated grid.

8257-29, Session 7

Laser fabrication of micro-optical components of hybrid polymers

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We present experimental results on nanostructuring of novel hybrid sol-gel materials by the femtosecond laser direct writing technique for the fabrication of various microoptical components for visible spectral range. This approach enables one to manufacture three-dimensional objects with controlled sub-100 nm spatial definition and surface roughness below 30 nm. After photopolymerization these materials inherit desired optical properties of high transmittance in 400 - 1500 nm spectral range and nearly glass matching optical refractive index. Additional functionalities can be added by doping the materials with organic dyes or quantum dots. We successfully produced microoptical components such as aspheric and Fresnel lenses of diameters within 10 to 100 micrometers range. We demonstrate the flexibility and reproducibility of this approach to fabricate custom shaped elements on the tip of the optical fiber, thus producing integrated microoptical devices on already existing and widely used platforms. The shape and surface properties of such micro/nanostructures were characterized by optical and scanning electron microscopy, optical profilometry and atomic force microscopy. Their optical functionality was evaluated using custom built setup to serve the purpose. The measured characteristics of the components were in close coincidence to the expected values. Additionally, we propose methods which can be implemented in order to increase fabrication throughput and improve shape and surface quality. Produced microoptical components can be applied in light guiding, coupling/extraction, trapping, signal processing and transferring, microscopy, life sciences and etc. Production of integrated and multi-functional components to be applied in the fields of photonics, plasmonics and telecommunications as well as opto-fluidics is currently in progress.

8257-30, Session 7

Numerical simulation of laser pulse propagation in rare-earth-doped materials

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We describe a general numerical method for calculating short-pulse laser propagation in rare-earth-doped materials, which are very important as gain materials for solid-state lasers, fiber lasers and optical amplifiers. The split-step, finite difference method simultaneously calculates changes in the laser pulse as it propagates through the material and calculates the dynamic populations of the rare-earth energy levels at any position within the material and for times during and after the laser pulse has passed through the material. Many traditional theoretical and numerical analyses of laser pulse propagation involve approximations and assumptions that limit their applicability to a narrow range of problems. Our numerical method, however, is more comprehensive and includes the processes of single- and multi-photon absorption, excited state absorption (ESA), energy transfer, upconversion, stimulated emission, cross relaxation, radiative relaxation and non-radiative relaxation. In the models, the rare-earth dopants can have an arbitrary number of energy levels. We are able to calculate the electron population density of every electronic level as a function of, for example, pulse energy, dopant concentration and sample thickness. We compare our theoretical results to published experimental results for rare-earth ions such as Er^{3+}, Yb^{3+}, Tm^{3+} and Ho^{3+}.

8257-31, Session 8

Compact silica-on-silicon planar lightwave circuits for high speed optical signal processing

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Silica-on-silicon planar lightwave circuits (PLC) have enjoyed significant commercial success, initially for low-loss passive components for wavelength division multiplexing, and more recently as a platform for the large scale hybrid integration of photonic components for applications in high-speed optical signal processing[1]. While hybrid integration enables implementation of active devices such as lasers and modulators on-chip, new functionalities and further reductions in costs could be achieved through direct processing of high speed optical signals within the silica device platform. Recently, thermally tuned lattice-form Mach-Zehnder interferometers in silica PLCs have been demonstrated for arbitrary waveform generation and envelope shaping of high speed optical pulse trains[2]. This approach can be applied to a number of applications in high speed optical networks; however, there remain inherent limitations in device size and optical response speed. In this paper we address these limitations through engineering of the doped silica layers that comprise a silica PLC device. The performance of compact devices implemented in silica PLC with high refractive index contrast will be presented, and detailed modeling of the optical and thermal properties of the doped layers to achieve low optical loss and minimized birefringence will be described. The implementation of ultrafast PLC devices is approached by the introduction of a nonlinear optical response achieved through poling of variously doped silica multilayers[3]. We will present recent work on optimizing both the optical nonlinearity and the properties of functional waveguides fabricated in the multilayered doped silica structures. Design of a high speed modulator based on these devices will be discussed.

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8257-32, Session 8

Influence of coating stress of diamond-like carbon coating on surface flatness of large germanium windows

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Diamond-Like Carbon (DLC) coatings using Plasma Enhanced Chemical Vapor Deposition (PECVD) tend to cause high amount of compressive stress in coated film. This is predominant when coating is applied to germanium windows with high aspect ratios (approximately 40) for applications with wavelengths in the region of 8-12 microns. In this paper, we show that process parameters may be varied in order to control the effect of the coating stress on surface flatness. We investigate the before and after effects of coating on surface figure. It is also found that there is a trade-off among various process parameters in order to achieve high coating durability with low stress in the finished coated film. Finally, we report that, with the appropriate process controls, we have achieved successful production of large germanium windows using DLC coating with surface flatness of less than 8 fringes at 633 nm over as window diameters of as large as 270 mm.

8257-33, Session 8

Three-phase photoconductive elements for directional free-space optical sensing

X. Jin, D. Guerrero, J. F. Holzman, UBC Okanagan (Canada)

An integrated photoconductive element is introduced as a new optoelectronic device in free-space optical wireless applications. The device is a fundamental extension of the standard photoconductive switch, as it has the capabilities for both local optoelectronic signal reception and active directional (angle-of-arrival) sensing. This second capability is brought about through the use of a three-phase differential technique in a new three-dimensional photoconductive architecture.

The presented three-phase photoconductive sensor incorporates three triangular photoconductive switches arranged in a three-sided corner-cube architecture. Each photoconductive switch consists of 50/150 nm Cr/Au electrodes, patterned on either side of a 200-micron GaAs photoconductive gap, and is biased with the superposition of DC and AC voltage waveforms, with 120° phase-off between each AC voltage. The photocurrent output is collected on the lower vertex electrode, and the three-fold characteristics of the structure and biasing are witnessed. In standard optoelectronic signal reception, the summed photocurrent is DC-filtered (as the encoded time-varying conductances on each photoconductive gap). In the directional-sensing form, the summed photocurrent is AC-filtered to record differential optical signals between the photoconductive switches. In a balanced state (illumination along the axis of three-fold symmetry), the photoconductive gaps have identical conductances and the summed output three-phase AC photocurrent is zero. In unbalanced states, the summed output AC photocurrents differ from zero, and the nature of it can be used to ultimately triangulate angle-of-arrival estimates. The complete operational speed and angular characteristics of this device are presented in this work with excellent agreements between the theoretical models and experimental results.

8257-34, Session 8

Demonstration of all-optical two bit digital comparator using self-locked Fabry-Perot laser diode

B. Nakarmi, M. Rakib-Uddin, Y. H. Won, KAIST (Korea, Republic of)

All-optical signal processing is one of the most promising solutions to meet the future high-speed large capacity optical communication networks. Various functions such as encryption and data encoding, pattern matching, binary addition, counting, addressing, de-multiplexing, regeneration, switching and computing are proposed using different techniques such as Er-doped optical amplifier, periodical poled $LiNbO3$ (PPLN), semiconductor optical amplifier (SOA) and some are realized using FP-LDs. The advantage of using single mode Fabry-Perot laser diode (SMFP-LDs) for optical signal processing are its simple configuration, less components, cost effective and power effective, compared to other all-optical technologies.

In this paper, a novel scheme for two bit comparator using SMFP-LDs are proposed and demonstrated with 10 Gbps input signal. The basic principle of the proposed comparator is based on the single input injection locking, multi-input injection locking and combinational input injection locking which can be obtained through the proper power management of input beams. Greater than, equal to and less than functions of two bit comparator is realized by the combination of different logic gate. The equal to function can be realized by implementing XNOR where the output will be 1 only when both the inputs are of same logic whereas the greater than and less than function can be realized with the combination of NOT and NOR gates so that the output will be 1 when only one input is high. The proposed all-optical comparator can be used for decision making circuits, threshold circuits, and analog to digital converters in all-optical networks

8257-35, Session 8

The focusing property of the spiral Fibonacci zone plate

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In the past few years, the concept of fractal was combined with the Fresnel zone plate (ZP) to improve its imaging capability and introduce additional freedom for optimizing. The fractal most frequently used is Cantor set, which formed by constructing the generator iteratively. Recently, novel fractal zone plate was introduced, i. e., Fibonacci zone plate (FiZP), which is generated by means of Fibonacci sequence and proved to be capable of focusing incident beam as ZP or fractal zone plate (FrZP). It is worth to emphasize that FiZP is distinguished with radially symmetric Fibonacci ring plate in terms of the conventional and square of radial coordinate. In this paper, we will study the focusing properties of the spiral FiZP, which overlap the spiral phase with FiZP. First, the analytical formula of the intensity distribution on axis was deduced according to the Fresnel diffraction theory and the generating rule of Fibonacci fractal. Multiple focusing optical vortices are formed due to the sequence focusing properties of the FiZP, which are expected to be employed for trapping and rotating microparticles located at various positions simultaneously. Experiment is also performed to verify the theoretical analysis by phase-only spatial light modulator (pSLM). The spiral phase and FiZp are encoded together in the phase pattern to generate the multiple focusing optical vortices. The recorded images by CCD in specific location along the propagation direction are coincident with theoretical prediction well. In additional, we also studied the fractal property of the on-axis intensity distribution.

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8258-01, Session 1

Photonics polymers for reconstructing Japan from the 11th March disaster (Keynote Presentation)

T. Kaino, Tohoku Univ. (Japan); Y. Koike, Keio Univ. (Japan); S. Miyata, Tokyo Institute of Technology (Japan)

At the international conference on advanced photonics polymers (ICAPP2011) that will be held on 1st to 2nd December, 2011, we had discussed the role of photonics polymers for reconstructing Japan from the 11th march disaster. more than 30 invited speakers from all over the world will discuss the theme. Special round table discussion as well as panel discussion will be held. Based on the discussion, results will be summarized and we hope to appeal what we can do for the world using photonics polymers, which includes plastic optical fibers, polymer waveguides, photorefractive polymers, liquid crystal polymers, polymer photonic memory devices, optical nano-fibers, nonlinear optical matetials, electro-optic polymers and so on. This results will work for developing next generation advanced photonic polymers.

8258-02, Session 1

Terahertz metamaterials for sensing nematic liquid crystals and carbon nanotubes

J. Wu, Ewha Womans Univ. (Korea, Republic of)

We introduce two metamaterials. The first metamaterial is composed of double split-ring resonators, which possesses a magneto-electric coupling at low frequency resonance for THz wave polarization parallel to the gap bearing arm. The lowest resonance is LC resonance and the higher resonances are dipole resonances, and the excitation of each resonance is polarization sensitive. The second metamaterial is composed of a four-fold rotational symmetric split-ring resonator, with the symmetric axes of x- and y-axis. It possesses the same resonance frequency for polarizations parallel and perpendicular to the gap bearing arm, hence polarization insensitive Time-domain terahertz transmission measurements were carried out with a TeraView TPS Spectra 3000 Spectrometer at a resolution of 1.2 cm−1 at room temperature in vacuum. In both metamaterials, anisotropic interactions between the electric field and two organic materials are enhanced in the vicinity of meta-resonances. In liquid crystal, meta-resonance frequency shift is observed with the magneto-optical coupling giving rise to the largest anisotropic shift. In carbon nanotube, meta-resonance absorptions, parallel and perpendicular to the cylindrical axis, experience different amount of broadening of Lorentzian oscillator of meta-resonance. In case of liquid crystal, red-shift of metamaterial resonance spectrum is attributed to a change in the dispersive part of refractive index, while an increase in absorption of metamaterial resonance observed in carbon nanotube is from a change in the absorptive part of refractive index. Anisotropic internations between metamaterials and anisotropic organic materials can be utilized in the application of metamaterials as a sensor for anisotropic materials.

8258-03, Session 1

Control of birefringence of styrene copolymers for optical devices

T. Kojo, A. Tagaya, Y. Koike, Keio Univ. (Japan)

Optical polymers have been applied to lenses, optical disks and various other optical devices. However, polymers tend to cause birefringence. Birefringence degrades the performance of optical devices using polarized light. Otherwise, birefringence is used to realize high-definition images in LCD. Therefore, birefringence needs to be eliminated or controlled.

Orientational birefringence and photoelastic birefringence of polymers were simultaneously compensated by random copolymerization. The composition of the copolymer was calculated by using the linear relationship between the birefringence of the constituent polymer and composition ratio. However, control of birefringence by using monomers which do not copolymerize randomly has not been investigated. When monomers do not copolymerize randomly, the copolymers have a compositional distribution; means that the copolymer is like blend polymers. The relationship between the compositional distribution and birefringence has not been clarified yet.

The purpose of this study is to control birefringence of monomers which do not copolymerize randomly. We investigated the influence of the compositional distribution on birefringence by utilizing poly(methyl methacrylate (MMA) / styrene (St)). We analyzed the relationship between orientational or photoelastic birefringence and composition ratio.

As a result, the compositional distribution of poly(MMA/St) hardly affects birefringence was indicated. A linear relationship was observed between the orientational birefringence and composition ratio, but not between the photoelastic birefringence and composition ratio. We expressed the curve between the photoelastic coefficient and composition ratio in a function and controlled birefringence of copolymers with the function. The possibility to control the birefringence of monomers which do not copolymerize randomly was demonstrated.

8258-04, Session 1

Self-assembled functional thin films towards nanophotonics

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In order to achieve the nanometer-scale control over the positioning and organization of functional molecules into monolayers at surfaces, we developed an original approach allowing the exact positioning of (photo)active organic molecules on the substrate (graphite) leading to the formation of nanostructured functional thin films. Here we present a strategy aimed at the decoupling of molecules from the surface, by lifting photoactive entities a few Å above the surface while maintaining the lateral organization of the array. This is achieved by using 2-level based building blocks. While the first level allows the precise organization of the building blocks on HOPG at the solid-liquid interface at room temperature, the second level is a photoactive compound, namely a chromophore. We will present a series of such building-block exhibiting tunable wavelength emission. This strategy results in the precise organization of chromophores arrays (subwavelength-sized photon sources) a few Å above the conducting surface, as determined by scanning tunneling microscopy (STM), opening interesting perspectives for applications in nanophotonics.

8258-05, Session 1

Tuning the refractive index of blended polymer films by RIR-MAPLE deposition

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Gradient index polymer films enable novel optics using rigid or flexible substrates, such as waveguides or anti-reflective coatings. Previously, such films have been fabricated by nanoimprint lithography[1] and the decomposition of a single component in polymer blends[2]. Yet, it is desirable to have precise control over the polymer film composition in order to have the most flexibility in designing refractive index profiles. Resonant-infrared matrix-assisted pulsed laser evaporation (RIR-MAPLE) is a polymer thin film deposition technique that enables multi-layer structures on a wide variety of substrate materials, regardless of the solubilities of constituent polymers[3,4]. In this work, the feasibility of tuning the refractive index of blended polymer films of polystyrene and poly(methyl methacrylate) deposited by RIR-MAPLE is demonstrated. Different polymer blend film compositions are deposited using RIR-MAPLE by varying the polymer target ratio and target geometry used for co-deposition, as well as the constituent polymer molecular weights. The refractive indices of the blended films are measured using spectroscopic ellipsometry. Transmission electron microscopy is used to characterize the film morphology, while additional optical properties are determined by transmission/reflection measurements using an integrating sphere and UV-Vis absorption spectroscopy.

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8258-06, Session 2

Biphotonic chromophores for photodynamic therapy: molecular engineering and biological data

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Photodynamic therapy is a cancer therapeutic approach based on the photo- production of cytotoxic singlet oxygen, through a photosentisizer near a tumoral tissue. In recent years, it has been used with success in the treatment of certain cancers; however, it suffers from one major limitation: due to biological absorption of the incident light, it is impossible to efficiently activate a conventional photosentisizer through more than few millimeters of tissue. Two-photon activation of sensitizers,in the tissues transparency domain at 800-900 nm, could be a advantageous strategy to overcome these limitations, avoiding undesirable damages of healthy tissues in the tumor's surroundings.

Two-photon activation of the sensitizers, using lasers with wavelengths around 800-900 nm could be a very advantageous strategy to overcome these limitations. This range of wavelengths corresponds to the domain of transparency of human tissues, which would allow deeper penetration of the light. Another advantage is the highly confocal character of two-photon excitation, leading to very localized sensitizer activation, which is ideal to avoid undesirable damages of healthy tissues in the tumor's surroundings.

In spite of all its promises, two-photon PDT is still in its infancy. The first part of this presentation will deal with recent results in our group concerning the structural optimization of chromophores for two-photon induced dynamic therapy. The second part will focus on the biological results using our photosensitisers

8258-07, Session 2

Nanocrystalline cellulose for covert optical encryption

M. P. Andrews, Y. Zhang, V. P. Chodavarapu, A. K. Kirk, McGill Univ. (Canada)

We present a technique and material approach to create binary covert (iridescent plus fluorescence) optical encoding for anticounterfeiting measures. We adopt a "green chemistry" approach that combines the optical response of nanocrystalline cellulose (NCC) with emission from a well known Optical Brightening Agent (OBA). The result is a fluorescent iridescent NCC film. We study the impact of OBA on NCC iridescence, chirality, and physical structure variation with polarized optical microscopy, white light diffraction, and circular dichroism spectrometry. OBA additions affect, in a sensitive way, the chiral pitch of NCC films, and this in turn alters solid film iridescence.

8258-08, Session 2

Describing two-photon absorptivity of (Zwitter)ionic fluorochromes and fluorescent proteins with a new vibronic coupling mechanism

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Application of traditional biologically-oriented fluorochromes, such as FITC, Alexa Fluors, BODIPY, and Fluorescent Proteins (FPs), is now successfully extended to two-photon absorption (2PA) microscopy. Understanding the physical basics of 2PA properties of these molecules is therefore crucial for creating better 2PA probes and optimizing excitation wavelengths. It has been observed that in a number of such molecules the 2PA maximum of the first electronic transition is shifted to higher frequencies with respect to the corresponding one-photon absorption (1PA) maximum. The effect was found only in chromophores whose pi-conjugated system enables charge-transfer resonance structures. The physical mechanism of such intensity redistribution has not been understood. Here we show that this shift is due to an intensification of a certain vibronic transition in the 2PA spectrum which, in contrast to the 1PA case, becomes stronger than the pure electronic transition. In addition to the transition dipole moment, determining 1PA, the 2PA tensor also contains a factor equal to the difference between the permanent dipole moments in the ground and excited states (d). This leads us to a model, explaining the effect of vibronic redistribution through the "Herzberg-Teller"-type coupling of d to the bond-length-alternating coordinate. The model is successfully applied to describe (vibronic) peak 2PA absorptivities in a series of Oxazines, Alexa Fluors, Fluorescein, BODIPY, and green and red FPs with anionic chromophore. It also enables us to explain unexpectedly large 2PA peak intensity in some red FPs through the interference between the "Herzberg-Teller" and Franck-Condon vibronic contributions to the 2PA tensor.

8258-10, Session 3

Conductive polymers as a hole transport materials in a solid state solar cell

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Conductive polymers were explored as a hole transport material (HTM)

in a solid state solar cell. Among the several possible methods, a solid state polymerization of a crystalline monomer afforded in-situ formation of conductive polymer HTM inside photoanode. Thus a monomer solution was successfully penetrated into the nanopores of a thick nanocrystalline TiO2 layer and polymerized at mild temperature. As prepared solar cell showed high photo energy conversion efficiency (PCE) due to the formation of effective hole transport conductive polymer channel, which filled the nanocrystalline TiO2 pore. Further enhancement of the PCE from the

solar cell was achieved by organized mesoporous TiO2 layer which was prepared onto the FTO layer without defects, exhibiting good adhesion to the thick nanocrystalline TiO2 film with increased transmittance. Here we present the successful examples of

electroactive polymers for solid state solar cell illustrating the

working principle of I2-free ssDSSC.

8258-11, Session 3

DNA for highly efficient phosphorescent organic light emitting diodes

E. F. Gomez, H. Spaeth, H. You, Univ. of Cincinnati (United States); J. G. Grote, Air Force Research Lab. (United States); A. J. Steckl, Univ. of Cincinnati (United States)

Natural DNA derived from the salmon industry is an inexpensive biomaterial that has been used in many photonics applications. Solid-state optoelectronic devices, such as biopolymer organic light emitting diodes (BiOLED) and lasers, that incorporate DNA demonstrate improved performances. DNA is prepared for thin film fabrication by modifying it with a cationic surfactant cetyltrimethylammonium chloride (CTAC). The DNA surfactant complex is insoluble in water, but dissolves in alcohol and forms excellent thin films by spin coating. Such DNA thin-film layers can readily be incorporated into device structures. DNA exhibits excellent electron-blocking HOMO/LUMO levels that make it ideal in OLED device and other solid-state devices.

We have previously reported on the superior performance of DNA-based BiOLEDs using fluorescent emission. In this paper, we discuss the incorporation of DNA into phosphorescent OLEDs using selected Ir-complexes. Green emitting phosphorescent OLEDs incorporating DNA as an electron-blocking layer have demonstrated outstanding performance in brightness and efficiency, usually superior to conventional OLEDs without DNA layers. This trend of increased light emitting performance for DNA OLEDs has proven true for red and blue emitting Ir phosphorescent OLEDs. The operation and performance of green, red and blue phosphorescent OLEDs with and without DNA will be presented.

DNA continues to distinguish itself as an inexpensive, performance enhancing, safe and 'green' material in the emerging field of biophotonics and bioelectronics.

8258-13, Session 3

Carrier mobility characterization of DNA-surfactant complexes

T. Lin, Y. Hung, National Tsing Hua Univ. (Taiwan)

Deoxyribonucleic acid (DNA) biopolymer has been emerging as a promising material for photonic applications. As many optoelectronic devices rely on carrier transportation to achieve desired functionality, carrier mobility is important for the exploitation of these biopolymer-based materials for practical implementation. In this study, we present the mobility measurement by employing time-of-flight technique and characterize the current-voltage (I-V) properties based on DNA-surfactant complexes. An additional NPB layer was introduced in the fabricated structure to serve as a charge generation layer (CGL). The dependency of hole mobility with respect to the applied electric field was characterized and a linear correlation was exhibited. Hole transport was found to be dispersive, indicating a high degree energetic disorder in these DNA-surfactant complexes. The characterization results show promises for the employment of DNA complexes in the applications of organic light-emitting devices and organic field-effect transistors.

8258-14, Session 4

Nanoscale templating and assembly in dye-sensitized and polymer solar cells

M. F. Durstock, G. Bazzan, J. R. Deneault, T. Kang, C. Tabor, B. E. Taylor, C. A. Bailey, Air Force Research Lab. (United States)

The development of low-cost, light-weight, and flexible energy harvesting devices are an enabling technology for many different solar power applications. The fabrication of highly efficient power conversion devices are highly dependent on the materials and device structures used to make up the active components. Two factors limiting the performance of organic and nanoparticle-hybrid solar cells are limited spectral response and restricted charge transport. These effects can result from poor light absorption, increased carrier recombination, low electronic charge carrier mobilities, or relatively random thin film morphologies. Our efforts to broaden the spectral response of dye-sensitized solar cells are based on developing a detailed understanding of the assembly of dye molecules on the surface of the mesoporous titania film. By utilizing an interfacial modification technique based on layer-by-layer assembly, nanoparticle surfaces can be functionalized with electronically active species and integrated into device structures. This technique is amenable to developing 'energy cascade' device architectures commonly utilized in photosynthetic organisms. Our efforts to develop a detailed understanding of this interfacial structure as well as approaches to fabricate multilayer assembled films for enhanced absorption will be described. For polymer-based cells, the use of low-bandgap conjugated polymers and the incorporation of plasmonic nanostructures into active device structures are being explored. In addition, our efforts to develop the materials and fabrication methodologies that result in highly ordered device structures to permit enhanced charge transport will be discussed. These include a nano-templating methodology based on porous anodic alumina in order to fabricate vertically aligned titania nanotubes of controllable shape and size. Structure-property correlations relating nanoscale morphology of the nanotubes to device performance will be discussed. In addition, we will highlight current barriers to improved performance and describe a number of specific approaches being investigated to address these issues.

8258-15, Session 4

Phase sensitive optical coherence tomography for organic solar cell characterization

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One problem that manufacturers of organic solar cells face is the distribution and organization of the polymers in the solar cells. We have developed a phase-sensitive optical coherence tomography (OCT) system for characterization of these thin (40-100 nm) organic solar cells. By using the solar cell surface as a reference, and compare it to the bottom of the substrate of the organic solar cell, usually a glass surface, a common path interferometer can be made, which is much more stable than the traditional Michelson interferometer with a separate reference arm. These measurements will then be compared to those obtained with the STM and AFM. The two main advantages of OCT technology, in comparison to the other microscopes, are speed and the ability to make a thickness measurement in transparent material. Using a Basler Sprint camera in the detection arm, 140,000 depth scans can be acquired per second. At a lateral resolution of 3 µm, an area of 1 mm^2 is imaged in 1.2s. While other techniques such as AFM and STM can image the surface of an organic solar cell, they cannot measure the layer thickness of the cell. In contrast, phase-sensitive OCT can measure the product of index of refraction and thickness with an accuracy of 50 pm.

8258-16, Session 4

Characterization of water-based thiophene polymers for organic photovoltaics

T. C. Sum, M. Kurniawan, K. F. Tai, C. H. A. Huan, Nanyang Technological Univ. (Singapore)

Organic photovoltaics (OPV) hold great promise for lowering the fabrication cost due to its ease of production, low production cost, light weight and flexibility. Devices comprising of thiophene polymers mixed with fullerene derivatives are most popular and have been extensively investigated (e.g. poly(3-hexylthiophene-2,5-diyl) (P3HT) and (6,6)-phenyl-C61 butyric acid methyl ester (PCBM)), with reported external quantum efficiencies of around 5%. In the recent years, there has been greater emphasis on the development of green technologies for renewable energy sources. It is highly desirable to replace the aromatic and halogenated aromatic solvents typically used in the fabrication of OPV devices. Nonetheless, reports on the replacement of organic solvents with water (as a solvent) in OPV devices are far and few. Usually, for a molecule to be dissolvable in water, a particular side chain is required. Herein, we report on the characterization of water-based thiophene polymers (with different side-chain length) as the active material in OPV, in particular that of the charge carrier dynamics. A comparative study between the organic solvent-based P3HT and the water-based thiophene polymers shows distinct differences in the steady state and transient absorption spectra. Transient absorption spectroscopy reveals a rapid decay of the 0-0 ground state bleaching signatures and the 650nm photo-absorption band associated with the polaron formation. Our study sheds new light on the morphology, crystallization and carrier dynamics in these materials that would be useful in aiding the design and optimization of this class of water-based photovoltaic materials.

8258-17, Session 4

White organic light-emitting diodes with ultra-thin mixed emitting layer

T. Jeon, Ecole Polytechnique (France); B. Geffroy, Ecole Polytechnique (France) and CEA (France); Y. Bonnassieux, D. Tondelier, Ecole Polytechnique (France); E. Ishow, Univ. de Nantes (France); S. V. Chenais, S. Forget, Univ. Paris 13 (France) and CNRS (France)

White light can be obtained from Organic Light Emitting Diodes by mixing three primary colors, (i.e. red, green and blue) or two complementary colors in the emissive layer. In order to improve the efficiency and stability of the devices, a host-guest system is generally used as an emitting layer. However, the color balance to obtain white light is difficult to control and optimize because the spectrum is very sensitive to doping concentration (especially when a small amount of material is used). We use here an ultra-thin mixed emitting layer (UML) deposited by thermal evaporation to fabricate white organic light emitting diodes (WOLEDs) without co-evaporation. The UML was inserted in the hole-transporting layer consisting of 4, 4'-bis[N-(1-naphtyl)-N-phenylamino]biphenyl (α-NPB) instead of using a conventional doping process. The UML was formed from a single evaporation boat containing a mixture of two dipolar starbust triarylamine molecules (fvin and fcho) presenting very similar structures and thermal properties and emitting in complementary spectral regions (orange and blue respectively) and mixed according to their weight ratio. The composition of the UML specifically allows for fine tuning of the emission color despite its very thin thickness down to 1 nm. Competitive energy transfer processes from fcho and the host interface toward fvin are key parameters to control the relative intensity between red and blue emission. White light with very good CIE 1931 color coordinate (0.34, 0.34) was obtained by simply adjusting the UML film composition.

8258-18, Session 5

Frontiers in organic semiconductor optoelectronics (Keynote Presentation)

I. D. W. Samuel, Y. Wang, G. Tsiminis, G. A. Turnbull, Univ. of St. Andrews (United Kingdom); A. McNeill, Ambicare Health Ltd. (United Kingdom); J. Ferguson, Ninewells Hospital and Medical School (United Kingdom)

The impressive progress of light-emitting organic semiconductors has led to the establishment of organic light-emitting diodes (OLEDs) as a major display technology. Furthermore, it has opened new directions for materials and devices, and exciting new applications. This presentation will focus on medical and security applications of OLEDs and organic semiconductor lasers (OSLs). One of the most promising medical applications is the use of OLEDs for skin cancer treatment. Skin cancer is a rapidly growing problem, and many skin cancers can be treated by photodynamic therapy (PDT) , in which combination of light and a photosensitiser are used to treat the lesion, avoiding the need for surgery. We have shown that bulky, cumbersome and expensive hospital based light sources for PDT can be replaced by wearable light sources. This avoids the need for a hospital visit, enables the patient to move freely during treatment and greatly reduces pain associated with PDT. OSLs are also advancing rapidly, and can now be indirectly electrically pumped by gallium nitride LEDs, providing a pathway to low cost, compact tuneable, visible lasers. An unusual and interesting application of such lasers is for sensing explosive vapours. We show that the binding of the model explosive vapour dinitrobenzene to a polyfluorene distributed feedback laser, changes the slope efficiency by a factor of three, providing a sensitive way of detecting explosive vapour. We also show that such lasers can readily be made by soft lithographic techniques.

8258-19, Session 5

Emission from strongly coupled exciton-waveguide modes in thin film organic semiconductor

T. Ellenbogen, K. Crozier, Harvard Univ. (United States)

We are studying the leaky emission from exciton polaritons (EP) excited at room temperature in semiconductor optical waveguides. Waveguide exciton polaritons (WGEP) are advantageous compared to cavity EPs since they can propagate and can be studied and directly probed at the near field through their evanescent tails. These strongly coupled waveguide modes can potentially lead to new physical studies and new devices, e.g. optically switchable interconnects.

Slab organic semiconductor waveguides are fabricated by deposition of thin polyvinyl alcohol film (~230 nm) doped with J-aggregating dyes on top of glass covered with thin silver film. The samples are pumped at room temperature by continuous wave laser diode with a wavelength of 488 nm and the leaky radiation is analyzed at the far field. Emission from the two cross polarized fundamental transverse electric and transverse magnetic WGEP modes of the system is identified and analyzed. It is shown that the momenta of the strongly coupled waveguide modes can be modified by changing the thickness of the polymer waveguide. The coupling strength of the modes is extracted by measuring the splitting in the dispersion relation of the eigenmodes of the system. The coupling strength as function of concentration of J-aggregates shows a linear relation just as it does for cavity EPs. We reconstruct the momentum space of the WGEPs and show that non-resonantly pumped excitons in the slab waveguide decay into WGEPs with radial symmetry, which leak to cones of light in free space that have radial and azimuthal polarizations.

8258-20, Session 5

Reconfigurable visible quantum dot microlasers integrated on a silicon chip

S. Mehrabani, The Univ. of Southern California (United States); H. K. Hunt, Univ. of Missouri-Columbia (United States); A. M. Armani, The Univ. of Southern California (United States)

Developing on-chip, dynamically reconfigurable visible lasers that can be integrated with additional optical and electronic components will enable adaptive optical components. In the present work, we demonstrate a reconfigurable quantum dot laser based on an integrated whispering gallery mode microcavity. The high intensity optical field present in the microcavity acts as the pump or excitation source for the quantum dot. In the present work, the microcavity is coupled to a 635nm tunable laser. Because semiconductor nanocrystal quantum dots can be excited over a wide spectral range, a single laser is able to generate emission from distinct quantum dots using only this laser.

The quantum dot is attached to the microcavity surface using a reversible, non-destructive bioconjugation process. The ability to reconfigure the device using an oxygen plasma treatment combined with the attachment of a different quantum dot has been verified. The lasing characteristics and quality factor of the fabricated devices through several rounds of attachment are measured, and minimal degradation of the optical behavior of the underlying device is observed. Additionally, fluorescence microscopy confirms that there is complete removal and replacement of the first quantum dot with the second quantum dot. It is important to note that, although this device utilizes a bioconjugation process for quantum dot attachment, the final microlaser is stable in air at room temperature. Therefore, unlike previous reconfigurable microlaser devices which relied on microfluidics to exchange gain media, this microlaser is able to operate in a wide range of environments with low pump threshold.

8258-21, Session 5

Towards the control of polarization of organic microlasers

I. Gozhyk, M. Lebental, Ecole Normale Supérieure de Cachan (France); S. Forget, S. V. Chenais, Univ. Paris 13 (France); C. Ulysse, Ctr. National de la Recherche Scientifique (France); A. Brosseau, R. Méallet-Renault, G. Clavier, R. B. Pansu, J. Zyss, Ecole Normale Supérieure de Cachan (France)

Although the phenomenon of fluorescence polarization has been thoroughly studied from many years, there are several difficulties while expanding this theory to solid-state organic lasers. Actually the theory of fluorescence anisotropy was purely linear and developed for quite a specific experimental geometry. Hence it doesn't provide all necessary information in a more general case. Taking the nonlinearities into account is also crucial while studying laser and Amplified Spontaneous Emission (ASE).

In this work we study optically pumped polymer-based lasers doped by various organic dyes in two different configurations, namely plane cavities of various shapes and vertical external cavity ("VECSOL"), and extend the fluorescence anisotropy estimation to these cases. This model allows interpreting several experimental results, like for instance the dependence of the laser threshold on the pump polarization, which illustrates the specific character of the emission anisotropy for ASE and laser and the dependence on the molecular structure of the laser dye.

A direct consequence on the lasing features is the strong influence of the pump polarization, which usually forces the emission polarization. However, we demonstrate experimentally that it is possible to release this constraint and to obtain laser emission with a polarization different from the pump one. We explore to this end the efficiency of two different mechanisms, namely the energy transfer between two different types of molecules, and the excitation through the S2 level of the dye while lasing normally appears between S1 and S0. This opens the way to new techniques to manipulate laser light polarization.

8258-22, Session 6

Photonic applications of photochromic molecules

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We present results of studies of the systems containing photochromic molecules, for all-optical switching, dynamic retrieval of optical information, and amplified spontaneous emission applications.
The systems consisted of: a) deoxyribonucleic acid doped with a different photochromic molecules like Disperse Red 1, Disperse Orange or spiropyranes, b) photochromic molecules of 4-alkyl-4-alkoxyazobenzenes with different length of substituents, showing nematic liquid crystalline properties close to the room temperature (from T =32 C).

Experiments of dynamic birefringence switching were done in Optical Kerr Effect set-up, where for the sample excitation picosecond or nanosecond pulsed lasers were used. Dynamic retrieval of optical information was realised in a typical Degenerate Two Wave Mixing experimental set-up. An excellent switching times and reversibility of the studied processes have been observed. The amplified pontaneous emission was achieved under the sample excitation by UV light pulses (355 nm) coming from pulsed Nd:YAG lasers and has been reinforced with green (532 nm) light excitation followed UV light pulse.

8258-23, Session 6

Metal and quantum dot containing patterns by two-photon lithography

P. Prabhakaran, K. K. Jang, S. Y. Park, S. Jeon, K. Lee, Hannam Univ. (Korea, Republic of); J. Park, Samsung Advanced Institute of Technology (Korea, Republic of); Y. Son, D. Yang, KAIST (Korea, Republic of)

Noble metal nanoparticles, metal oxide nanoparticles as well as quantum dots have generated much interest as components in photonic microstructures like waveguides photonic crystals and negative refractive index materials because of their high refractive indices. A gradient in refractive index is a pre-requisite for most of the above mentioned applications. Incorporating nanoparticles with high refractive indices into microstructures is an easy way to achieve such a gradient. This present many challenges due to aggregation of nanoparticles. Here we report our research involving fabrication of microstructures containing silver or quantum dot nanoparticles. Microstructures containing silver are of great interest in photonics as well as plasmonics because of the high optical nonlinearities of this material. Quantum dots are semiconducting nanocrystals that are of interest due to their highly efficient optical properties such as high fluorescence, multiple exciton generation as well as high refractive index. Two-photon lithography is a maskless technique that allows the swift fabrication of microstructures on a sub-micron scale.

8258-24, Session 6

Reversible multi-color electrofluorescence switching

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The color of the electrofluorescence switching device was tuned to white by adding extra electroactive fluorophores with different emission colors. The reversible electrochemistry of fluorophores between neutral and anion radical was accompanied by fluorescence on and off, respectively, allowing fluorescence switching. Since the fluorophores have different emission color and also different redox potential, emission color could be further modified by quenching of the particular emission with precise voltage control. A reversible multi-color switching device was prepared by packing electroactive fluorophores blend of polymer electrolyte between ITO electrodes, and its emission color was examined with various fluorophore contents and potentials.

8258-25, Session 6

Organic nanofibers from squarylium dyes: local morphology, optical, and electrical properties

F. Balzer, M. Schiek, H. Rubahn, Univ. of Southern Denmark (Denmark)

Environmentally stable, non-toxic squarylium dyes with strong absorption maxima in the red and near infrared spectral region are known for almost fifty years. Despite the fact that their optoelectronic properties distinguish them as promising materials for organics based photovoltaic cells, they have regained attention only very recently. For their application in heterojunction solar cells the nanoscopic morphology as well as nanoscopic electrical properties are paramount. In this paper thin films from two different squarylium dyes, i.e. from squarylium and from hydroxy-squarylium are investigated. The thin films are either solution casted or vacuum sublimed onto substrates such as muscovite mica, which are known to promote self-assembly into oriented, crystalline nanostructures such as nanofibers. Local characterization is performed via atomic force microscopy (AFM), Kelvin probe force microscopy (KPFM), and conductive atomic force microscopy (c-AFM) to evaluate their application potential.

8258-26, Session 6

All-printed touchless human-machine interface based on only five functional materials

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Here we demonstrate the printing of a complex smart integrated system using only five functional inks: the fluoropolymer P(VDF-TrFE) (Poly(vinylidene fluoride trifluoroethylene) sensor ink, the conductive polymer PEDOT:PSS (poly(3,4-ethylenedioxythiophene):poly(styrene sulfonic acid) ink, a conductive carbon paste, a polymeric electrolyte and SU8 for separation. The result is a touchless human-machine interface, including piezo- and pyroelectric sensor pixels (sensitive to pressure changes and impinging infrared light), transistors for impedance matching and signal conditioning, and an electrochromic display. Applications may not only emerge in human-machine interfaces, but also in transient temperature or pressure.

8258-27, Session 7

High performance photorefractive polymer composite and organic glass based on diphenylhydrazone

N. Kim, Hanyang Univ. (Korea, Republic of)

Photorefractive (PR) polymers are emerging as promising photonic materials for a variety of applications, such as holographic recording, optical data storage, telecommunications, information processing. For practical application, fast response time and long term phase stability are crucial. Here we attempted to improve these factors.

We synthesized PSX-Hz, (poly[4-(diphenylhydrazonomethyl)-phenyl]-[3-(methoxy-dimethyl-silanyl)-propyl]-methyl-amine), as a photoconductive matrix. Photorefractive polymer composite was prepared by mixing PSX-Hz with nonlinear optical chromophore (P-TH-DC), plastisizer (BBP), and TNF. This composite showed maximum diffraction efficiency of 77% and response time of 140 ms at 60V/µm with laser intensity of 60mW/cm2.

Also we synthesized a multifunctional molecule that possesses photoconductive and electro-optic properties in one molecule as a photorefractive organic glass. Diphenylhydrazone as a photoconductive moiety was covalently bound to the enamine derivative as an electro-optic chromophore via a flexible ester link. The sample prepared from a mixture of the 99 wt % of multifunctional molecule and 1 wt % of fullerene C60 showed good photorefractive properties. The 100 µm thick film showed a maximum diffraction efficiency of 69% at a low applied field of 25 V/µm.

8258-28, Session 7

Fabry-Perot resonant switch using electro-optic polymer

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An electro-optic (EO) switch based on Fabry-Perot resonator design was fabricated and tested. The switch is comprised of two high index glass substrates with indium tin oxide (ITO) coated Bragg mirrors, surrounding an electro-optic polymer layer. The ITO top layers were patterned, the electro-optic polymer, SEO100 (Soluxra Inc.), was spun coat onto each of the two Bragg substrates, and the two samples were wafer bonded. The sandwich device was then electric field poled using a field between 80 and 90 V/µm in order to induce a second-order nonlinear optical activity in the electro-optic polymer. The experimental results done at 1.13 micron laser wavelength with a drive voltage of ±200 volts yielded a modulation depth of around 85% and 80% for frequencies of 1kHz and 10kHz, respectively. Operations at higher frequencies up to 1 MHz will be presented.

8258-29, Session 7

Organic single crystalline electro-optic films for hybrid integration with silicon photonic wires

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The functionality of photonic integrated circuits, for example those based on silicon photonics, will benefit significantly if active materials for light generation, detection and modulation can be integrated with otherwise passive structures. For example, electro-optic poled polymers have already shown a great potential in terms of reducing the half-wave voltages and increasing the modulation speed beyond 100 GHz, well beyond the limits of inorganic $LiNbO_3$ or silicon modulators. Organic electro-optic crystalline materials offer similar benefits as poled polymers with a considerably improved thermal and photochemical stability and do not need complex electric-field poling procedures. An epitaxial-like growth process of organic electro-optic crystals could therefore lead to a novel type of highly efficient, ultrafast and stable hybrid structures for photonics.

We developed new techniques for the deposition of single-crystalline electro-optic organic thin films on inorganic substrates based on various organic materials, e.g. OH1 (2-(3-(4-hydroxystyryl)-5,5-dimethylcyclohex-2-enylidene)malononitrile). OH1 is a new organic material with very high electro-optic figures of merit, n^3r = 530 pm/V at 1319 nm, as well as a high thermal stability allowing for both solution and melt-based processing. We developed epitaxial-like crystal deposition techniques that allow fabrication of OH1 single-crystalline films of more than 1 cm^2 area and 50-4000 nm thicknesses on various structured substrates. Electro-optic modulation has been demonstrated in silicon-on-insulator (SOI) waveguides, functionalized by single crystalline OH1 grown directly on top of the silicon structures. By using melt growth in pre-fabricated micro- and nano-size structures, organic electro-optic single crystalline Mach-Zehnder and microring modulators have been also demonstrated.

8258-30, Session 7

Solution phase assisted reorientation of chromophores: a modern approach to electro optic materials processing

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Organic electro optic materials offer much higher non-linear properties than traditional crystalline materials. This makes these materials a promising avenue for future high bandwidth, low power consumption, electro optic modulators. These materials however, generally come with some fabrication tradeoffs. Besides the usual fabrication steps required to create a photonic integrated circuit, organic electro optic materials require an additional step known as poling, where the chromophores are reoriented through the application of a high electric field. The application of this field can be accomplished in two different manners; contact poling and corona poling. This effort will focus on corona poling, where a gas is ionized and the electric field across the sample is applied through the relocation of these charged ions. Traditionally both styles of poling require raising the temperature of the organic material to around the glass transition temperature of the host polymer, in order to allow mobility of the chromophores so that they may reorient themselves with the applied electric field. The proposed technique avoids this by applying the electric field while the material is in its solution phase. We accomplish this by applying the field while using a spin processor to deposit the solution. This technique offers the advantage that it is easily scaled up to a wafer scale process. Also as the spin processing occurs in an inert highly controllable environment, the need to perform these techniques in the traditional clean room setting, required by standard techniques is avoided.

8258-31, Session 8

Advances in third-order nonlinear optical materials (Keynote Presentation)

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In this presentation we will discuss recent advances in the design, synthesis, characterization and application of molecules with large real and imaginary third-order optical nonlinearities, focusing on how variation in chemical structure relates to the observed nonlinearities.

8258-32, Session 8

Nonlinear absorption and nonlinear refraction: maximizing the merit factors

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Both nonlinear absorption and nonlinear refraction are effects, which are potentially useful for a plethora of applications in photonics, nanophotonics and biophotonics. Despite substantial attention given to these phenomena by researchers studying the merits of disparate systems like organic materials, hybrid materials, metal containing molecules and nanostructures, it is virtually impossible to compare the results obtained on different materials with various parameters of the employed light beams and using different techniques. We attempt to address the problem by studying the properties of various systems in a systematic way, within a wide range of wavelengths, including the regions of one-photon, two-photon and three-photon absorption.

The objects of our studies have been typical nonlinear chromophores, like π-conjugated molecules, oligomers and polymers, organometallics and coordination complexes containing transition metals, organometallic dendrimers, small metal-containing clusters, and nanoparticles of various kinds, including semiconductor quantum dots, plasmonic particles and rare-earth doped nanocrystals. We discuss ways of quantifying the nonlinear response of all of these systems, by defining and comparing the merit factors relevant for various applications.

8258-33, Session 8

In vivo polarization-resolved second harmonic generation imaging of collagenous tissues

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Second harmonic generation (SHG) microscopy enables specific and contrasted visualization of unstained collagenous tissues such as tendons or corneas. We implemented polarization-resolved SHG measurements to measure the fibrils orientation within collagenous tissues and the ratio of the main second order nonlinear tensorial components. Distortion of the polarimetric response due to birefringence and diattenuation during propagation of the laser excitation and to polarization scrambling in the SHG detection was observed in rat-tail tendons. We developed a model to account for these effects and to correct them in thick anisotropic tissues. We then studied human corneas that are composed of very small collagen fibrils organised in 2-3 µm thick stacked lamellae. Orientation maps obtained from polarization-resolved trans-detected SHG signals are in good agreement with the micrometric striated features observed in the raw images. Most importantly, polarization analysis of the epi-detected SHG signals also enables to map the fibrils orientation within the collagen lamellae while epi-detected SHG images of corneal stroma are spatially homogenous and do not enable direct visualization of the fibrils orientation. We also calculated depth profiles of the polarimetric SHG response and consistently modelled their variations considering orientation changes of the collagen lamellae within the focal volume. Finally, we performed in vivo polarization-resolved SHG in rat corneas and determined structural organization of corneal stroma using epi-detected signals. To conclude, polarization-resolved SHG is a new modality that can be used for in vivo quantitative epi-imaging of collagenous organizations in tissues. Our study therefore opens great opportunities for biomedical studies.

8258-34, Session 8

Proposal of cyano-group containing polymers as new host materials of the NLO polymers

A. Sugita, Y. Tamaki, N. Mase, Y. Kawata, S. Tasaka, Shizuoka Univ. (Japan)

Here, we will propose poly (cyano phenylene sulfide) (PCPS), the polymers consisting of poly (phenylene sulfide) substituted with cyano groups, as novel host materials of nonlinear optical (NLO) polymers. Our previous studies exhibited that some of the amorphous polymers with cyano groups self-organized non-centrosymmetric structures just by depositing on metal surfaces. Taking advantage of these unique polarization self-organization properties, second-order NLO susceptibilities may be obtained without conventional poling procedures. In the present study, the second-order NLO susceptibilities were examined for the thin films of the PCPS doped with disperse red 1 (DR1), one of the most well-known NLO chromophores. The measurement of second harmonic (SH) signals were conducted for the 10w%-DR1 doped PCPS thin films deposited on the glass substrates coated with Au thin layers. The SH signals appeared from the samples annealed at the temperatures higher than the glass transition points of the PCPS. The polar order were determined from the excitation beam polarization dependences of the SH signal. The polar order was expressed as a function of the film thickness and the annealing temperatures. The optimized annealing temperatures for the NLO susceptibilities was 120 ºC, the temperatures by 20 ºC higher than the glass transition points. On the other hand, the polar order was the largest at 1 microm film thickness. With an aid of lithographic nano- or micro-patterning techniques, we may prepare the one-dimensionally or two-dimensionally periodically-poled structures in the materials for the second-order NLO active photonic crystal pretty easily.

8258-09, Session 9

Additional donor modification by oxy groups for strengthening electro-optic response of molecules

A. Otomo, T. Yamada, National Institute of Information and Communications Technology (Japan)

The electro-optic (EO) effect is one of the second order nonlinear optical effects, and it is used for high-speed optical modulation and switching in laser systems and optical communication network. Organic EO devices are expected to have large modulation bandwidth exceeding 100 GHz, due to the low dielectric constant of the organic material. The basic structure of the organic EO molecule is a donor (D) - conjugate bridge (π) - acceptor (A) structure which expresses a large hyperpolarizability β. Two decades of research and development in the EO molecules has found out effectiveπ-conjugate structures such as the phenyl vinylene thiophene vinylene structure and acceptors such as tricyanofuran (TCF) derivatives improving hundredfold total. However, the donor structure has not shown dramatic progress and variations from the amino group. We have found that the hyperpolarizability improves by almost twice by introducing several substituted oxy groups such as methoxy group etc. at the ortho-position of the phenyl on the donor side. We have further investigated the dependence of the effect on several π-conjugate structures.

8258-35, Session 9

EO-polymer waveguide based high dynamic range EM wave sensors

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Electro-magnetic (EM) wave measurement has played a crucial role in various scientific and technical areas, including process control, E-field monitoring in medical apparatuses, ballistic control, electromagnetic compatibility measurements, microwave-integrated circuit testing, and detection of directional energy weapon attack. Conventional EM wave measurement systems use active metallic probes, which can disturb the EM waves to be measured and make the sensor very sensitive to electromagnetic noises. Photonic E-field sensors exhibit significant advantages compared to their electronic counterpart due to their smaller size, lighter weight, higher sensitivity and extremely broad bandwidth. Because of these exclusive merits, photonic E-field sensors based on integrated optical devices and optical fibers have emerged in the last ten years. These photonic E-field sensors using Mach-Zehnder (MZ) interferometers or ring resonators, however, offer very limited spurious free dynamic range (SFDR) that are not capable of high fidelity measurement of the EM waves.

In this paper, we present the design and experimental demonstration of a high dynamic range E-field sensor based on electro-optic (EO) polymer directional coupler waveguides that leverages the strong and ultra-fast EO response of EO polymer. As compared to conventional photonic E-field sensors, our directional coupler waveguide design offers several advantages such as bias-free operation, highly linear measurement response up to 70dB, and an high electric field detection range from 16.7V/m to 750KV/m at a frequency of 1GHz. Further investigations on sensitivity enhancement using EO polymer infiltrated slotted photonic crystal waveguide will also be discussed.

8258-36, Session 9

Two-photon absorption of the nonlinear optical chromophore/polymer on SiN slot waveguide

S. Yokoyama, F. Yu, K. Yamamoto, Kyushu Univ. (Japan)

We fabricated a 100 nm-scale slot waveguide of SiN/SiO2. The waveguide was covered with the nonlinear optical chromophore/polymer film in order to demonstrate the enhanced two-photon absorption of the chromophore due to the strong field confinement of the light in the slot. The optical slot waveguide devices have recently attracted attention because of the field confinement in the region of a low index material embedded between two high index material wires. Generally, a slot waveguide consists of two strips of a high-index material separated by a subwavelength low-index (slot) region. Because of the electric-field discontinuity at the interface between high-index-contrast materials, enhanced electromagnetic field is generated in the slot low index region. Although Si/SiO2/Si (SOI) films have been widely used for the Si slot applications, use of SiN film is the another challenge for the fabrication of slot-polymer optical hybrid having the large optical gain such as nonlinear optical polymers. In this study, we designed and fabricated the slot waveguides of SiN/SiO2 covered with the chromophore/polymer thin film, and measured enhanced fluorescence through the two-photon absorption. Obtained two-photon induced fluorescence showed significant dependence on the polarization of excited laser at 730 nm with the pulse width of 100 fsec. The TE mode excitation resulted in the much stronger two-photon fluorescence than the TM mode excitation. Observation is consistent with the theoretical prediction that the TM mode produces a strong confinement of the field due to the light guided in the SiN wire cores.

8258-38, Session 9

Design and characterization of poly(styrene)-based GI-POF with high bandwidth and high thermal stability for home networks

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PMMA-based graded index plastic optical fiber (GI-POF) has too high attenuation to be utilized at a wavelength of light source (670-680 nm) for home networks. On the other hand, it has been reported that poly(styrene) (PSt) based step index POF (SI-POF) prepared by the extrusion process had low attenuation at 672 nm. Although PSt is one of the most promising base materials of POF, few studies of PSt-based GI-POF have been reported. In this study, therefore, we investigated PSt-based GI-POF having high thermal stability, high bandwidth and low transmission loss for home networks. In study of PSt-based GI-POF, maintaining thermal stability is an important problem. In home networks, the thermal stability of POF would be required over 65 oC, which corresponds to a glass transition temperature (Tg) of approximately 85 oC. The Tg of PSt is about 100 oC, however, the Tg of PSt doped with conventional dopant, diphenylsulfide (DPS), becomes about 55 oC by plasticization. Therefore, we adopted a novel dopant having small plasticization to fabricate PSt-based GI-POF with the required thermal stability for home networks.

In this study, we investigated 9-bromophenentherene (BPT) and dibenzothiophene (DBT) having higher refractive indices than DPS as new dopants. Thus, amount of additive dopants can be reduced, resulting in maintaining high Tg and improving plasticization. From the results, BPT and DBT are adequate dopants of the GI-POF for home networks. We demonstrated that the GI-POF doped with DBT satisfied the requirements of bandwidth, thermal stability and transmission loss for home networks.

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8258-39, Session 10

Photopolymer-based three-dimensional optical waveguide devices

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Photopolymer based three-dimensional (3D) waveguide devices are very attractive in low-cost optical system integration. Especially, Light-Induced Self-Written (LISW) technology is suitable for this application, and the technology enables low-loss 3D optical circuitry formation from an optical fiber tip soaked in photopolymer solution employing its photo-polymerization by irradiation from the optical fiber. This technology is expected drastic mounting cost reduction in fields of micro-optic transceiver module assembly and hybrid integration devices formation. The principle of the LISW optical waveguides is self-trapping effect of the irradiation flux into the self-organized waveguide, where, used wavelength can be chosen to fit photopolymer's reactivity from visible to infrared. Furthermore, the effect also makes possible "optical solder" effect which realizes a passive optical interconnection between two faceted fibers or devices by the LISW waveguide even if there is a certain amount of gap and a small degree of misalignment exist. The LISW waveguides grow towards each other from both sides to a central point where the opposing beams overlap and are then combined into one waveguide. This distinctive effect is confirmed in all kind optical fibers, such as from a singlemode to 1-mm-core-diameter multimode optical fiber. For example of complicated WDM optical transceiver module, mounted a branched-waveguide and filter elements, effectiveness of LISW technology is outstanding. In assembling and packaging process, neither dicing nor polishing is needed. In this paper, we introduce LISW technology principles and potential application to integrated WDM optical transceiver devices for both of singlemode and multimode system developed in our research group.

8258-40, Session 10

Fabrication of low loss binary amorphous copolymers for graded-index plastic optical fiber

T. Araki, S. Nishino, T. Kado, K. Koike, A. Kondo, Y. Koike, Keio Univ. (Japan)

Graded-index plastic optical fiber (GI POF) has been expected as a high-speed communication medium for many applications such as home networks, in-vehicle networks, medical uses, etc. Since different properties are required for each application, varieties of materials with different properties are needed to be prepared.

Copolymers have the appearance of being the candidate materials of GI POF, since most of the properties can be controlled by copolymerizing. However, copolymers have not been adopted as GI POF materials, because copolymers tend to have extremely high scattering losses due to the optical heterogeneities caused by composition distributions, which is described in Debye's theory.

In this study, we have proposed two methods to obtain transparent copolymers as a result of comprehensive study on the light scattering properties of binary amorphous copolymers. One of the two methods is to use a pair of monomers with comparable refractive indices, and the other is to use a pair of monomers which forms narrow composition distributions. These methods were confirmed by analyses of light scattering properties of MMA-co-PFPhMA and MMA-co-BzMA, each satisfies the above two conditions. The total light scattering losses of the two copolymers were both 35 dB/km, which was comparable with those of homopolymers. From these results, it was clarified that the methods are effective to obtain copolymers with sufficient transparency for GI POF.

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8258-41, Session 10

Critical angle in fluorescent polymer optical fibers

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With the development of plastic optical fibers (POFs) in the last year, increased research activities have also been carried out in the field of active POF amplifiers and lasers. POF amplifiers that generate signal light in the visible and near-infrared are potentially important because of their adaptability for POF-based short span optical local distribution networks. Amplifiers with high gain and efficient lasers have been obtained with organic dye-doped POFs. Conjugated polymers and related materials are being actively investigated as active dopants in plastic optical fibers (POFs) to provide amplification and switching capability]. Because of their large gain cross sections and little concentration quenching they are the ideal candidates for the manufacture of active media in POF networks. On the other hand, the transmission of radiation beams through optical fibers in a stable and uniform manner is a critical requirement in many laser and sensor applications.

The aim of this work is to analyze the propagation of the emitted light in fluorescent POFs by using the side-illumination technique. In particular, we have studied the angular distribution of the emitted light as a function of the launching angle, the height of the incident beam, and the propagation distance. A theoretical modeling has been developed in order to explain the experimental measurements. A good agreement between the theoretical and the experimental results has been obtained both qualitatively and quantitatively. Simple expressions for the maximum angle of acceptance (critical angle) have been derived in some particular cases. The study has been performed in POF samples doped with two different conjugated polymers.

8258-42, Session 10

On-chip sensing of volatile organic compounds in water by hybrid polymer and silicon photonic-crystal slot-waveguide devices

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We experimentally demonstrate a silicon photonic crystal slot waveguide near infrared absorption spectrometer that enables the simultaneous and specific detection and identification of volatile organic compounds in water. The unique dispersive properties of two dimensional photonic crystal devices that enable confinement and manipulation of light on length scales of the optical wavelength, together with unique optical, structural and chemical properties of polymers, have generated the prospect of chip scale miniaturized nanophotonic devices in diverse organic-inorganic hybrid applications in optical interconnects and sensing. On chip absorption spectroscopy governed by the Beer Lambert absorption law is enabled by the enhanced optical absorption path length due to the combined effects of slow light in photonic crystal waveguides and enhanced optical interaction with the analyte in the low index slot at the center of the photonic crystal waveguide. The slot infiltrated PDMS sensing phase enables determination of absorption spectrum of volatile organic compounds independent of the strong near infrared absorption signatures of water. Two compounds, xylene and toluene, will be specifically identified simultaneously with high sensitivity and selectivity, by near infrared absorption signatures in a chip-integrated device.
We have demonstrated on chip sensing by near infrared absorption signatures in a 300 micron long photonic crystal slot waveguide that enabled the detection of 100ppb xylene in water that is five times more sensitive on an order of magnitude smaller length scale. Integration with PTMSP will be investigated for higher sensitivity in addition to packaging with optical fibers for remote monitoring.

8258-43, Session 11

Quickly updatable hologram images with high performance photorefractive polymer composites

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We present here quickly updatable hologram images using high performance photorefractive (PR) polymer composites based on poly(N-vinyl carbazole) (PVCz). PVCz is one of the pioneer materials for photoconductive polymer. PVCz/7-DCST/CzEPA/TNF (44/35/20/1 by wt) gives high diffraction efficiency of 70 % with fast response speed. Response speed of optical diffraction is the key parameter for real-time 3D holographic display. Key parameter for obtaining quickly updatable hologram images is to control the glass transition temperature lower enough to enhance chromophore orientation. Object image of the reflected coin surface recorded with reference beam at 532 nm (green beam) in the PR polymer composite is simultaneously reconstructed using a red probe beam at 642 nm. Instead of using coin object, object image projected on the spatial light modulator (SLM) from the computer is used as object for holograms. SLM is convenient because it provides both amplitude modulation and phase modulation modes. Reflected object beam from a 1920 ×1200 Holoeye LCR-1080 SLM interfered with reference beam on PR polymer composite to record a hologram and simultaneously reconstructed by a red probe beam. Movie on a computer screen and a SLM was recorded as a real-time hologram in the PR polymer composites and simultaneously clearly reconstructed. To the best our knowledge, this is the first time of real-time hologram recording and simultaneous reconstruction using organic PR polymer composite.

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8258-44, Session 11

Grating couplers in polymer with a thin Si3N4 layer embedded

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Polymer has been considered to be an ideal material option for integrated photonics devices, with which many different kinds of devices with good optical properties have been fabricated. The advantages of the polymer material platform are as follows. First, the cost of the material itself is very low, which makes it attractive where the economic factor needs to be taken into account. Second, many special characteristics such as nonlinearity or amplification can be obtained with proper synthesizing. Moreover, besides the traditional semiconductor process methods, polymer is also compatible with many novel fabrication techniques like soft lithography or nanoimprint lithography. The latter methods have lots of merits such as minimal requirements for complicated equipments, simple fabrication processes involved, and a huge potential for high throughput.

However, the coupling problem between the single mode fiber and polymer waveguide exists. Normally the route of horizontal coupling is chosen in order to couple the light into or out of the polymer waveguide, in which case a good waveguide facet is required. Another drawback is the small tolerance on the alignment. In this paper, we propose a surface grating coupler implemented in polymer platform. Rather than expensive CMOS fabrication, the device is fabricated through a simple UV based soft imprint technique utilizing self-developed low loss polymer material. The coupling efficiency is enhanced by embedding a thin Si3N4 layer between the waveguide core and the cladding layer. Around -22dB insertion loss (fiber to fiber) is obtained for a straight waveguide with a grating coupler at each end, which means the proposed grating coupler has a coupling efficiency of around 10%. The 3dB bandwidth is 32nm centered at 1550nm. Further improvement is being carried out. Above 25% of the coupling efficiency is expected.

8258-37, Poster Session

Development of fibre Bragg grating based strain/temperature sensing system

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Advances in photosensitivity lead to the development of fibre Bragg grating (FBG) sensors that have a wide variety of applications including monitoring of civil structures, smart manufacturing and non-destructive testing, remote sensing, as well as traditional strain, pressure and temperature sensing. This type of sensor has many benefits such as small size, extremely low sensitivity to electromagnetic interference, good resistance to corrosion, large capacity for multiplexing, high temperature capacity, long working lifetime, excellent sensitivity to strain and temperature and the signal is wavelength encoded.

A strain sensing system is being developed for quazi-distributed strain sensing in locations and environments that are not accessible to conventional strain sensors. [1] The system comprises an Optical Interrogator that has been designed and constructed by Southern Photonics [2], and optical fibre coupled Bragg grating strain sensors. It has been tested using commercial fibre Bragg gratings [3] that were attached to 316 stainless steel test samples and cycled in strain and temperature using an Instron mechanical testing machine and temperature controlled cabinet. The results have been compared to the performance of conventional electrical resistance strain gauges. Pairs of fibre Bragg gratings were simultaneously interrogated at 1535 and 1550 nm centre wavelengths to demonstrate the ability of the system to use multiple sensors for quazi-distributed sensing.

Conventional fibre Bragg gratings are ideally designed for the measurement of the strain magnitude. However, there are applications where the strain tensor is also required. Furthermore, strain sensors are also needed for strain measurements at high temperatures. For these reasons we have been researching new materials and methods for strain tensor and high temperature strain measurements. In this report we discuss our optics-based strain sensing system as well as our progress towards the development of new strain sensors for the measurement of the strain tensor as well as for high temperature applications.

8258-45, Poster Session

Picosecond polarization spectroscopy of fluorescein attached to different molecular volume polymer influenced by rotational motion

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Time-resolved fluorescence spectroscopy of fluorescein dye-labeled polymers chain of molecular volume ranging of ~410 angstrom3 to ~5000 angstrom3 at two polarization directions, parallel and perpendicular to that of the linearly polarized exciting light, were measured. It was observed in all measurements that the decay rate of the fluorescence component polarized parallel to the exciting beam is faster than that of the fluorescence component perpendicular to the excitation.

A theoretical fluorescence depolarization model developed by G. Weber was extended from micro-second to pico-second regimes to investigate and demonstrate the origin of the different decay rate of the two fluorescence components. This model describe the time-resolved fluorescence dynamics of fluorescein-polymer using a system the linear differential equations containing two main parameters: the decay rate of emission and the rate of one orthogonal emission component transferring to another. Experimental tests of this theory were verified by measuring the time-resolved parallel and perpendicular components of the fluorescence emission using streak camera optical multi-channel detections. Both experimental observation and theoretical calculation conclude that the fluorescent molecular rotation is the cause of the depolarization. The dipole's rotational time was extracted and shows increasing with the molecular volume obeying the Einstein-Stokes relation. Optical images of objects containing varying molecular volume fluorescein-polymers embedded inside turbid media were investigated. The results demonstrate that larger volume dye-polymer can be used to enhance the imaging depth and visibility of objects hidden inside scattering media and tissues.

8258-46, Poster Session

A photo-aligned self-assembled monolayer for polymer transistors

T. Kawaguchi, T. Okura, Y. Suenaga, T. Hanasaki, I. Fujieda, Ritsumeikan Univ. (Japan)

There is a continuing interest in improving electrical characteristics of an organic thin-film transistor (OTFT). One can accomplish this by controlling molecular orientations of semiconductor materials in the vicinities of an insulating layer as well as an electrode material. First, it is widely known that a self-assembled monolayer (SAM) is effective for this purpose. Second, a thin structured layer underneath an organic semiconductor material is effective for aligning the organic molecules in a specific direction. Irradiating azobenzene compounds with ultraviolet light converts trans isomers into cis-forms. When exposed to linearly-polarized ultraviolet light, the difference in the absorbance between the two isomers leads to a state where the azobenzene molecules are aligned perpendicular to the polarization direction of the ultraviolet light. Such a photo-alignment layer results in anisotropic charge transport in an OTFT and the current flow along the channel direction is enhanced. In principle, we expect that combination of these two technologies (SAM and photo-alignment) would further improve the current flow in OTFTs. In experiment, we synthesized a compound 4-(3-(trichlorosilyl)propoxy) azobenzene (Azo-SAM) and used this material to align an organic semiconductor poly(3-hexylthiophene) (P3HT). We formed the Azo-SAM on a glass substrate, spin-coated a P3HT/1, 2, 4-trichlorobenzene solution, annealed in nitrogen atmosphere and exposed it to linearly-polarized ultraviolet light. Absorbance spectroscopy in the visible range revealed anisotropy in the two samples exposed to the two polarization directions orthogonal to each other. Fabrication of organic transistors with this photo-alignment SAM is under way.

8258-47, Poster Session

Vibration-induced mobility enhancement for a polymer transistor

Y. Kondo, T. Hiraki, Y. Suenaga, T. Hanasaki, I. Fujieda, Ritsumeikan Univ. (Japan)

Charge transport in an organic thin-film transistor (OTFT) is controlled by many factors such as molecular packing in the semiconductor material and the contact property at the source/drain electrode. One approach utilizes an alignment layer to influence the molecular packing. Charge transport becomes anisotropic. However, additional processes are required to form such a structured layer. Solution processes offer more pathways in influencing the molecular packing. These include the use of solvent mixtures for adjusting the evaporation-induced flows, the temperature gradient in molten materials, drop-casting on tilted substrates, and other flow-induced processes. Common to these approaches is the fact that some forms of forces introduce directionality in semiconductor materials. Here, we propose to agitate organic molecules in a solution by applying ultrasound vibrations during the solvent evaporation. The vibration would translate and rotate the molecules and this might introduce ordering in the organic layer when the solvent evaporation is completed. In experiment, we fabricated bottom-contact polymer transistors by dispensing a poly(3-hexylthiophene)/1,2,4-trichlorobenzene solution on a substrate and subsequently drying it in a container immersed in an ultrasound bath. The average field effect mobility of the transistors prepared from a 0.1wt% solution with 30-min ultrasound vibration was 2.5 times higher than that of the control devices prepared without the vibration. We attribute this result to enhanced ordering of the P3HT molecules in the vibrated solution. Atomic-force microscope observation revealed longer polymer chains for the samples prepared with the vibration. We attribute this mobility enhancement to changes in molecular packing during the solvent evaporation.

8258-48, Poster Session

Ultrafast nonlinear optical studies of 3,8,13,18-Tetrachloro-2,7,12,17-tetramethoxyporphyrin and its derivatives

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Recently we synthesised 3,8,13,18-tetrachloro-2,7,12,17-tetramethoxyporphyrin and its metallo-derivatives.1 The free-base molecule is unique owing to the presence of an electron donating methoxy and electron withdrawing chloro group on the adjacent β-positions of each pyrrole moiety. We could synthesize these molecules through two different routes; the first route provided pure isomer, albeit in low yield, whereas the second route provided mixture of isomers with higher yield. Here we report the third-order nonlinear optical properties of these porphyrins obtained from the open-aperture and closed-aperture Z-scan measurements using ~40 fs, 800 nm pulses. We have compared the data of the pure isomer with that of the mixture of isomers. Nonlinear optical coefficients were evaluated in both the cases.

8258-49, Poster Session

Femtosecond and picosecond nonlinear optical studies of Corroles

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We present our results on the femtosecond (fs) and picosecond (ps) nonlinearities in two novel Corroles (a) Tritolyl Corrole (TTC) and (b) Triphenyl Corrole (TPC) studied using the Z-scan technique. Both open and closure aperture Z-scan curves were recorded with ~40 fs and ~2 ps laser pulses at same wavelength of 800 nm and the nonlinear optical coefficients were extracted from both the studies. Picosecond open aperture data clearly suggested complicated nonlinear absorption with the presence of three photon absorption (3PA) at higher peak intensities and switching behavior (from SA to RSA) at lower peak intensities for both the molecules. Femtosecond nonlinear absorption data of both the samples (TPC&TTC) demonstrated the behavior of saturable absorption (SA). Solvent contribution to the nonlinearity was also identified in the fs case. We discuss the nonlinear optical performance of these organic molecules.

8258-50, Poster Session

The effect of intramolecular charge transfer via biphenyl group on the optoelectronic properties of red fluorophore

N. R. Park, G. Y. Ryu, D. M. Shin, Hongik Univ. (Korea, Republic of)

A new red fluorescent material, (2Z,2'Z)-3,3'-[4,4"-bis(dimethylamino)-1,1':4',1"-terphenyl-2',5'-diyl]bis[2-(pentafluorophenyl)acrylonitrile] (ABCV-PFP) for organic light-emitting diodes (OLEDs) was synthesized. To verify the effect of intramolecular charge transfer (ICT), UV-visible absorption and photoluminescence (PL) emission spectra of ABCV-PFP were measured with the variation of solvent polarity (n-hexane, n-hexane/chloroform = 1/1; chloroform; methylene chloride). The absorption peaks of ABCV-PFP were measured to be 330 (methylene chloride), 331 (chloroform), 328 (n-hexane/chloroform = 1/1) and 323 nm (n-hexane), respectively. PL emission spectra of ABCV-PFP were peaked at 645 (methylene chloride), 639 (chloroform), 609 (n-hexane/chloroform = 1/1) and 556 nm (n-hexane), respectively.

UV-visible and PL emission spectra measured in various solvents showed large Stokes shifts. The UV-visible absorption maxima of ABCV-PFP showed small red shifts with increasing solvent polarity. This can be interpreted as that dipolemoment of the ABCV-PFP molecule in ground state is very small. Unlike the UV-visible absorption spectra, PL emission spectra showed strong solvatochromic red shifts with increasing solvent polarity. Strong positive solvatochromism of PL emission spectra of ABCV-PFP supported that ABCV-PFP molecule has a large molecular dipolemoment in its excited state which is ascribed to the molecular structure of ABCV-PFP in excited state caused by ICT between electron donating dimethylamino group attached to the biphenyl group and electron accepting moiety in the molecule. UV-visible absorption and PL emission peaks of ABCV-PFP thin film spin-coated on quartz were measured to be 342 nm and 648 nm, respectively, which showed bathochromic shift compared to those of solution and this is due to the aggregation of molecules in solid state.

8258-51, Poster Session

Influence of the polymer processing conditions on the performance of bulk heterojunction solar cells

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Polymer solar cells have exhibited improved efficiency in recent years, and they attracting increasing attention as a possible low cost alternative to inorganic solar cells. Poly(3-hexylthiophene) (P3HT):[6,6]-phenyl C61-butyric acid methyl ester (PCBM) is a commonly used material combination in polymer bulk heterojunction solar cells. However, reported efficiencies of these cells in the literature exhibit considerable variation. Here we performed a systematic study of the effect of processing conditions on the performance of P3HT:PCBM solar cells. We have investigated the influence of the source material (P3HT and PCBM from different suppliers), solution preparation (stirring vs. sonication), solution concentration, solvent used, additives (such as 1,8-octanedithiol), pre-formation of P3HT nanowires, and annealing on the device performance and/or morphology and phase separation in the active layer. Furthermore, the influence of spin-coating PCBM on top of P3HT and PCBM on top of the P3HT:PCBM layer has been investigated (with and without annealing). We found that all of these factors affect the performance of the solar cells, although there are several alternative methods which can result in similar improvements of the performance. We found that the improvement trends for various procedures (additives, PCBM top layer, P3HT nanowires, etc.) are similar, and that the main determinant factor in the obtainable efficiency is the solution preparation and the source material. Obtained results and the implications on further improvement of solar cell performance are discussed in detail.

8258-52, Poster Session

Dependence on molecular stacking orientation of open-circuit voltage in organic solar cell based on pentacene and its derivatives

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Molecular stacking orientation-dependent organic heterojunction photovoltaic cells that are based on pentacene and its derivatives are fabricated. Two functionalized forms of pentacene - 6,13-dipheynl-pentacene (DP-Penta) and 6,13-Di-bipheynl-4-yl-pentacene (DB-Penta) - are used. Different molecular stacking orientations of the pentacene-derivatives are identified by angle dependent near-edge X-ray absorption fine structure (NEXAFS) measurements. Pentacene molecules stand up on the PEDOT:PSS surface, and the functionalized pentacene molecules lie down on the surface upon the addition of extra orthogonal phenyl rings. The functionalized pentacene OPV cells have almost triple the VOC of a conventional device that is based on pentacene/C60 cells (0.28 V vs. 0.83 V). This result can be attributed to the fact that lying down molecular stacking orientation of functionalized pentacene induced the vacuum level (V. L.) shift, and improved the VOC of the devices. This approach has important implications for organic electronic devices that comprise multiple organic layers, and particularly for improving the power conversion efficiency of organic photovoltaic cells.

8258-53, Poster Session

Vertical external cavity surface-emitting organic lasers: a dynamical laser modeling towards optimized performance

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Organic lasers offer the promise to build compact, inexpensive, broadly tunable solid-state lasers in the visible range, with potential applications in spectroscopy, bio/chemo sensing or short-haul data telecommunications. Among existing laser architectures of optically-pumped organic lasers, external-cavity resonators enable the highest conversion efficiencies, excellent beam quality, power scalability and versatility due to the open cavity. Recently, we reported on an open-cavity laser architecture using a thin film of dye-doped polymer as the gain medium, named Vertical External Cavity Surface-emitting Organic Laser (VECSOL). The laser architecture consists of a highly-reflective plane mirror onto which a film of PMMA doped with e.g. Rhodamine 640 was directly deposited by spin coating. A remote output coupler closed the cavity; under pumping by a frequency-doubled Nd:YAG laser at 532 nm (10 Hz, 7 ns), a record conversion efficiency of 57% was achieved at 620 nm. In this paper we provide a full description of the laser dynamics, using Statz-deMars coupled rate equations, and compare the numerical simulations to experimental data. The simulations account very well for the observed drop of efficiency with cavity length, for instance, which is shown to be the result of a pulse buildup time being of the same order of magnitude as the photon lifetime in the cavity. The pump pulse duration is also a key parameter: a pulse longer than the oscillation buildup time (~a few ns) is required to ensure good efficiency. The laser spectrum, beam quality, polarization as well as photodegradation issues will also be discussed.

8258-54, Poster Session

Multi high-order anisotropic self-diffraction in Cerium doped BaTiO3 crystal

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Higher-order anisotropic self-diffraction up to third orders have been observed in Cerium doped barium titanate (Ce:BaTiO3) by two-wave coupling using red beam at 633 nm from He-Ne laser. In our experiment, the third orders and second orders have been observed simultaneously for the first time from our knowledge. From our observation, the phase conjugate beam has not been generated before and after the appearance of higher orders as observing when the green beam from the Argon-ion laser at 514.5 nm has been used. In the red light case, due to the early appearance of the grating of higher order and their high diffraction efficiency, there is no light power enough to generate phase conjugate beam. By comparing between the green light and red light cases, the grating of phase conjugate beam can be destroyed by the generation of higher order beams grating, however the grating of the higher order beams are not affected by the generation of the phase conjugate beam respectively. Finally, the satisfied diffraction efficiency and the decay rate of the grating have been measured as well in the red light case.

8258-55, Poster Session

Fabrication of electronic device based on photonic gel films

S. W. Lee, D. M. Shin, Hongik Univ. (Korea, Republic of)

Block copolymers have been investigated for fabricating functional nanomaterials due to their properties of self-assembly. We prepared polystyrene-b-poly(2-vinyl pyridine) (PS-b-P2VP) lamellar films which is hydrophobic block-hydrophilic polyelectrolyte block polymer have 57 kg/mol-b-57 kg/mol. The lamellar stacks are obtained by exposing the spin coated film under chloroform. The P2VP blocks were then quaternized and crosslinked to various extents using 5wt% of iodomethane.The band gaps of the lamellar films were drastically shifted to longer wave length as increasing concentration of calcium hydroxide solution. The band gaps of the lamellar films were drastically shifted to longer wave length as increasing concentration of calcium hydroxide solution.

This study shows that the low driving voltage and good durability which make them potentially useful in information techniligies.

8258-57, Poster Session

Efficient configuration transition in a new azobenzene-LC polymer for updatable hologram

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Recently, updatable hologram has attracted significant attention owing to their potential applications in real-time holographic display and telemonitoring. Up to date, no holographic materials are ideal for updatable recording. Commercial photopolymers have high diffraction efficiency and photo-sensitivity, but lack the capability of image-updating. Photorefractive polymers are widely used in dynamic holographic recording, and have been shown to achieve a quasi-real-time dynamic 3D display when combined with holographic stereographic technique. However a high voltage up to 9 kV should be applied. In our previous works, we have designed and developed a new azobenzene-LC polymer based recording material by which two types of laser holographic systems can be applied for direct light recording corresponding to the crucial configuration transition of trans-to-cis and reverse transition of cis-to-trans. Efficient crucial transition for high diffraction efficiency and photo-sensitivity by selected wavelengths is a key for rewriting and erasing. In this work, based on the newly developed azobenzene-LC polymer and using 632.8 nm He-Ne laser (35 mW) holographic recording system, an efficient configuration transition is demonstrated by selective wavelengths (560-580 nm). Meanwhile much higher photo-sensitivity and diffraction efficiency have been achieved. For the first time, we can directly record updatable holographic images with 632.8 nm He-Ne laser.

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8259-01, Session 1

Novel step-tunable wavelength-swept optical system based on a SSB modulator driven by a RF generator for fiber sensing networks

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High resolution wavelength-tunable lasers are essential to sensing applications. For sensing applications, high resolution is needed to improve the spatial resolution and/or measurement accuracy, and fast tuning (sweeping) is required to enhance the measurement speed for dynamic sensing. However the demand of high resolution conflicts with the requirement of fast continuous wavelength tuning. The solution to this issue is tuning the wavelength of the output in a quasi-continuous way in which the length of each step is dependent on the frequency of a RF generator which is used to drive a single-sideband (SSB) modulator in the wavelength-swept optical system. The step-tunable wavelength-swept optical system we designed is different from a conventional system that has a wide-spectrum light source and a narrow scanning bandwidth filter which produces spectrum slices as narrow as possible for high resolution measurements at a very weak optical power level. On the contrary, in this work, a few-milliwatt optical power and ultra-narrow bandwidth single frequency distributed-feedback (DFB) laser diode is used as the light source in the step-tunable system in which a SSB modulator is driven by RF signals for implementation of the wavelength sweeping. There is a fiber amplifier in this system to compensate for the insertion loss of the SSB modulator. The two special features of narrow bandwidth and fairly high optical power make the system unique for improving the accuracy of the measurement of the center-wavelength of a fiber Bragg grating (FBG) sensor. In this paper we will review several tunable light sources to show the possible applications of our system, especially the advantages for fiber sensing applications.

8259-02, Session 1

Passive millimeter-wave holography enabled by optical up-conversion

J. Murakowski, G. J. Schneider, D. W. Prather, Univ. of Delaware (United States)

To capture a three-dimensional scene, information about the distance from the aperture is required. For this purpose, in conventional holography, phase information of the scattered light is recorded by interfering it with a reference beam on a photosensitive plate. At longer, RF wavelengths, relative phases between pairs of points of the aperture can be measured directly, without a reference beam. To this end, waveguides coupled to discrete antennas forming a sparse aperture, RF splitters, and RF combiners are used to measure the correlation of the signal reaching each antenna with that reaching every other antenna. For millimeter waves in the range of ~50 GHz to few hundred GHz, such direct pair-wise cross-correlation measurement is complicated by excessive RF losses in waveguides operating at these frequencies. Given the extremely low power emitted within this frequency range by objects at terrestrial temperatures, the waveguide losses make this approach to reconstruct the 3D scene passively (i.e. without external illumination) impractical. We circumvent these difficulties by up-converting millimeter waves to the optical domain using electro-optic phase modulators. The modulation is a coherent process in that it preserves the phase information carried by the millimeter waves and encodes it in the phase of the optical carrier. In the optical domain, the signal is then transmitted using optical fibers known for their inherently low-loss characteristics and delivered to an optical cross-correlation engine where all pair-wise cross-correlation terms are measured. The 3D millimeter-wave representation of the scene is then reconstructed digitally from those cross-correlation terms.

8259-03, Session 1

Wideband analog photonic links: some performance limits and considerations for multi-octave implementations

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High-performance analog photonic links with radio-frequency noise figures 120 dB in 1 Hz are surveyed. The prevalent modulation formats to that end are discussed. Because of its inherent multi-octave potential, special attention is given to intensity modulation with direct detection (IMDD) employing an external Mach-Zehnder modulator (MZM). The theory for IMDD is reviewed and some previous experimental results are used to exemplify some performance limits. Three limiting factors in multi-octave IMDD implementations are quantified with the implications for millimeter-wave applications highlighted. The straightforward tradeoffs of using an electronic preamplifier to reduce link noise figure are given in terms of photonic link parameters. The MZM bias requirements in order to remain third-order limited are shown to be very stringent in high-performance links. Photodiode nonlinearites, perhaps the most inhibiting factor in present-day wideband analog photonics, are cast in terms of output intercept points and tied to the IMDD link performance.

8259-04, Session 1

Widely tunable opto-electronics oscillators

J. Maxin, G. Pillet, L. Morvan, D. Dolfi, Thales Research & Technology (France)

Heterodyning of optical modes of a diode-pumped solid-state dual-frequency laser (DFL) is a simple way to generate optically carried microwave signals. That can be used for the distribution of radar local oscillator or the implementation of stable and tunable optoelectronic oscillators. We present here the stabilization of the beatnote of an Er,Yb:glass DFL at 1.53 µm with an optical frequency locked loop (OFLL).

Used as a voltage controlled oscillator (VCO), the DFL generates a widely tunable microwave signal from 0 to 14 GHz by heterodyning its two orthogonally polarized optical modes. The optical beatnote is detected on two different high-speed photodiodes, the first one directly at the laser output, the second one after an optical fiber delay line (inducing a delay T). These two microwave signals are mixed together, we then obtain an error signal which is injected through a baseband filter to the DFL frequency control input. This results in the stabilization of the beatnote frequency on a multiple of 1/T.

With a 100 m optical fiber delay line, the beatnote phase noise is improved by 60dB leading to a level of -20 dBc/Hz, at 10 Hz from the carrier, a fairly good result for such a short delay. The beatnote linewidth is then reduced from few hundreds of hertz to few hertz. Since this architecture does not require an RF filter, this oscillator is tunable from 3 to 5 GHz, actually limited by the RF components of our frequency discriminator.

8259-05, Session 1

Integrated silicon-photonic module for generating widely tunable, narrow-line RF using injection-locked lasers

G. J. Schneider, G. A. Ejzak, D. W. Grund, J. Murakowski, S. Shi, D. W. Prather, Univ. of Delaware (United States)

We have developed a system for generating widely tunable, narrow-line RF signals from a pair of injection-locked lasers. This system is based on injection seeding one laser with a comb of sidebands obtained by phase modulating a second laser with a narrow-line, low-frequency RF reference oscillator. The locked laser can be tuned, e.g. thermally, to place its free-running frequency near any one of the sidebands in the comb, hence locking can be achieved using one of many sidebands, allowing the lasers to be mutually coherent while oscillating at a selectable frequency difference. When these coherent optical outputs are mixed on a suitably fast photodiode, a narrow-line RF output is obtained owing to the cancellation of the individual lasers' phase noise. The RF output has linewidth and phase noise characteristics that are limited by the reference oscillator. Furthermore, if the reference oscillator is tunable, the tuning range of the generated RF is scaled by the order number of the selected sideband, yielding wide, continuous tunability. This system has been demonstrated using a discrete benchtop system with an Agilent Vector Network Analyzer as the reference oscillator. Continuously tunable RF signals have been demonstrated from ~1-50 GHz, using a reference signal frequency up to 10 times lower than the output, with ~1-Hz linewidth and excellent phase noise. In this paper, 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.

8259-06, Session 1

A wideband photonic and compressive sampling analog-to-digital converter: architecture, requirements and applications

T. R. Clark, Jr., P. T. Callahan, M. L. Dennis, The Johns Hopkins Univ. Applied Physics Lab. (United States)

Present day radio frequency systems must simultaneously cover many RF and microwave bands and are being tasked with the delivery of accurate processed-information on an always decreasing time scale and in an ever more cluttered electro-magnetic environment. The power of digital signal processing has long been recognized and utilized to provide the necessary tools for increased multi-functionality and improved system performance. Essential to realizing these benefits is the analog-to-digital converter. Today's technology, based on temporally uniform electronic sampling, represents a key limitation on the achievable dynamic range, instantaneous bandwidth and versatility of RF systems.

In this work, an analog-to-digital converter architecture utilizing the precision timing and wide bandwidth capability of photonics technology and the versatility and efficient data processing of compressive sampling techniques is explored. The wideband analog-to-digital converter is capable of the non-ambiguous processing of multi-signal inputs without the static or instantaneous frequency blindness typical in conventional scanning or highly parallel hardware systems. The keys to the approach are the use of wideband photonic downsampling, synchronous clocking of low speed digitizing electronics, and compressive sampling processing. The generation, control and transfer of the precision timing and sampled resolution to the final digitization stage is a key technical challenge to realizing the potential of the architecture involving significant component, sub-system and interface developments as well as optimizations to capitalize on the unique benefits of compressive sampling techniques. Concept demonstration experiments, device and subsystem requirements and potential applications will be discussed.

8259-07, Session 2

DNA-based nanoparticle composite materials for EMI shielding

D. Zang, IPITEK, Inc. (United States); J. G. Grote, Air Force Research Lab. (United States)

Composite materials, such as polymer-matrix containing conductive fillers, are very attractive for EMI shielding due to their high EMI shielding efficiency and seamlessness, processability, flexibility, light-weight and low-cost. Here, we report novel DNA-based, nanoparticles (metal) composite materials (DNCM) for electromagnetic interference (EMI) shielding applications. The new materials benefit from both favorable properties of the matrix (DNA) and fillers (metal particles). A wide selection of metal nanoparticle fillers has been tested for the performance in EMI shielding effectiveness. Among them, silver and carbon-based nanoparticles have the best performance and were selected for further investigation. High EMI shielding effectiveness over wide RF frequency ranges has been obtained from the silver, graphite and graphene-doped DNA-based composite materials. For a RF frequency range from KHz to tens GHz, a thin DNCM layer (typically ~ 100 m) could block 10 - 50 dB EMI radiation effectively. Due to relatively higher percolation threshold of silver nanoparticles in DNA, silver-DNA films can be non-conductive while they could still have high EMI shielding effeciency. The nonconductive DNCM could be very useful in the microelectronics industries for EMI shielding on electronic devices and circuit boards. Potentially, the DNCM could harden electric/electronic components, devices, equipment and even transmission lines in the national power grids to protect the grids from electromagnetic pulse (EMP) generated by nuclear weapons or solar storms.

8259-08, Session 2

High bandwidth constant current modulation circuit for carrier lifetime measurements in semiconductor lasers

U. Singh, Univ. of Central Florida (United States)

Carrier lifetime measurements are a powerful tool to understand the fundamental properties of semiconductor lasers. One of the techniques to measure carrier lifetime is the small signal modulation technique which requires the modulation of laser by a constant current source at high frequency to determine carrier lifetime. At low bias currents not only does the dynamic impedance of laser diode changes significantly with bias but it also becomes frequency dependant thus causing the modulation current to change with bias and frequency introducing an error in carrier lifetime extraction. To correct this situation additional measurement steps are required, making this technique time consuming and ineffective. In this talk we present a novel implementation of high bandwidth constant modulation current circuit to the traditional small signal optical response technique to directly determine lifetime. This circuit uses a high frequency dc biased NPN SiGe transistor with very high output resistance and is designed for the voltage to current conversion to deliver a constant modulation current to the laser diode from 500 KHz to 3GHz. This circuit also rectifies parasitic effects of high value surface mount resistor at high frequencies used in the small signal modulation technique. This circuit decreases RF crosstalk between instruments significantly enabling collection of laser response at very low sub-threshold currents. Excellent agreement has been obtained in measured differential lifetime using small signal optical response and electrical impedance techniques. The application of this circuit can be generalized where the requirement arises for a high bandwidth constant modulation current circuit.

8259-09, Session 2

Direct modulation of injection-locked external-cavity laser

J. Murakowski, G. J. Schneider, G. A. Ejzak, D. W. Grund, D. W. Prather, Univ. of Delaware (United States)

Modulation of an optical signal in electro-optic modulators suffers from nonlinearities induced by sine transfer function, whereby the signal detected by a photo-detector is proportional to , where U is the input signal, and m is the modulation efficiency. For amplitude-modulation in Mach-Zender configuration, this nonlinearity is already apparent at the modulator output, whereas for phase-modulation, it results from the mixing of a reference beam with the signal-carrying beam at the photo-detector. As a result of this nonlinearity, spur-free dynamic range of signals transmitted using optical links is compromised. The sine-function nonlinearity of a direct-phase modulation is cancelled if the phase modulator exhibits arc-sine transfer function instead of linear dependence of phase on the modulating signal. This can be achieved by taking advantage of Adler's effect, according to which, modulating the effective cavity length of an injection-locked laser produces phase-modulated laser oscillations, where the optical phase is an arc-sine function of the modulating signal. In this presentation we report on using a laser cavity made of lithium niobate coupled to an external gain chip realized in III-V material system. Such heterogeneous integration exploits the relative advantages of the respective materials where III-V compound semiconductor is ideal for light generation and amplification, and lithium niobate enables extremely fast electro-optic modulation by virtue of its second-order nonlinearity.

8259-10, Session 3

Fabrication and characterization of hybrid 1x4 silicon slot optical modulator array built on silicon photonics and EO polymer photonics technologies for optical phase array antenna applications

R. S. Kim, A. A. Szep, Air Force Research Lab. (United States); A. Chen, H. Sun, Univ. of Washington (United States); S. Shi, Univ. of Delaware (United States); D. C. Abeysinghe, Univ. of Cincinnati (United States); L. R. Dalton, Univ. of Washington (United States)

No abstract available

8259-11, Session 3

Broadband low-drive voltage electro-optic polymer modulator

D. L. K. Eng, S. Kozacik, B. C. Olbricht, S. Shi, D. Prather, Univ. of Delaware (United States)

An all-polymer Mach-Zehnder modulator fabricated using standard UV lithography that is capable of operating at high frequencies is proposed. The optical waveguide structure consists of three polymer layers, two outer cladding layers and an organic EO material (OEOM) as the core. Low index polymers are used as the cladding layers to isolate the optical mode vertically. Lateral confinement is provided by a trench that is etched into the lower cladding layer, resulting in an inverted OEOM ridge waveguide. The fabrication of this inverted structure is favorable for OEOM integration because the material can be spun on as a last step and is not directly patterned. Material integration in this manner allows waveguide fabrication without processes that compromise the stability of the OEOM. Microstrip transmission line electrodes are then patterned over the optical waveguides, providing strong confinement of the RF field and large mode overlap with optical mode. In order to achieve maximum modulation efficiency, particularly at high frequencies, i.e. over 40 GHz, an outer cladding layer of TiO_2 enclosing the polymer guide will be introduced to match the index between the optical carrier and RF modulation fields. Additionally, recently developed OEOMs have achieved EO coefficients ten times larger than DR1. The greater nonlinearity of these materials will be accessed using our in house in Situ poling apparatus, and will yield a device with a lower V_π. In this paper we will theoretically and experimentally explore the development of low drive voltage and high speed EO modulators incorporating next generation materials.

8259-12, Session 3

Vertical dual-slot modulator for mmW photonics

S. Kozacik, D. L. K. Eng, M. Murakowski, B. C. Olbricht, S. Shi, D. W. Prather, Univ. of Delaware (United States)

High throughput telecommunications, military imaging applications, and the crowding of the electromagnetic spectrum necessitate the development of electro optic modulators in the millimeter wave band. Slot waveguides have been used for modulators as the enhancement of the electric field strength in the slot creates a large overlap with the active electro optic material. This paper presents a design that utilizes the field enhancement provided by a slot waveguide geometry for both the optical field and the RF modulating field. The RF and optical dual slot configuration maximizes the overlap of the optical field and the modulating field in the electro optic material, creating the maximum amount of phase change per Volt of modulating signal. The effect traditionally used for the optical fields in slot waveguides can be duplicated for the millimeter wave modulating field by using materials which have a higher dielectric constant in the millimeter wave region than silicon. Because they also exhibit a lower optical refractive index, they maintain the optical enhancement while providing additional enhancement to the modulating field inside the optical slot. Modulating electrodes have been optimized to reduce impedance mismatch and loss, and to match the effective index of the modulating field with the optical field to preserve modulation, to as high as 250 GHz thus covering nearly the entire millimeter wave band. This device fabrication requires techniques to deposit the highly dispersive materials necessary for the dual enhancement effect, as well as electron beam lithography and advanced processing techniques for the preparation of the organic electro optic material.

8259-13, Session 3

Double mushroom 1.55 um waveguide photodetectors for integrated E-band (60-90 GHz) wireless transmitter modules

V. Rymanov, Univ. Duisburg-Essen (Germany); T. Tekin, Technische Univ. Berlin (Germany); A. Stöhr, Univ. Duisburg-Essen (Germany)

High data rate photonic wireless systems operating at millimeter-wave carrier frequencies are considered as a disruptive technology e.g. for reach extension in optical access networks and for 4G mobile backhauling. Recently, we demonstrated 60 GHz photonic wireless systems with record data rates up to 27 Gb/s. Because of the oxygen absorption at 60 GHz, it is beneficial for fixed wireless systems with spans exceeding 1 km, to operate at even higher frequencies. Here, the recently regulated 10 GHz bandwidth within the E-Band (60-90 GHz) is of particular interest. Designed to coexist, the 71-76 GHz and 81-86 GHz allocations allow up to 10 GHz bandwidth for multi-gigabit wireless transmission. For this purpose, wideband waveguide-PDs with high external quantum efficiency are required.

In this work, we report on advanced double mushroom 1.55 µm waveguide-PDs for integration in an E-band wireless transmitter module. The integration concept of the E-band transmitter will be reported in a second paper. The developed PD consists of a partially p-doped, partially nid-InGaAs absorbing layer centered in a mushroom type optical waveguide for overcoming the trade-off between junction capacitance and series resistance. For efficient SMF coupling, a second mushroom type passive optical waveguide is used. Experimentally, a very flat frequency response with a deviation up to ±1.4 dB in the whole E-band has been found together with an output power level of -22 dBm at only 2 mA photocurrent and a frequency of 73 GHz. Maximum photocurrent levels of up to 30 mA are expected from previous devices.

8259-14, Session 4

Passive fully polarimetric W-band millimeter wave imaging

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We present the theory, design, and experimental results obtained from a scanning passive W-band fully polarimetric imager. Passive millimeter wave imaging offers persistent day/nighttime imaging and the ability to penetrate dust, clouds and other obscurants, as well as thin layers of clothing and even dry soil. The selection of the W-band atmospheric window at 94 GHz offers a design compromise as there is sufficient angular resolution for imaging applications using modestly-sized reflectors suitable for mobile as well as fixed location applications. In addition to the intensity-only image, polarimetric imaging can help reveal the presence of man-made objects due to their typically anisotropic nature and the interaction of these objects with incident millimeter wave radiation from overhead skyshine. The imager is based upon an F/2 off-axis parabolic reflector that exhibits -34 dB of cross polarization suppression for far-field imaging, as well as a F/2.4 off-axis ellipsoid for near-field studies. The heterodyne radiometer produces a 6 GHz IF with 4 GHz of bandwidth resulting in an NEDT of < 250 mK. The imager is mounted on a computer-controlled pan-and-tilt stage to create the image by scanning a single detector in a raster fashion. Using both near- and far-field fore-optics, a variety of scenes including natural and man-made objects were imaged and these results will be presented showing the utility of polarimetric imaging for anomaly detection. Analysis will include conventional Stokes-parameter based approaches as well as multivariate image analysis methods.

8259-15, Session 4

Advanced millimeter-wave security portal imaging techniques

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Millimeter-wave (mm-wave) imaging is rapidly gaining acceptance as a security tool to augment conventional metal detectors and baggage x-ray systems for passenger screening at airports and other secured facilities. This acceptance indicates that the technology has matured; however, many potential improvements can yet be realized. The authors have developed a number of techniques over the last several years including novel image reconstruction and display techniques, polarimetric imaging techniques, array switching schemes, as well as high frequency high bandwidth techniques. All of these may improve the performance of new systems; however, some of these techniques will increase the cost and complexity of the mm-wave security portal imaging systems. Reducing this cost may require the development of novel array designs. In particular, RF photonic methods may provide new solutions to the design and development of the sequentially switched linear mm-wave arrays that are the key element in the mm-wave portal imaging systems. High frequency, high-bandwidth designs are difficult to achieve with conventional mm-wave electronic devices and RF photonic devices may be a practical alternative. In this paper, the mm-wave imaging techniques developed at PNNL are reviewed and the potential for implementing RF photonic mm-wave array designs is explored.

8259-16, Session 4

Integration platform for 72 GHz photodiode-based wireless transmitter

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The growth in mobile data communication applications requires increased bandwidth. Here, microwave photonics can provide the superior advantages of photonics towards ultra-wideband wireless communications. Key elements for such systems are optical sources and fast optical detectors to enable optical generation of continuous wave millimeter waves. 60GHz photonic wireless systems with record data rates up to 27Gb/s have been recently demonstrated.

In this work, we present an integration platform for 72GHz photodiode based wireless transmitter. To enable high data rate transmission, the integration platform has to be developed from the single mode fiber end upto E-band 72GHz output coupling antenna in terms of mechanical, electrical and thermal aspects. Therefore, the placement and positioning of discrete low-noise amplifier (LNA) and power amplifier (PA) components, the bias-tee design parameters of photodiode, LNA and PA, and the design parameters for low-loss transition from coplanar waveguide (CPW) output of amplified electrical signal at the output of PA to E-band WR12 rectangular waveguide have to be carefully determined. The thermal energy dissipation from the amplifiers and transmission lines has to be removed to have no operation point drift of amplifiers, temperature sensitive discrete components and to enhance ´signal-to-noise ratio (SNR) of transmitted signal by suppressing the thermal noise. It is also important to reduce the temperature induced mechanical stress throughout the substrate.

We present the general design principles of 72GHz photodiode integration platform. Further, we compare different substrates, which have been implemented into the platform, based on numerical and experimental results.

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8260-01, Session 1

Ultrafast investigations of carrier and spin dynamics in an artificial molecule

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Ultrafast photocurrent spectroscopy provides exquisite sensitivity, facilitating coherent charge and spin control in individual quantum dot (QD) nanostructures [1-3]. Here, we apply pump-probe photocurrent spectroscopy to directly probe few-Fermion charge dynamics in an individual QD-molecule formed from a pair of vertically stacked self-assembled InGaAs dots. Besides revealing the rich spectrum of excitonic states in the molecule (2X0, X+), the results obtained elucidate the comparative roles of elastic and inelastic intra-molecule electron tunneling. Polarization dependent measurements reveal a near perfect spin blockade (>99% purity) and hole spin qubits are initialized over timescales limited only by the laser pulse duration (X+ or X0 -> 2X0 we directly monitor electron and hole tunneling dynamics as a function of the electric field. Both elastic and inelastic resonant tunneling processes are observed upon electrically tuning excited states of the molecule [4] through resonances. The spectrum and rate of inelastic tunneling between the dots is extracted. In polarization dependent measurements, a perfect spin blockade is observed in the conditional absorption of the X -> 2X and h+ -> X+ transitions, depending on the polarization of the pump and probe pulses, representing an ultrafast optical initialization of a single hole spin, with >99% fidelity.

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[2] S. J. Boyle et al., Phys. Rev. Lett. 102, 207401 (2009)

[3] M. Zecherle, et al., PRB 82 125314 (2010)

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8260-02, Session 1

THz quantum-confined Stark effect in semiconductor quantum dots

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We demonstrate an instantaneous all-optical manipulation of optical absorption at the ground state of InGaAs/GaAs quantum dots (QDs) via a quantum-confined Stark effect (QCSE) induced by the electric field of incident THz pulses with peak electric fields reaching 200 kV/cm in the free space. As a result, a THz signal with the full bandwidth of 3 THz can be directly encoded onto an optical signal probing the ground state absorption in QDs, resulting in the encoded temporal features as fast as 460 fs. The optical absorption modulation at highest THz fields reaches about 30% of the total optical absorption in QDs at the ground state. The dependency of electro-absorption modulation depth on the peak THz field is found to be strongly nonlinear, as expected from the QCSE. From this dependency we conclude that the dominant contribution to the observed electro-absorption modulation in our sample is made by the overall optical absorption quenching via a reduction of the overlap integral and hence the probability of inter-band transition, rather than by the Stark shift of the QD absorption peak away from the spectrum of the optical probe. As expected from the three-dimensional geometry of a QD, the THz QCSE was found to be independent of the polarization of the THz field. The instantaneous nature of THz QCSE in QDs enables femtosecond all-optical switching at very high repetition rates. This allowed us to demonstrate the potential for applications in THz-range wireless communication systems with the data rate of at least 0.5 Tbit/s.

8260-03, Session 1

Theory of phonon-assisted intraband transitions in semiconductor quantum dots

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The investigation of the intersubband dynamics occurring in the conduction band of doped semiconductor quantum dots (QD's) has emerged as a powerful tool to probe their electronic structure and properties. Here, the temperature, the dephasing and the relaxation dynamics are of interest, both from a fundamental point of view but also regarding the performance of QD-based optoelectronic devices. The electron-phonon interaction for QD interband transition are well described by the independent boson model: In this case, a diagonal electron-phonon coupling is assumed. In contrast, for intraband transitions both diagonal and non-diagonal electron-phonon coupling exist. Typically, such problems involving diagonal and non-diagonal coupling are treated within a perturbation approach (Born-Makovian approximation). Here, we present a fully quantized theory to calculate the coupled electron phonon dynamics based on a non-perturbative equation of motion approach for LO-phonons and not limited by the rotating wave approximation:

First, we calculate self-consistently the polaron ground state, which is formed due to the strong non-diagonal coupling. To investigate and to determine these new states, the system is coupled to a additional heat bath with a defined temperature. The influence of the heat bath is calculated by incorporating a phonon-phonon interaction in the Hamiltonian and evaluating the non-Markovian dynamics. Second, we probe the system semi-classically and calculate the optical response of the system. Here, the full strength of our theory comes into play and we discuss higher-order phonon processes, exhibiting remarkable Rabi splitting in the spectra. These strong coupling signatures reveal the underlying polaron structure. For a strong non-diagonal electron-phonon interaction, a multiple set of splittings of the energy levels appear.

8260-04, Session 1

Theory of non-equilibrium phonon statistics and multi-phonon assisted light emission from semiconductor quantum dots

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The investigation of strong electron phonon coupling- and multi-phonon effects in the light emission of quantum emitters are motivated by the current interest in the realization of phonon lasers or squeezed phonon emitters. In the strong excitation regime, light and phonon emitters, such as semiconductor quantum dots (QDs), show several emission features, originating from the simultaneously strongly coupled electron phonon dynamics.

Here, we focus on the temporal evolution of phonon statistics and phonon signatures in the emission spectrum of a QD. While in the weak optical excitation regime, the phononic system can be assumed to remain in a thermal equilibrium, the phonon statistics are drastically changed for stronger laser pulses. Strong electron-phonon dynamics is induced, changing the phonon number distributions from equilibrium to hot- and non-equilibrium statistics. The average phonon-number and phonon-probabilities become dynamic quantities via optical excitation. In order to describe the evolution from thermal to poissionian phonon statistics and the emission spectrum in the strong excitation regime, a non perturbative equation of motion approach is employed, which incorporates the electron phonon interaction up to converging orders. Within this approach, additionally we calculate the time resolved luminescence spectum: Next to the common emission-triplet around the exctiting laser frequency, the coupling to phonons results in additional phonon-assisted emission triplets centered around the Raman-frequencies. At Rabi-frequencies, which match a phonon frequency, the spectrum shows strong anti-crossings, which scale with the Huang-Rhys-factor.

8260-05, Session 2

Ultrafast spin dynamics in wide-gap magnetic semiconductors

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The prediction that wide-gap magnetic semiconductors such as GaN or ZnO would become ferromagnetic at room temperature has attracted considerable interest in the spintronics community. Presently, experimental observations of this effect are strongly debated. In particular, the semiconductor ZnO has drawn much attention, due to its wide bandgap and a large exciton binding energy of 60 meV, which holds the promise for room temperature operation of spintronic devices.

We perform time-resolved Faraday rotation measurements in the ultraviolet on colloidal ZnO quantum dots and magnetically doped ZnO sol-gel thin films to reveal the ultrafast spin dynamics. Relevant spin dephasing mechanisms governed by charge-separated states or electron-magnetic ion coupling are discussed.

8260-06, Session 2

One- and two-photon indirect injection of carriers and spins in silicon

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Degenerate two-photon indirect absorption in silicon is an important limiting effect on the use of silicon structures for all-optical information processing at telecommunication wavelengths, and the optical injection of spins across the indirect gap in silicon is potentially important for spintronics applications. We theoretically investigate one- and two-photon indirect carrier and spin injection in silicon, using a pseudopotential description of electron energy bands and an adiabatic bond charge model to describe phonon dispersion and polarization. We identify the selection rules, the contribution to the carrier and spin injection in each conduction band valley from each phonon branch and each valence band, and the temperature dependence of these processes. The transition from the heavy hole band to the lowest conduction band dominates the injection due to the large joint density of states. The calculated maximum spin polarization of one-photon indirect spin injection is 25% at 4 K at the band edge, and it is still 15% at room temperature. Our calculated two-photon indirect absorption coefficient is about 1 cm/GW at 1.55 microns and 300 K, in good agreement with some recent experimental results.

8260-07, Session 2

Optical orientation and coherent spin dynamics in bulk germanium

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Circularly polarized light is demonstrated to inject partially spin-polarized electrons and holes in bulk germanium via both direct and indirect optical transitions. While the degree of spin polarization is markedly reduced when compared to prototypical III-V-semiconductors, coherent spin precessions in an external magnetic field are well resolved in ultrafast magneto-optics. At cryogenic temperatures, hole (electron) spins exhibit remarkably long coherence times of 100 ps (1 ns}.

8260-08, Session 3

Ultrafast optical control of interacting spins in coupled quantum dots

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A single spin in an InAs quantum dot has many advantages as a quantum bit since the spins can have relatively long coherence times, the semiconductor platform is scalable, and the spins can be controlled on an ultrafast timescale using short optical pulses. Much progress has been achieved in this system with single spin qubits, but it is essential for quantum information applications to move toward entangled multi-qubit systems. Here we demonstrate ultrafast optical control of two interacting qubits consisting of two electron spins [1] or two hole spins [2] in separate InAs dots.

We first initialize the system into a spin singlet state using a narrowband laser that pumps population out of the triplet states. We then manipulate the entangled state of the two spins with single qubit gates (acting only on one spin) by using picosecond pulses faster than the exchange interaction. Two-qubit gates are obtained either by the natural exchange precession or by using a longer laser pulse that induces a phase shift in the precession. These results demonstrate the versatility of using short pulses to control multi-qubit systems, the ability to engineer interactions and energy levels, and also important differences between electron and hole spins. For hole spins we measure a dephasing time an order of magnitude larger than for electron spins, which is limited by electric field fluctuations instead of the hyperfine interaction. Decreasing these fluctuations should enable much longer dephasing times, giving a powerful combination of long coherence times and the fastest single and two-qubit gates of any candidate for quantum information processing.

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8260-09, Session 3

Room temperature spin relaxation in quantum dot based spin-optoelectronic devices

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Spin-optoelectronic devices have become a field of intensive research in the past few years. Here we present electrical spin injection into spin light-emitting diodes both at room temperature and in magnetic remanence. Our devices consist of a Fe/Tb multilayer spin injection structure with remanent out-of-plane magnetization, a MgO tunnel barrier for efficient spin injection and an InAs quantum dot light-emitting diode. The ground state emission and first excited state emission both show circularly polarized emission in remanence, i.e. without external magnetic fields which is due to spin injection from our ferromagnetic contact. Using a series of samples with varying transport path lengths between the spin injector and the active region, we investigate the spin relaxation length during vertical carrier transport through our devices. Due to our spin injector with remanent out-of-plane magnetization, this spin relaxation can be investigated without the need for external magnetic fields, which would possibly influence the spin relaxation process. The decrease in circular polarization with increasing injection path length is found to be exponential, indicating drift-based transport which is in accordance with theoretical calculations. From the exponential decay a spin relaxation length of 26 nm as well as a lower bound for the spin injection efficiency of 25% are calculated. Additionally, influences of magnetic field, temperature and current density in the devices on the spin relaxation process are discussed.

8260-10, Session 3

Ultrafast charge transfer in Cu-doped ZnO nanowires

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Copper is one of the most pervasive and important impurities in ZnO. Over the past four decades, there have been extensive studies on this CuZn defect which manifest itself as the green luminescence (GL) band peaking at ~2.45eV. At low temperatures, the GL exhibits a distinct phonon-related fine structure and a zero-phonon line at ~2.86 eV. The origin of this GL band is attributed to the [Cu+(d9+e),h]→[Cu2+(d9)]+hv charge transfer transitions where the hole is transferred from a level highly perturbed by the surrounding oxygen to the highly shielded d shell of the copper atom. In this intermediately bound exciton model, the electron wavefunction of the tenth electron in the Cu+ ion is delocalized due to the hybridization of the d states with the bottom of the conduction band, thus being depicted as: [Cu+ (d9 + e), h]. While there are general consensuses that the CuZn transitions are of the charge transfer (CT) type, direct experimental evidence of the CT process and the CT rate between the ZnO host and the Cu subsystem has not been reported. Investigating the dynamics of this CT mechanism is the main objective of this work. Ultrafast optical spectroscopy reveal the presence of an ultrafast CT process between the ZnO host and the Cu dopants following above-bandgap photoexcitation. An electron capture lifetime of 39 ± 9 ps by Cu2+ (d9) was measured.

8260-11, Session 3

Relationship of second order susceptibility to the dimensions of ZnO nanorods based on Lorentz local field

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As a promising material in laser and display technologies, ZnO owns its special characteristics of wide direct band gap (~3.37eV at room temperature) and large exciton binding energy (~60meV). The nonlinear optical (NLO) properties of ZnO nanocrystals, especially nanorod (NR) structures, have drawn a lot of attention in recent years. In this work, we have experimentally demonstrated enhanced second harmonic generation (SHG) in ZnO NR with detailed investigations on polarization anisotropy and size/aspect ratio dependency. The $\chi(2)$ values of ZnO NR were obtained via Maker fringe technique. In addition, we have provided, for the first time, quantitative theory that correlates rod diameter d and $\chi(2)$ nonlinearity in ZnO NR. The theory is based on Lorentz local field and the subsequent dielectric constant shift in off-resonant regime. Lorentz local field induced spectral red shift would influence dielectric constant as well as band gap energy in semiconductor materials. Moreover, the band gap energy is strongly dependent on the size of nanostructures, and in turn affects nonlinear susceptibility. Thus the connection from nonlinear susceptibility to particle size is established. The theory matched well with our experiments. We also found that the enhancement will approach equilibrium as particle size is close to optical wavelength when bulk contribution exceeds surface local field contribution. Consequently, our theory is readily to be extended to other kind of semiconductor NRs when addressing nonlinear optical properties in them.

8260-12, Session 3

Strong THz emission from low-energy acoustic-like surface plasmons in InAs nanowires

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It is now known that nanowires and particularly that of InAs are efficient emitters of THz radiation, when excited via NIR pulses. In this work we report on complementary 3 sets of measurements: (i) THz radiation (as measured via autocorrelation with a broadband bolometric detection); (ii) THz reflection of a broadband pulses (bandwidth of ~ 1-15 THz); and (iii) DC transport measurements on individual nanowires, allowing for direct determination of the charge density in the wires. Separate analysis of the dielectric response function (adapted from known theory of dielectric response of metallic cylinders- or DRMC) is carried out that is essential in the interpretation of both sets of optical data, namely complementary radiation and reflection signals. Reflection and radiation optical data show bulk plasmon edge reflectance response at ~ 12 THz, together with signatures of surface plasmon modes of the wires and in particular emission from lowest energy longitudinal surface plasmons at ~ 1 THz. DC transconductance measurements determine carrier concentration of 2e17 cm-3, in a good agreement with the plasmon edge reflectance data at 12 THz as predicated by RMC model. The role of spatial order of the nanowire arrays is also discussed, as we compare measurements carried out on disordered as well as ordered arrays of InAs nanowires.

8260-13, Session 4

Ultrafast optical nonlinearities in a plasmonic nanorod metamaterial

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Plasmonic nanorod metamaterial provides a flexible platform with tuneable resonant optical properties that can be specifically designed by changing the length, diameter and separation between the nanorods. Here, we demonstrate that plasmonic properties of such metamaterial enable an enhanced, ultrafast, nonlinear optical response in both bare nanorods as well as in hybrid metal-dielectric composites. The nonlinearity is enhanced due to the nonlocal optical response of metamaterial. The use of nonlocality to enhance the nonlinear optical response of metamaterials, demonstrated here in plasmonic nanorod composites, could lead to ultrafast, low-power all-optical information processing in subwavelength-scale devices.

8260-15, Session 4

Giant AC Stark effect in germanium quantum wells

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Germanium is considered as one of the promising candidates for integration of optical functionalities onto Si, often referred to as Si photonics. It has successfully been applied in emitters, modulators, and detectors as its physical properties in many ways are very similar to direct-gap semiconductor materials despite the indirect nature of its band gap. For example, the quantum-confined Stark effect, direct gap photoluminescence, transient optical amplification, and even steady-state gain, as well as optically-pumped lasing have been reported.

The AC Stark effect has been discussed for many different materials and structures over the last few decades. Especially a systematic combination of experimental and theoretical studies on typical III-V semiconductors clearly established underlying physical mechanisms. Here, we present the ac Stark effect in Ge/SiGe QWs in order to explore the full potential of the ultrafast modulation capabilities in this material system.

Even at room temperature, we find an extremely large ac Stark shift of up to 67meV. For better comparison with previously published data we extrapolating the observe shift at cryogenic temperatures to lower pump fluence comparable what is reported for (GaIn)As/GaAs QWs in the literature yielding a shift twice as large in magnitude. This is at least partially due to the fast dephasing times in Ge caused by intervalley scattering which, of course is less important in GaAs-based direct gap materials. The data are qualitatively analyzed using dependencies from a simple atomistic description again confirming that the coherent response of Ge in the context of the ac Stark effect are largely governed by the direct gap transition. However, a microscopic many-body theory is desirable in order to quantitatively describe the experimental finding.

8260-16, Session 4

Nonlinear propagation of strong-field THz pulses in doped semiconductors

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We report on nonlinear propagation of single-cycle THz pulses with peak electric fields reaching 300 kV/cm in n-doped semiconductors at room temperature. Dramatic THz saturable absorption effects are observed in GaAs, GaP, and Ge, which are caused by the nonlinear electron transport in THz fields. The semiconductor conductivity, and hence the THz absorption, is modulated due to the acceleration of carriers in strong THz fields, leading to an increase of the effective mass of the electron population, as the electrons are redistributed from the low-momentum, low-effective-mass states to the high-momentum, high-effective-mass states in the energy-momentum space of the conduction band. Further, we observe the typical nonlinear effects of saturable absorption on the THz pulses: pulse shortening, and an increase of the group time delay of the single-cycle THz pulse in a doped semiconductor, as the peak electric field of the THz pulse increases. The latter is caused by the effective reduction of the plasma frequency in an n-doped semiconductor as the carrier effective mass increases, leading to a spectral redshift of the free-carrier absorption maximum. The Kramers-Kronig relation dictates the increase in the dispersion of phase refractive index at lower THz frequencies with the redshift of the absorption peak. Consequently, stronger dispersion of the phase refractive index results in a higher value of a group refractive index at lower THz frequencies, which in turn leads to a larger group time delay of stronger THz pulses in doped semiconductors.

8260-17, Session 4

Spatiotemporal dynamics of few-cycle optical pulses in nonlinear media: collapse vs bullet cast

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In the recent years, there has been a great deal of interest in the area of ultraintense light pulses comprising merely a few optical cycles. These few-cycle pulses (FCPs) have both been widely exploited in ultrafast nonlinear optics and also pushed extensive modeling studies beyond the slowly-varying envelope approximation (SVEA). In particular, numerous applications speed up interest towards deep understanding the pulse self-compression down to the single-cycle pulsewidth that goes on in a transparent medium with instantaneous cubic (Kerr-like) nonlinearity. The dynamics of a FCP in a self-focusing medium can be described beyond the SVEA by means of using the modified Korteweg-de Vries equation (mKdV) [1], sine-Gordon (sG) [2,3] or mKdV-sG equations [4]. The mKdV and sG equations are completely integrable by the inverse scattering transform [5] whereas the mKdV-sG equation is completely integrable only if conditions are imposed on the nonlinear properties of the medium [6]. All these equations admit breather solutions which can realistically describe the FCP solitons. In (2+1) dimensions, the mKdV-based model should be replaced with the (non-integrable) generalized Kadomtsev-Petviashvili equation (GKPE) which, in turn, supplies a very distinct electrodynamical explanation for the stable few-cycle beam propagation [7,8].

These findings have driven us to a specific question if the two-breather solution of the mKdV-sG equations describes the interaction in a Kerr-medium of two few-cycle optical solitons initially well separated, can be modeled in any optically reasonable setting. In this Report, we first consider the propagation of optical FCPs in a (1+1)D optical medium, such as a highly nonlinear optical waveguide. Our second goal is to expand this generic mKdV-sG model onto a (2+1)D medium in such way to answer the practical question of optical collapse and possibility of its arrest for the FCP.

In any physical implementation, a train of FCPs can be launched into the medium in such a way that these propagate as a train of solitons. Due to the fluctuations of the intensity of the laser, the consecutive FCPs may have different energy/peak power, and, subsequently, different velocities. Therefore, it is only natural to expect them to overlap with each other and our goal is to predict what can happen during the interaction. Owing to the analytic solutions that describe the two-breather solution of the mKdV-sG equation, we manage to define in explicit form, the amplitude, time location and shift resulting from the interaction.

In the (2+1)D case of a Kerr-like medium, the evolution equation (1) should be replaced with a cubic GKPE as (see [10])

(1)

where the dimensionless variables U, z, and τ are proportional to the electric field, propagation distance, and retarded time, correspondingly, and y is proportional to the transverse coordinate. Notice that U is not the amplitude of the FCP, but is proportional to the true electric field itself. The constants $\sigma 1,2 = \pm 1$ are related to the dispersion and nonlinearity properties of the medium; see, e.g., Refs. [2-4]. As an input FCP train we chose a linear superposition of the two-breather solution which we believe is the best fit for the two-cycle optical pulse. Since the final expressions are somewhat cumbersome, here we restrict ourselves to the highlight of the results obtained analytically.

Let us assume first that $\sigma 1,2 = -1$, that is, the nonlinearity and dispersion yield temporal self-compression while nonlinearity and diffraction tend to defocus the FCP and what is more memory effects come into action here. The peculiarities of such diffraction are displayed at Fig. 1 where the optical field is strongly localized in time domain yet considerably spatially delocalized. This typical crescent shape is due to the conjugated action of temporal self-compression and diffraction. If the joint effect of nonlinearity and diffraction is focusing ($\sigma 1,2 = +1$), and if the input is strong enough, the self-focusing might happen and two distinct regimes of the collapse are found numerically. At the same time, the spectrum of the FCP presents a strongly asymmetric oscillatory behavior that is in strict contrast with the case of the “long” pulses described within the SVEA.

In other typical case (the so called short-wave limit), when the characteristic frequency of the optical transition is much smaller than the carrier frequency of the FCP, the spatiotemporal dynamics is described by a two dimensional sine-Gordon equation as [11]:

(2)

where C depends on z and is proportional to the inverse population.

a) b)

c) d)

Figure 3 Nonlinear diffraction of the FCP: (a) input profile at the (y, t)-plane; (b) an intermediate stage with a typical crescent shape; (c) nonlinear diffraction; (d) linear diffraction.

The numerical simulations to Eq. (3) reveal evolution (not shown here) of the Gaussian pulse into a stable localized structure being affected neither by dispersion nor by diffraction; after a transient stage where the FCP radiates energy, its amplitude decreases and stabilization in the form of a localized oscillatory structure is reached eventually.

In conclusion, we study the spatiotemporal dynamics of few-cycle optical solitons by making use of the two-breather solution of the mKdV-sG equation (or GKPE-sG) found earlier [7, 9-11]. The shapes of input and output soliton envelopes as well as the phase and location shifts are computed by mean of the exact expressions for the four-soliton (two-breather) solutions of the mKdV-sG equation. The remarkable feature is that, contrary to the case of the traditional (SVEA-type) soliton envelopes, no phase matching of any kind is required for the two-cycle pulses to interact efficiently. This interaction may bring novel features into the nonlinear propagation of trains of few-cycle optical pulses. At the same time, light bullet formation is proven for a medium, where the characteristic frequency of the optical transition is much smaller than the carrier frequency of the FCP. Contrary to that, the FCP propagation might also lead to the true wave collapse or nonlinear diffraction, depending on the sign of nonlinearity and dispersion.

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8260-18, Session 4

Numerical analysis of multi-photon parameters from ultrafast laser measurements

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We describe a unique mathematical/numerical model to analyze ultrafast laser experimental data and obtain two-photon (TPA) and multi-photon (MPA) absorption parameter(s). The material used to demonstrate the numerical method is a hybrid organic-inorganic nano-structured semiconductor quantum dot-polymer composite. Chemical, biological and engineering studies require advancements in TPA/MPA absorbers for microscopy, fluorescence, imaging, and micro-processing of materials. We illustrate the numerical method by fitting data from the well-known z-scan experimental method. Traditionally an analytical model is used to analyze data from such experiments, which is limited in scope with certain restrictions on laser intensity and material thickness.

We derive a more general mathematical/numerical method-without these limitations-that includes TPA/MPA and can be extended to free carrier absorption and stimulated emission. Under certain circumstances, we can also calculate the electron population density on every electronic level to demonstrate physical effects such as saturation. Additionally, we include diffraction in our numerical calculation so that the TPA/MPA can be obtained even for thick optical samples. We use the numerical method to calculate published z-scan measurements on quantum-dot CdS-polymer composites, and show excellent agreement with published traditional analytical results.

In general, laser induced applications require less light intensity with higher TPA/MPA parameters. Therefore numerical methods that enable better analysis of these parameters from experiments are needed.

8260-19, Session 4

Chirped pulses sum frequency generation for deep-UV picosecond pulse shaping

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Deep-UV pulses are achieved in nonlinear crystals by sum frequency generation (SFG) between the fundamental and the second harmonic of a Ti:Sapph laser. The acceptance bandwidth of the process dramatically limits the maximum energy and the spectral width attainable in the deep-UV. In our system, the SFG input pulses are linearly chirped so that at any time two instantaneous input frequencies produce a perfectly phase matched sum frequency. In this case the spectral width is not restricted to the acceptance bandwidth of the crystal, and the conversion efficiency is greatly enhanced. We present spectra about ten times beyond the acceptance bandwidth of the SFG and remarkable efficiency of 12% for ps pulses. In this scheme the output spectral phase and amplitude are simply related to the corresponding properties of the input pulses. Therefore, IR spectral manipulation can be performed for high-resolution control of temporal intensity in the deep-UV. The setup allows high-energy, deep-UV top-hat pulse suited for driving radio frequency photocathode gun. We obtained up to 200 uJ, 4.5 ps FWHM top hat pulse having sub---ps rise and fall time and 10% rms modulation at the plateau. Experimental characterizations and simulations, in time and spectral domain are presented.

8260-20, Session 5

Compact and portable terahertz source based on frequency mixing using dual-frequency solid-state laser

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Recently, we have made great progress on designing, assembling, and testing of dual-frequency solid-state lasers. Using such lasers, we have implemented portable and compact terahertz sources. We have significantly scaled up output powers through solid-state laser engineering. By replacing an active Q-switch with a passive Q-switch, we have investigated terahertz parametric generation. Such a novel configuration allows us to substantially reduce the dimension of the terahertz source and realize a monolithic terahertz source.

8260-21, Session 5

Detection of ultrafast THz pulses via electro-absorption in coupled asymmetric quantum wells

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We utilize quantum-confined Stark-effect in coupled asymmetric quantum wells (ADQW), consisting from 90 pairs of 5 nm and 6 nm wide wells separated by 2.5 nm wide Al0.3Ga0.7As barrier and coupled quantum well units are separated by 7.5 nm of Al0.3Ga0.7As barrier. The asymmetry is designed to allow for linear electro-absorption under suitable excitation conditions. To realize coherent detection, broadband THz transients formed by a two-color air plasma are focused onto ADQW, in turn dynamically shifting the ADQW bands, with the bandedge at ~ 825 nm. Spectrally-resolved detection scheme analyzes absorption modulation signatures imprinted onto the transmitted NIR probe spectrum. Using sample lengths much smaller than THz wavelength (~IR pulse length) eliminates any temporal walk-off and ensuring a large detection bandwidth, currently demonstrated up to ~ 15 THz. For spectral components near the bandedge of the ADQW, time-domain analysis of this signal shows pronounced bi-polar as well as small unipolar signals. Orientation, polarization and power-dependence of the observed electro-absorption are currently being investigated.

8260-22, Session 5

Nonlinear response of semiconductors driven by intense THz pulses

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The nonlinear response of semiconductors under influence of strong THz fields is a subject of particular interest both for fundamental science and high speed semiconductors electronics. Recent progress in generation of intense THz pulses has stimulated the research in this field [1].

Here we report two examples of nonlinear spectroscopy of bulk semiconductors performed using our novel high-field phase-stable THz source [2, 3]: In a THz-bias / near-infrared probe experiment we monitor the ultrafast interband dynamics of InP in electric fields as high as 8 MV/cm. Remarkably the near-infrared transmission is modulated at twice the carrier frequency of the driving THz pulse. This behavior and the spectral response of the sample can be well understood using the theory of the dynamic Franz-Keldysh effect. We also present the results of two-photon four-wave mixing experiment in the narrow-gap semiconductor InSb. The non-collinear wave-mixing geometry allows spatial selection of nonlinear signals and background-free measurements. The temporal profile of the strong four-wave-mixing signal suggests first indications of a THz photon echo in InSb.

The presented results demonstrate that intense THz pulses possess a very high potential for study of extereme nonlinear response of bulk semiconductors.

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8260-23, Session 5

Ultrafast nonlinear terahertz studies of high-field charge transport in semiconductors

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Charge transport driven by strong electric fields represents an important area of semiconductor research which is relevant for both basic and device physics. Terahertz (THz) transients with electric field amplitudes of up to several MV/cm allow for driving and monitoring charge transport in a regime where quantum coherences and quantum-kinetic scattering processes come into play. Recent work using strong femtosecond THz fields has demonstrated coherent polaron dynamics and partial Bloch oscillations of electrons in bulk GaAs. For understanding the damping of such quantum coherences, the transition from ballistic to incoherent drift-like transport is particularly revelant, as characterized by the onset of friction due to interactions among carriers and with the lattice. In this talk, we present a combined experimental and theoretical study of this transition regime in bulk GaAs, comparing transport in single-component electron and hole plasma with transport in presence of a photoexcited electron-hole plasma. Ballistic transport predominates in an electron plasma, whereas a transition from ballistic to drift-like electron motion is observed when holes are present. Holes introduce a friction force that builds up on a time scale of approximately 1 ps, due to the gradual heating of the hole distribution by THz absorption and the resulting enhanced electron-hole scattering. We describe our data with a theoretical model for the transient dielectric function of the electron-hole system and show that the time-dependent screening of the external field by the carrier plasma leads to pronounced local-field effects.

8260-24, Session 6

Coherence properties and excitation spectra of single and coupled microcavity polariton condensates

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Remarkable key features of Bose-Einstein condensation (BEC) like superfluidity, linearized Bogoliubov excitation spectra have been verified for atomic BECs. In the solid state, BEC of exciton-polaritons has been reported [1]. Exciton-polaritons are strongly coupled light-matter quasiparticles in semiconductor microcavities and also composite bosons. However, they are subject to dephasing and decay and need external pumping to reach a steady state. Accordingly, the polariton BEC is a nonequilibrium state of a degenerate polariton gas which offers properties which are partially similar to a true atomic BEC and partially similar to lasers. As the lifetime of microcavity polaritons relative to their thermalization time can be tuned by varying the detuning between the cavity mode and the exciton, it is possible to study whether signatures of condensation remain as the system switches from a locally thermalized to a completely non-equilibrium system for which no effective temperature can be defined.

Here we test this system for several of these signatures of a BEC like macroscopic occupation of the ground state, spontaneous build-up of coherence and linearized excitation spectra at varying detunings. To this end, we developed an experimental technique using a modified streak camera to record second-order correlation functions with picosecond temporal resolution as is necessary to distinguish whether the ground state emission of the polariton system is thermal or coherent. As an outlook we discuss coupled polariton BECs which allow to observe features like Josephson plasma oscillations in optically created Josephson junctions.

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8260-25, Session 6

Ultrafast transition from a photon to a polariton Bose-Einstein condensate in a semiconductor microcavity

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Semiconductor Microcavities offer great opportunities to trap light on timescales of tens of picoseconds and provide light matter interactions by means of embedded resonant media (eg. quantum wells). Depending on the type of quantum well resonance the arising dressed photon states can either be in the strong coupling regime (exciton polaritons) or the weak coupling regime (photons). In the present study switching between strong and weak coupling is obtained by utilizing the dependency of the exciton linewidth on the carrier density. Recent work on exciton polaritons [1] and photons [2] in a dye filled microcavity show clear evidence of Bose- Einstein condensation in optical microcavities. We study the transition from the weak to the strong coupling regime in time after an ultrafast excitation pulse. Time, energy and angle resolved measurements are performed. The time resolved dispersion relation reveals that the system is initially in the weak coupling regime and condensed photons are in thermal equilibrium with the excited states of the cavity mode. After a brief relaxation period strong coupling is recovered and the polariton mode is occupied according to a Bose-Einstein distribution with a macroscopically occupied ground state, that depletes as time progresses. Further investigations are focused on the temporal evolution of first order long- range coherence obtained by interferometric measurements. Polarization properties of the two condensed phases underline the fundamental differences to conventional lasing and provide insight into the nature of the heatbath that provides means for thermalization.

8260-26, Session 6

Phonon-driven resonantly enhanced polariton luminescence in organic microcavities

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Recent studies of semiconductor microcavities in strong coupling regime have made significant steps towards realization of practical polariton devices. One of the most important applications envisioned is the possibility of creating ultralow threshold polariton laser. A key prerequisite for low-threshold polariton lasing in organic or inorganic microcavity systems is the efficient population of the lower polariton ground state. However, in strongly coupled organic microcavities the physical conditions required for observation of cooperative phenomena (e.g. lasing and parametric amplification), are more difficult to achieve in respect to inorganic semiconductors.

Recent experiments have reported on nonlinear emission in crystalline based organic microcavity at room temperature, based on enhanced scatterings mediated by vibronic resonance, to populate ground polariton states, highlighting the potential of organic microcavities for achieving polariton lasing. However, the complexity of the structures used requiring crystalline growth of organic material imposes practical limitations of their applicability.

In our work we present clear evidence for the enhanced scattering of excitons with discrete molecular vibrational modes in disordered J-aggregate microcavity systems creating an efficient relaxation channel for fast and controllable nonthermal population of lower polariton (LP) branch states. As a result strong enhancement of light emission from LP states whose energy separation from the exciton reservoir matches the discrete Jaggregate Raman peaks is observed. Furthermore, ultrafast pump-probe measurements clearly demonstrate faster exciton-phonon scattering rates for population of LP states at which resonance condition is met, offering an alternative approach towards achievement of polariton lasing in disordered systems which concentrate significant processing advantages.

8260-27, Session 6

The single quantum-dot laser-emission properties in weak and strong coupling

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A single quantum-dot emitter coupled to a single microcavity mode harbors a multitude of interesting effects in different regimes. We study the emission properties covering the whole excitation range from single-photon source to lasing on the basis of a semiconductor model. As a function of the pump rate of the system we investigate the onset of stimulated emission, the possibility to realize stimulated emission in the strong-coupling regime, as well as the excitation-dependent changes of the photon statistics and the emission spectrum. The role of possible excited charged and multi-exciton states and the different sources of dephasing for various quantum-dot transitions are discussed in detail.

The starting point for our model are the confined single-particle states, which allow for multiple electron and hole excitations, as well as the Fock states for the cavity field. We directly solve the von-Neumann equation, in which we include the Jaynes-Cummings Hamiltonian and the Coulomb interaction of the confined carriers. The latter leads to the multi-exciton states according to the configuration interaction. Carrier capture, scattering and dephasing are included via Lindblad terms.

With our microscopic model we are able to provide insight into the characteristics exhibited by a single QD under high and low excitation, both in the weak and strong coupling regime. Our intention is also to aid the experimental progress, where to date the purity of single-QD emission is degraded by off-resonant emitters. This leads to deviations from the properties of the ideal single emitter and may conceal the underlying physics.

8260-28, Session 6

Addressing phonons in semiconductor quantum dot-QED: entanglement, non-equilibrium phonon, and photon distributions

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Self-assembled semiconductor quantum dots (QD) allow the study of a true quantum regime, in which the fluctuation properties of lattice vibrations (phonons) and photon distributions have a strong impact on the optical and electronic response of the system.

These fluctuations draw a lot of attention in recent experimental and theoretical work with respect to non-classical photon distributions (anti-bunching), polarization entanglement of photons from a biexciton cascade and temperature effects due to hot bulk phonons.

In our contribution, we present a fully non-Markovian, quantized theoretical framework to study the quantum optical properties of a QD, including the solid-state environment. Our framework is based on the equation of motion approach, which allows us to generate numerically exact solutions for the combined photon, phonon and photon dynamics, and furthermore gives access to the full photon and phonon distributions in the case of a fixed number of electrons inside the QD (exciton, biexciton).

As an example, we investigate the biexciton cascade in a QD in the strong coupling regime numerically exact and discuss the impact of phonons on the degree of entanglement and the repetition rate.

Furthermore, we derive in the weak coupling limit an analytical solution of the quantum state tomography of the QD biexciton cascade and show that pure dephasing does not affect the degree of polarization entanglement for temperatures below 60K.

These analytical formulas are valid for arbitrary photon loss, dephasing,relaxation and detuning in the material, and are widely usable as a paramter study tool and as a fit formula for experiments.

8260-29, Session 7

Generation of coherent charge oscillations in the plane of GaAs quantum wells

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Ultrafast charge oscillations in the plane of unbiased and undoped (110)-oriented GaAs quantum wells have been generated by coherent optical excitation of heavy-hole and light-hole exciton transitions. These observations are evidence for the existence of a substantial far-infrared transition-dipole moment between heavy- and light-hole subbands for non-zero in-plane wave vectors in the GaAs quantum wells. This may prove important for the design of novel far-infrared lasers and detectors.

So far, ultrafast charge oscillations in GaAs quantum wells between heavy-hole and light-hole states have been observed along the growth direction and were based on a displacement of the slowly varying envelope functions. In contrast, the in-plane charge oscillations observed in this work result from an in-plane displacement of the periodic parts of the Bloch wave functions. The experiments were performed on (110)-oriented GaAs/AlGaAs quantum wells of different well widths with 150 fs excitation laser pulses at 80 K. The charge oscillations were detected by measuring the simultaneously emitted THz radiation. A variation of the excitation photon energy showed that the charge oscillations are at a maximum for simultaneous excitation of heavy- and light-hole excitons. The beat frequency obtained from several samples with different well width is in excellent agreement with the energy difference between the n=1 heavy-hole and light-hole excitons measured by photoluminescence experiments. Modelling the measured beat pattern using the optical Bloch equations for a three-level system thetransition dipole moment between heavy-hole and light-hole excitons of ~0.5 eÅ has been determined for a 15 nm wide QW.

8260-30, Session 7

Quantum interference control of electrical currents: applications for ultrabroadband field-resolved spectroscopy

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We demonstrate an ultrabroadband concept to characterize modifications to femtosecond pulses in amplitude and phase. The radiation is superimposed with first subharmonic spectral components from the same laser source. This harmonically related pulse pair induces a coherently controlled charge current in a time-integrating semiconductor detector. An interferometric variation of the time delay between the harmonically related components then reveals the electric field of the pulse. This method is realized with the second harmonic of a compact Er:fibre source centered at 390 THz and a GaAs based detector. Most strikingly, it is sensitive to minute phase changes and can be utilized to analyze fJ pulses.

8260-31, Session 7

Revealing exciton dephasing and transport dynamics in semiconductor quantum well/ quantum dot systems using optical 2D Fourier transform spectroscopy

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Optical spectroscopy is a valuable tool for capturing details of excitonic dephasing and transport properties in semiconductor nanostructures. Optical two-dimensional Fourier transform (2DFT) spectroscopy is a particularly powerful technique for studying resonant light-matter interactions because of its ability to separate and isolate spectrally overlapping features and to measure homogeneous and inhomogeneous linewidths simultaneously. [1] 2DFT spectroscopy uses a sequence of laser pulses to generate coherent signals in the material, and the phase evolution of these signals is recorded while the pulse time delays are varied. A 2D spectrum is generated by Fourier transforming the signals with respect to two of the time periods while the third is held fixed.

2DFT spectroscopy is used to investigate exciton-exciton and exciton-phonon interactions in a single GaAs/AlGaAs quantum well (QW) and interfacial quantum dot (QD) ensemble. [2] A temperature-dependent study of the homogeneous linewidth reveals that exciton-phonon interactions are elastic up to 35 K and the interaction strength increases for higher-energy excitons localized in smaller QDs. At low excitation density, the homogeneous linewidth decreases with QD size. As the density increases this trend reverses, suggesting that intra-QD exciton-exciton interactions dominate.

The appearance of additional spectral features at higher temperatures and long time between the first and second excitation pulses indicates strong coupling between QW and QD states. [3] The population and coupling dynamics are modeled using a system of rate equations that incorporate radiative and nonradiative decay, coupling between bright and dark exciton states, and QW-QD population transfer at high temperature.

8260-32, Session 7

Coherent ultrafast Rabi oscillations in metal-j-aggregate hybrid nanostructures

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The optical properties of hybrid nanostructures comprising active materials, e.g., semiconductors or J-aggregated molecules and metals are currently attracting substantial attention since they may form the basis for novel optoelectronic devices. Such nanostructures are fundamentally interesting because, in favorable geometries, the near-field electromagnetic coupling between excitons and surface plasmon polaritons (SPPs) is so strong that their optical response is governed by a new class of short-lived quasiparticles, exciton - surface plasmon polaritons, with hitherto essentially unexplored nonequilibrium dynamics.

Here, we study the ultrafast coherent dynamics of exciton-surface plasmon polaritons excitations in metal-semiconductor hybrid nanostructures. When resonantly exciting the nanostructure, we observe pronounced temporal oscillations in the nonlinear optical response near the polariton resonance wavelengths. These oscillations with a period of ~50 fs are the time-domain signature of Rabi oscillations between excitons and SPP induced by vacuum fluctuations of the electromagnetic near field.

8260-33, Session 7

THz control of matter states: coherent excitons beyond the Rabi-splitting

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Strong external electromagnetic fields can be used to induce highly nonlinear modifications of the electronic matter states. We show experimentally and theoretically how optically induced excitonic polarization in semiconductors is modified and controlled by intense, single-cycle terahertz (THz) pulses. A resonant low-intensity excitation of GaAs-type direct-gap semiconductors induces coherent excitons with s-like orbital symmetry. The additional application of an electromagnetic field in the range of THz frequencies allows for a direct coupling of the coherent excitons to polarization states with p-type symmetry. By monitoring the low-intensity optical pulse we find a pronounced bleaching of the 1s-exciton resonance, a THz-induced Rabi-splitting, and a pronounced modulations on the high-energy side of the 1s-exciton resonance. All these features are fully explained by our quantum-mechanical many-body theory. Our quantum-mechanical many-body theory attributes the pronounced nonlinear changes in the transmission spectra to a THz driven excitation of 1s-2p transition he all the way to excitonic multi-THz-photon ionization. These results constitute a first step towards the systematic control of coherent matter states.

8260-34, Session 8

Ultrafast carrier dynamics in graphite probed with time-resolved XUV photoemission

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The combination of ultrafast light sources in the UV spectral regime and the technique of photoelectron spectroscopy provides a unique tool for a most direct access to ultrafast processes in condensed matter systems that couple to electronic degrees of freedom. Angular resolution enables one in this context to monitor the temporal evolution of the valence electronic band structure of a solid at selected - and possibly critical - points in momentum space [1]. The application of XUV photon pulses enlarges the accessible momentum regime considerably so that band structure transients within the entire first Brillouin zone or even beyond can be recorded [2].

Here we present a time- and angle-resolved photoemission study of the relaxation dynamics of photoexcited carriers in graphite and graphene. The electronic and optical properties of these materials are determined by electron states located at the boundary of the Brillouin-zone in the visinity of the K-point, which, in the case of graphene, give rise to the emergence of the well-known Dirac cone. The application of femtosecond XUV pulses as used in our experiment give therefore most direct insights into the energy- and momentum dependent redistribution of the hot carriers resulting from the interaction with the electronic subsystem and the lattice. Our findings will particularly be discussed under consideration of results obtained using pure optical time-resolved spectroscopy [3].

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8260-35, Session 8

Terahertz imaging and spectroscopy of large-area single-layer graphene

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We demonstrate terahertz (THz) imaging and time-domain spectroscopy of a single-layer graphene film. The large-area graphene was grown by chemical vapor deposition on Cu-foil and subsequently transferred to a Si substrate. We took a transmission image of the graphene/Si sample measured by a Si:bolometer (pixel size is 0.4 mm). The graphene film (transmission: 36-41%) is clearly resolved against the background of the Si substrate (average transmission: 56.6%). The strong THz absorption by the graphene layer indicates that THz carrier dynamics are dominated by intraband transitions. A theoretical analysis based on the Fresnel coefficients for a metallic thin film shows that the local sheet resistance varies across the sample from 420 to 590 Ohm, consistent with electron mobility ~3,000 cm2V-1s-1. We also measured time-resolved THz waveforms through the Si substrate and the graphene/Si sample. The waveforms consist of a series of single-cycle THz pulses: a directly transmitted pulse, then subsequent “echos” corresponding to multiple reflections from the substrate. The amplitude difference between graphene/Si pulses and Si pulses becomes more pronounced as the pulses undergo more reflections. From these measurements, we obtained spectrally flat transmission spectra of the transmitted pulses and the average sheet resistance 480 Ohm, consistent with the results of the power transmission measurement. The flat spectral responses indicate that the carrier scattering time in our graphene sample is much shorter than the THz pulse duration.

8260-36, Session 8

Nanoscale imaging of interface dynamics in polymer blends by ultrafast confocal microscopy

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Femtosecond pump-probe spectroscopy is a powerful technique to study the primary photoinduced dynamical processes in molecules. In its standard implementation it requires macroscopic samples, so that the experimental results are averaged over many mesoscopic domains. For many applications, however, it is required to study single nano/micrometer-sized objects or to map the inhomogenous distribution of structured samples in order to correlate the physical processes with the sample morphology. For this purpose we have developed a new instrument combining broadband femtosecond pump-probe spectroscopy and confocal microscopy, with high temporal (150fs) and diffraction-limited spatial (300nm) resolution, acquiring four-dimensional differential-transmission maps as a function of x-y sample position, probe delay and wavelength in the visible to near-IR region.

We applied this instrument to study polymer blends for organic solar-cell devices. One of the major technological challenges in organics optoelectronics is the control of the physical processes occurring at the molecular interface between materials that form the bulk heterojunction, which determine the ultimate device performance. Such phenomena are poorly understood due to the variety of possible electronic states and processes and to their complicated dynamics, requiring a combination of high spatial and temporal resolution to be observed.

After introducing the instrument, we will present recent results on:

(i) thin films of a polyfluorene dispersed in PMMA, where pump-probe dynamical imaging reveal different photo-relaxation pathways, highlighting PFO domains with aggregated/isolated chains in the center/border of the region;

(ii) a donor/acceptor bulk heterojunction sample, where a peculiar charge-transfer state is pinpointed at the interface between crystals.

8260-37, Session 8

Photoinduced dynamics in a terpyridine-based zinc(II) coordination polymer and their molecular fragements

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This contribution focuses on the photoinduced dynamics in a ZnII-bis-terpyridine coordination polymer and its molecular fragments - in particular the bis-terpyridine ligands bearing conjugated chromophore units, which resemble the structural features of poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV). The ZnII coordination polymer, which forms ridgid linear macromolecular structures, combines up to about 35 such individual MEH-PPV-like chromophores and is investigated - to the best of our knowledge - for the first time by single molecule fluorescence spectroscopy (SMS). Upon incorporation of the individual chromophores into the coordination polymer the fluorescence quantum yield of an individual chromophore is found to be reduced. The molecular mechanism underlying this experimental finding is addressed by investigating the brightness of isolated polymer molecules in various environments. The SMS results show that the ZnII-bis-terpyridine coordination polymer with the MEH-PPV-like chromophore structure contains a significantly larger fraction of bright chromophores compared to MEH-PPV alone. This finding is attributed to the particularly rigid geometry of the system at hand. Finally, single-molecule fluoresecence experiments with millisecond time-resolution identify two different types of intensity fluctuations: Small amplitude intensity fluctuations correlate with switching of individual chromophores by structural fluctuations, while large amplitude jumps switch off the emission of the entire molecule. These experimental fluctuations will be correlated with ultrafast time-resolved spectroscopy pointing to the photoinduced geometrical rearrangement in the bis-terpyridine chromophores. Finally, experiments on the ZnII coordination polymer under different atmospheric conditions offer further insights into the molecular mechanism and the nature of the quenchers involved in the blinking.

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8260-38, Session 8

Ultrafast optical analyses and characteristics of nanocomposite media

C. M. Collier, X. Jin, B. Born, J. F. Holzman, UBC Okanagan (Canada)

Nanocomposites are an appealing material for photonics. The discrete nature of embedded nanoparticles in surrounding (typically polymer) hosts allows the physical structure and resulting optical responses to be tailored for use in refractive and absorptive optical applications. Emerging systems have applied optically-active nanocomposites-in sensors, switches, and amplifiers-and optically-passive nanocomposites-in lenses and waveguides-for the creation of a new generation of devices with enhanced refraction, absorption, nonlinearity, and sensitivity.

The above photonic applications share an inherent need for characterizing and ultimately understanding the refractive and absorptive properties of nanocomposites, particularly in photonic applications requiring high refractive indices (enhanced refraction) or strong third-order nonlinearities (enhanced absorption), as such systems often apply wide-bandgap semiconductor nanoparticles in polymer hosts to form high-contrast states between the respective refractive indices. The effective refractive indices and overall nonlinearity are successfully increased, although the optical response refractive index inhomogeneity must also be considered, as diffractive effects can dominate over the desired refractive and absorptive optical characteristics.

This work introduces an ultrafast refractometry technique as a new method for characterizing nanocomposite refractive indices, absorption coefficients, and inhomogeneity. Ultrashort laser pulses probe refractive, absorptive and diffractive material conditions with in-situ intensity and interferometric autocorrelations. The phase delay, power loss, and phase coherence of the interacting 100 fs optical pulses are extracted for overall nanocomposite state characterization. The technique is demonstrated for a 20 nm SiC nanoparticle/polymer nanocomposite material. The physical characteristics of the nanocomposites-particularly the nanoparticle sizes and volumetric ratios-are shown to be decisive factors in the resulting optical temporal/spatial phase response and attenuation.

8260-39, Session 9

Ultrafast metatronics (Keynote Presentation)

N. Engheta, Univ. of Pennsylvania (United States)

In recent years, in my group we have introduced and been developing the concept of “optical metatronics”, in which the three fields of “electronics”, “photonics” and “magnetics” can be brought together seamlessly, effectively having a paradigm we call “Unified Paradigm of Metatronics”. In this optical circuitry, the nanostructures with specific shapes and values of permittivity and permeability may act as the optical lumped circuit elements such as nanocapacitors, nanoinductors and nanoresistors. Moreover, nonlinearity in metatronics can also provide us with novel optical nonlinear lumped elements. We have investigated the concept of metatronics through various analytical and numerical studies, computer simulations, and recently in a set of proof-of-principle experiments at the IR wavelengths. We are now theoretically investigating the ultrafast nature of such optical metatronics, exploring the temporal and spatial dispersions of such optical nanocircuitry. The arrangement of deeply subwavelength nanostructures, when properly positioned, can affect the quality factor of such optical nanocircuits, and in turn its ultrafast behavior. Furthermore, we have been exploring how metamaterials can be utilized for controlling the flow of photons, providing the possibility of unidirectional flow of photons, analogous to a diode in electronics. We are now extending the concept of metatronics to other platforms such as graphene, and we are also interested in the temporal response of such one-atom-thick devices. We study the graphene as a new paradigm for metatronic circuitry and as a “flatland” platform for IR metamaterials and transformation optical devices. I will give an overview of our most recent results in these fields.

8260-40, Session 9

High refractive index terahertz metamaterials

B. Min, KAIST (Korea, Republic of)

We demonstrated extremely high indices of refraction from large-area, freestanding, flexible terahertz metamaterials. By periodically arranging I-shaped metallic patches with narrow gaps in-between, we can increase the capacitance of constituting subwavelength-scale capacitors (I-shaped metallic patches). As the gap closes, the capacitance diverges rapidly and this leads to the huge accumulation of charges at the end of the I-shaped metallic patches. This huge accumulation of charges, in turn, results in extreme polarization density and the huge effective permittivity. In addition to this, diamagnetic effect that gives rise to the decrease in effective permeability was suppressed simply by thinning the metallic structure. To confirm the theoretical prediction, the measurement of complex refractive index of the proposed high index metamaterial was performed with terahertz time-domain spectroscopy. For the smallest gap width (80 nm) sample, we obtained the peak refractive index of 38.64 and the quasi-static limiting value greater than 20. In addition, we fabricated polarization-independent high index metamaterials composed of hexagonal/square metallic ring and demonstrated polarization-insensitive effective refractive indices. High refractive index terahertz metamaterials composed of unit cells having certain rotational symmetry are proposed for the realization of polarization insensitive high refractive index. Terahertz time-domain spectroscopy on metamaterials with rectangular and hexagonal metallic ring shows polarization-insensitive transmission and effective refractive index profiles.

8260-41, Session 9

Strong coupling of the cyclotron transition of a high mobility 2D electron in a THz metamaterial

G. Scalari, D. Turcinkova, C. Maissen, C. Reichl, ETH Zurich (Switzerland); D. Schuh, Uni Regensburg (Germany); W. Wegscheider, ETH Zurich (Switzerland); D. Hagenmuller, S. De Liberato, C. Ciuti, Univ. Paris 7-Denis Diderot (France); M. Beck, J. Faist, ETH Zurich (Switzerland)

Strong light-matter coupling in the THz range in intersubband systems has gained recently great attention due to the possibility to obtain very large ratios between the Rabi frequency and the unperturbed frequency of the system. We report about observation of ultrastrong light-matter coupling between the cyclotron resonance of an high-mobility two dimensional electron gas (2DEG) and the resonances of a planar THz metamaterial composed by LC split-ring resonators. A THz-TDS spectrometer coupled to superconducting magnet probes the transmission of the sample in the banwidth 0-3.5THz. The LC resonances observed with no applied magnetic field are at 1 THz and 2.3 THz. Once the magnetic field value is increased, we observe a strong modification of the transmission spectra with some clear anticrossings between the different branches. Uncoupled cyclotron signal is also observed because the 2DEG in between the resonators is still present. We observe the disappearing of both cavity modes as the system enters the strong coupling regime and the evolution of the magnetopolaritonic branches as the value of the field is swept through the resonances. A theoretical model which includes the anti-resonant terms of the light-matter coupling Hamiltonian shows very good agreement with the experimental data. A ratio between the Rabi frequency and the cyclotron frequency in excess of 0.3 is observed for an applied magnetic field of 2.4 T, demonstrating that the system is driven in the so-called ultrastrong light-matter coupling regime.

8260-42, Session 9

Adjusting the functionality of terahertz split-ring resonators through geometry

H. Merbold, ABB Ltd. (Switzerland) and Univ. Bern (Switzerland); A. Bitzer, Univ. Bern (Switzerland); F. Carbone, Ecole Polytechnique Fédérale de Lausanne (Switzerland); A. Murk, Univ. Bern (Switzerland); J. Wallauer, M. Walther, Univ. Freiburg (Germany); T. Feurer, Univ. Bern (Switzerland)

The last decade has seen significant progress in the development of a novel class of materials which may exhibit intriguing optical properties not found in nature. These metamaterials consist of subwavelength metallic inhomogeneities, such as arrays of split-ring resonators (SRRs). We show that the functionality of planar and concentric double split-ring resonators (DSRRs) can be adjusted by varying the relative orientation of the constituting rings. For oppositely oriented DSRRs, we observe the emergence of hybridized modes featuring very narrow line widths, a property particularly beneficial for SRR based sensing applications. Similarly oriented DSSRs yield a behavior reminiscent of electromagnetically induced transparency where we directly resolve the underlying asymmetric current distribution using our experimental near-field imaging approach. For asymmetric DSSRs, on the other hand, we observe the excitation of very sharp dark resonances which are characterized by a suppression of radiation damping. The shape of the resonance peak is therefore mainly determined by ohmic damping which in turn allows for sensing of the metal's optical properties. For complementary DSRRs made from copper, a deviation from the predictions of the Drude model is observed indicating that the assumption of non-interacting electrons may not hold.

We further find that THz SRRs featuring very narrow gaps on the micro- or nanoscale can be used as field enhancing devices providing in-gap enhancement factors of several 10,000, a property that is particularly useful for the realization of nonlinear THz experiments.

8260-43, Session 10

Closely coupled plasmons: real-space mapping and SERS

Z. H. Kim, Korea Univ. (Korea, Republic of)

I will present two experimental approaches to understand the coupling between closely spaced nanostructures. In the first part of the talk, I will present near-field scattering microscopy studies on isolated and coupled nanoparticles to directly investigate the strong coupling between two localized plasmons. In the second part of the talk, I will present the SERS studies on individual nanoparticle - molecular monolayer- thin film junctions, which reveals rich structural and dynamical information on how the adsorbed molecules interact with metallic surface at single molecule level.

8260-44, Session 10

Plasmonic platform for rainbow trapping effect: from theoretical design to experimental realization

Q. Gan, Univ. at Buffalo (United States); Y. Ding, F. J. Bartoli, Lehigh Univ. (United States)

Catching a light or rainbow is always a dream for artists. It is also the aspiration of engineers working in optical technologies. Light waves transmit data with much greater speed than do electrical signals. If they are guided with sufficient precision inside the tiny circuits of an electronic chip, they can bring about applications in spectroscopy, sensing and medical imaging. And they can hasten the advent of faster all-optical telecommunication networks, in which light signals transmit and route data without needing to be converted to electrical signals and back. To enable light waves to store and transmit data with optimal efficiency, engineers must learn to slow or stop light waves across the various regions of the spectrum.

In this talk, we discuss the novel rainbow trapping effect in plasmonic nanostructures. We first explain the design principle of the structure based on theoretical investigations, and then report the experimental observation of a trapped rainbow in adiabatically graded metallic gratings. One-dimensional graded nanogratings were designed and fabricated, and their surface dispersion properties tailored by varying the grating groove depth. Tunable plasmonic bandgaps were observed experimentally, and direct optical measurements on graded grating structures show that light of different wavelengths in visble region is "trapped" at different positions along the grating, consistent with computer simulations, thus verifying the "rainbow" trapping effect.

8260-45, Session 10

Terahertz subwavelength ribbon waveguide based plasmonic sensors for refractive index and thickness detection

B. You, J. Lu, National Cheng Kung Univ. (Taiwan); T. Liu, J. Peng, Industrial Technology Research Institute (Taiwan)

We experimentally demonstrate a terahertz plasmonic waveguide sensor exploiting excitation of spoof surface plasmons (SSPs) in a subwavelength plastic ribbon waveguide sandwiched between two 1D metallic gratings. The excited THz-SSP enables a large propagation length (>5cm) and a highly modal confinement (>50%) compared with the subwavelength ribbon waveguide. Based on the Bragg reflection of SSPs from the periodic metallic grating, the wavelength of the transmission dip could serve as a measure of the refractive index and thickness of the ultra-thin overlayers covered on the metallic gratings. The detected minimum index- and thickness-variation could be down to 0.01 and 500nm, respectively.

8260-46, Session 11

Long-term CEP-stable high energy few-cycle pulses using the feed-forward method

F. Lücking, FEMTOLASERS Produktions GmbH (Austria) and Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ.München (Germany); A. Anderson, FEMTOLASERS Produktions GmbH (Austria); A. A. Apolonskiy, F. Krausz, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); G. Steinmeyer, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); G. Tempea, FEMTOLASERS Produktions GmbH (Austria); A. Assion, FEMTOLASERS Produktions GmbH (United States)

We present the latest developments in Carrier Envelope Phase (CEP) stabilization of compact tabletop ultrafast amplifier systems. The feed-forward CEP stabilization approach for ultrafast oscillators has already pushed the boundaries of frequency comb stabilization. In combination with independent phase stabilization of the amplifier itself, this provides high performance and robustness at the same time for the complete laser system. Additionally, we employ the Hollow Fiber Compression technology to generate few-cycle multi-mJ CEP stabilized laser pulses.

8260-47, Session 11

Ultrafast spectroscopy of metal-based hybrid nanoparticles

F. Vallee, D. Mongin, V. Juvé, A. Crut, P. Maioli, N. Del Fatti, Univ. Claude Bernard Lyon 1 (France)

The size, shape and structure dependencies of the properties of nanoobjects, and the concomitant possibilities they opened to control them, lead to considerable activities in the academic and industrial domains. Confinement effects in nanoobjects formed by a single material, e.g., a metal or a semiconductor, have now been extensively studied. Less interest has been devoted to complex systems, combining multiple material components in the same nanoparticle, e.g., hybrid metal-semiconductor or dielectric particles. Combining the nanoscale response of their components offer many possibilities for developing novel plasmonic systems, and also raise fundamental questions on the material interaction, e.g., on plasmon-plasmon or plasmon-exciton coupling, or on energy and charge transfer mechanisms.

We report on ultrafast spectroscopy of hybrid nanoparticles formed by a metal (Au) and either a semiconductor (CdS) or a dielectric (SiO2). In the first system, femtosecond carrier photoexcitation in the semiconductor part is shown to induce an ultrafast spectral shift of the gold surface plasmon resonance. This yield evidence for ultrafast electron transfer between the two-materials with an upper limit for the electron transfer time of about 10 fs. Mechanical coupling is investigated in the second system, via measurement of the acoustic vibration period of metal-core - SiO2-shell nanoparticles. The results show a period shift of the dominant mode with the shell thickness, in agreement with a theoretical model assuming perfect mechanical contact between the metal and dielectric. More generally, this approach offer a unique way of probing the mechanical contact between materials forming hybrid nanoparticles.

8260-48, Session 11

Nanoantenna-enhanced ultrafast nonlinear spectroscopy of a single gold nanoparticle

T. Schumacher, D. Ullrich, M. Hentschel, Max-Planck-Institut für Festkörperforschung (Germany); H. W. Giessen, Univ. Stuttgart (Germany); M. Lippitz, Max-Planck-Institut für Festkörperforschung (Germany)

Optical nanoantennas, just like their radio-frequency equivalents, enhance the light-matter interaction in their feed gap. Antenna enhancement of small signals promises to open a new regime in linear and nonlinear spectroscopy on the nanoscale. Without antennas especially the ultrafast nonlinear spectroscopy of a single nanoobject is very demanding. We present the first antenna-enhanced ultrafast nonlinear optical spectroscopy. In particular, we utilize a disc-shaped dipole antenna (diameter 75 nm) to determine the nonlinear transient absorption signal of a single gold nanoparticle (diameter 40 nm). The transient response is caused by mechanical breathing oscillations, reflection the elastic properties on the nanoscale. We trigger the mechanical oscillations of nanoparticle and antenna by impulsive heating through a pump pulse (800 nm). After a variable time delay a probe pulse (530 nm - 750 nm) interrogates the transient absorption of both particles. Due to their different mechanical oscillation frequencies, we can separate the two responses.

In our current setup, a single 40nm particle is at the limit of our detection capabilities. Using the optical nanoantenna, we increase the signal amplitude by an order of magnitude which is in good agreement with our analytical and numerical models. We expect to be able to study the mechanical properties of structures with dimensions below 10 nm, where classical continuum mechanics is no longer applicable. Beyond that, our method will find applications in linear and nonlinear spectroscopy of nanoobjects, ranging from single protein binding events via nonlinear tensor elements to the limits of continuum mechanics.

8260-49, Session 11

Subradiant plasmon resonances for spasing

D. Vercruysse, P. Van Dorpe, V. Niels, L. Lagae, IMEC (Belgium) and Katholieke Univ. Leuven (Belgium)

One of the key ingredients that would allow a wide penetration of surface plasmon based technologies in several application domains, is the availability of an integrated, coherent source of surface plasmons, or SPASERS. These spasers have a similar working principle as lasers. However, whereas a laser exploits stimulated emission of photons, a spaser is based on plasmons.

The work of Noginov et al. has shown that a spaser can be fabricated using a gold nanoparticle as a local surface plasmon resonator by coating it with OG488 doped silica.[1] This is a remarkable result, given the large absorption and radiation losses in spherical gold particles. The efficiency of this type of spaser might be improved significantly by utilizing lower-loss resonances, e.g. based on higher order modes. Local surface plasmon resonators with an affinity for dark or subradiant modes have been investigated for sensing purposes. [2] The gold nanocross is an ideal candidate for this. Based on FDTD simulations and experimental results we show that by changing the size and the offset between the arms of the nanocross the resonant frequency of its quadruple mode as well as its radiative character can be altered. After covering these e-beam defined nanocrosses on a glass substrate with ATTO740 doped PMMA we investigate the effect of the plasmonic resonator on this gain material. Changes in the dyes fluorescent spectra can be linked to spectral position of the higher subradiant modes

[1] Noginov, M. A., et al. (2009). Demonstration of a spaser-based nanolaser. Nature, 460, 1110-1112.

[2] Verellen, N., et al (2011) Dark and bright localized surface plasmons in nanocrosses. Optics Express, Vol19, 11034-11051

8260-50, Session 11

Are there novel resonances in nanoplasmonic structures due to nonlocal response?

M. Wubs, S. Raza, G. Toscano, Technical Univ. of Denmark (Denmark); A. Jauho, Technical Univ. of Denmark (Denmark) and Aalto Univ, (Finland); N. A. Mortensen, Technical Univ. of Denmark (Denmark)

In tiny metallic nanostructures, quantum confinement [1] and nonlocal response [2,3] change the collective plasmonic behaviour with resulting important consequences for e.g. field-enhancement and extinction cross sections. We study the nonlocal response of a confined electron gas within the hydrodynamical Drude model. We address the question whether plasmonic nanostructures exhibit nonlocal resonances that have no counterpart in the local-response Drude model. Avoiding the usual quasi-static approximation, we find that such resonances do indeed occur, but not in the visible spectrum [3]. Thus the recently found nonlocal resonances at optical frequencies for very small structures, obtained within quasi-static approximation, are unphysical. We also address the need for additional boundary conditions apart from the usual Maxwell boundary conditions. As a specific example we consider nanosized metallic cylinders, for which extinction cross sections and field distributions can be calculated analytically. Differences between local and nonlocal-response emerge for structures with details smaller than 10 nanometers. Even though there are no nonlocal resonances in the visible, plasmonic field enhancements are affected by nonlocal response. We present both analytical results for simple geometries and our numerical implementation for arbitrary geometries, and address some computational issues related to the several length scales involved.

[1] Z. F. Ozturk et al., J. Nanophot. 5, 051602 (2011).

[2] J. M. McMahon et al., Phys. Rev. Lett. 103, 097403 (2009).

[3] S. Raza et al., submitted (2011); ArXiv:1106.2175.

8260-51, Session 12

Coherent acoustic excitation of membranes and nanostructures

T. Dekorsy, Univ. Konstanz (Germany)

invited talk

8260-52, Session 12

Ultrafast dynamics of coherent optical phonons in GeTe/Sb_{2}Te_{3} superlattices: thermal conductivity and coherent control

M. Hase, Univ. of Tsukuba (Japan); J. Tominaga, National Institute of Advanced Industrial Science and Technology (Japan)

Phase change data storage technology offers high-speed, rewritable nonvolatile solid-state memory, which may overcome the current generation of Si-based memories. One of the most common and reliable materials for the modern optical recording is Ge_{2}Sb_{2}Te_{5} (GST), in which the phase change between the crystalline and amorphous phases serves rewritable recording, and the phase switching time scale could be less than 1 nanosecond.

Here we report on evaluation of lattice thermal conductivity of GST superlattice (SL) by using a coherent phonon spectroscopy at various lattice temperatures. The time-resolved transient reflectivity obtained in amorphous and crystalline GeTe/Sb_{2}Te_{3} SL films exhibits the coherent A_{1} optical modes at terahertz (THz) frequencies with picoseconds dephasing time. The dephasing time and frequency of the coherent A_{1} modes are used to compute the lattice thermal conductivity based on the Debye theory, including scattering by grain boundary and point defect, umklapp process, and phonon resonant scattering. The results indicate that the thermal conductivity in the amorphous SL film is less temperature dependent, due to the dominant phonon-defect scattering, while in the crystalline SL it is temperature dependent because of the main contributions from umklapp and phonon resonant scatterings. We argue the higher thermal conductivity in the GeTe/Sb_{2}Te_{3} SL films than that in the conventional GST alloy films implies that the phase change in GeTe/Sb_{2}Te_{3} SL under the irradiation of ultrashort laser pulses is not promoted by thermal process, i.e., lattice heating, but rather by nonthermal process, i.e., coherent control of lattice excitation, because the thermal process generally requires lower thermal conductivity.

8260-53, Session 12

Modulation of magnetization by picosecond acoustic pulses in ferromagnetic semiconductor GaMnAs

A. V. Scherbakov, Ioffe Physical-Technical Institute (Russian Federation)

In this work we apply the methods of ultrafast acoustics to manipulate magnetization of ferromagnetic structure. We send a picosecond strain pulse to a ferromagnetic semiconductor (FMS) epitaxial layer and detect the tilt of magnetization followed by the coherent magnetization precession. The observed effect is attributed to the strong dependence of magneto-crystalline anisotropy (MCA) of FMS layer on strain.

The structure studied is (Ga,Mn)As layer grown by low-temperature MBE on GaAs substrate. The epitaxial strain determines the MCA of FMS layer and leads to the in-plane orientation of easy magnetization axis. At external magnetic field B the balance between the MCA and B determines the magnetization direction. The idea of our experiment is to modulate the MCA by a strain pulse and, thus, to tilt magnetization.

At experiment a Ti-sapphire laser pulse (200-fs duration) is split to pump and probe pulses. The pump pulse generates picosecond strain pulse in 100-nm Al transducer deposited on the polished substrate. Measuring the Kerr rotation angle of the linearly polarized probe pulse we monitor the time evolution of magnetization. A variable delay between pump and probe pulses provides the time resolution.

We discuss the observed experimental signals and their dependence on the strength and direction of magnetic field considering a linear dependence of the MCA coefficients on strain. Numerical analysis provides perfect agreement with the experimental results.

Collaborators: A.S. Salasyuk, M. Bombeck, A.V. Akimov, C. Brüggemann, D.R. Yakovlev, X. Liu, J. Furdyna, B. Glavin, T. Linnik and M. Bayer.

8260-54, Session 12

Nonthermal processes of coherent acoustic phonons generation in semiconductors by femtosecond laser

P. Ruello, V. Goussev, P. P. Babilotte, G. Vaudel, T. Pezeril, D. Mounier, Univ. du Maine (France)

Seeking for the new opportunities to efficiently excite GHz-THz coherent acoustic phonons by femtosecond lasers is an active field of research which aims at paving the way for new opto-acoustics and opto-mechanics devices. Several fundamental objectives have to be addressed in order to achieve this acoustic phonons manipulation by femtosecond laser. Among them, the understanding of femtosecond generation of coherent acoustic phonons remains a key route. Several electron-phonon, photon-phonon and phonon-phonon interaction mechanisms are involved in the processes of generation and remain only partially understood up to now. Moreover, the success of these fundamental researches will open possible applications only once efficient and tunable coherent acoustic phonon sources are obtained. In this communication, we will present a survey of ultrafast photo-generation of coherent acoustic phonon in semiconductors. We will focus first on the generation of the phonons by fs-laser excitation through the photo-induced modifications of nanoscopic internal electric fields (deformation potential) in non-piezo-active [100] GaAs semiconductor. We will show secondly how it is possible to develop more efficient sources by using piezo-active [111], [-1-1-1] and [411] GaAs semiconductors. Generation due to inverse piezoelectrical effect based on ultrafast light-induced screening of the near surface built-in electric field or based on photo-induced Dember electric field will be both discussed. In the last part, we will finally discuss new routes of fs-laser generation employing ferroelectrics which are materials that exhibit huge internal macroscopic electric field and, commonly to the oxides family, also present large electron-phonon coupling.

8260-55, Session 12

Time-resolved acoustic phonons in low dimensional objects

A. Devos, Institut d'Electronique, de Microélectronique, et de Nanotechnologie (France)

Ultrashort laser-pulses can be used to excite and detect very high frequency acoustic wave. The so-called picosecond acoustic technique has reached this way an unexplored frequency range by using femtosecond laser pulses in a pump and probe scheme. Such frequency falls typically in the hundreds of gigahertz range, a range which suits very well the acoustic vibrations of nanoscale objects. The pump-probe setup thus offers an unique way of studying the impact of size reduction on elastic properties and phonon confinement.

In this talk I present some results obtained on various nanoscale low-dimensional systems. First, suspended membranes and nano-wires in which acoustic waves are confined. Time-resolved technique is shown to be very efficient for studying the confinement of acoustic and thermal energy within such objects. Second, we present results obtained on semi-conductor quantum dots which in some cases can be very efficient in photon-phonon conversion. We also discuss the influence of the organization of the nanostructures in artificial crystals. Such crystals present both photonic and phononic character from which unprecedented properties are expected.

8260-56, Session 13

Control and observation of attosecond electron dynamics in nanostructures

M. F. Kling, Max-Planck-Institut für Quantenoptik (Germany) and Kansas-State Univ. (United States)

The acceleration of electrons in local near-fields of nanoparticles driven by few-cycle laser pulses was studied (S. Zherebtsov et al., Nature Phys., DOI: 10.1038/NPHYS1983). The short pulse duration of 5 fs in our studies ensures that the electron dynamics responsible for the observed phenomena occurs before any nuclear dynamics. Angular-resolved detection of emitted electrons from SiO_2 nanoparticles, modeled by semi-classical calculations, provides insight into the mechanisms responsible for the acceleration. The dynamics is governed by the local near-field of the nanoparticle and affected by the build-up of a surface trapping potential and electron-electron interactions. We investigated the dynamics in small nanoparticles, which can be described within the dipole approximation as well as extended our first studies to larger SiO_2 particles (beyond 200 nm in diameter), where propagation effects play an important role. The emitted electrons and their acceleration can be controlled via the laser waveform (which is altered via the carrier-envelope phase). In addition, we will present theoretical results for the time-resolved probing of collective electron motion in spherical nanoparticles with attosecond nanoplasmonic streaking (F. Süßmann et al, arXiv:1105.2738). For a variety of structural and laser parameters, we evaluated how plasmonic fields in nanoparticles can be probed via employing a few-cycle NIR pulse for the excitation of the collective motion and a time-delayed attosecond extreme ultraviolet (XUV) pulse, which emits photoelectrons into the unfolding near-field. The recorded acceleration and deceleration of these photoelectrons permits the reconstruction of the plasmonic near-fields at the surface of the particles.

8260-57, Session 13

Engineering high harmonic generation in semiconductors via pulse shaping

M. Reichelt, A. Walther, J. Förstner, T. Meier, Univ. Paderborn (Germany)

If a two-level absorber is excited with a short intense light field one can achieve the regime in which the Rabi energy becomes comparable to or larger than the transition energy. Particular non-linear effects, like the occurrence of the carrier-wave Mollow triplet, dominate the emission spectrum. An analogous behavior can be expected for a semiconductor model. However, due to the continuous band structure and the many-body Coulomb interaction between the photogenerated charge carriers the optical response of a semiconductor is much more intricate. We consider a two-band semiconductor with a direct band gap and numerically solve the semiconductor Bloch equations including the interband and additionally the intraband dynamics. Besides excitonic effects, this model also includes the light-field-induced carrier acceleration which gives rise to a strong enhancement of high-harmonic generation. Furthermore, when the spectral shape of the input pulse is altered, the frequency pattern of the reradiated light emission also changes significantly. We show that it is possible to utilize this effect and specifically enhance the emission for a given higher harmonic frequency by applying a non-trivially shaped laser pulse while simultaneously keeping the input power constant. To find the light field we apply different optimization techniques. Besides a standard genetic algorithm, algorithmic differentiation methods in combination with calculus-based optimization techniques are used. The general effect of the demonstrated frequency conversion might turn out to be useful in combination with photonic cavities. For instance, a semiconductor quantum dot can emit into an off-resonant photonic crystal cavity mode when excited with a properly shaped intense laser pulse.

8260-58, Session 13

Ultrafast magnetism as seen by x-rays

I. E. Radu, Radboud Univ. Nijmegen (Netherlands) and Helmholtz-Zentrum Berlin, BESSY II (Germany); K. Vahaplar, Radboud Univ. Nijmegen (Netherlands); C. Stamm, T. Kachel, N. Pontius, Helmholtz-Zentrum Berlin (Germany); H. Duerr, SLAC National Accelerator Lab. (United States); T. Ostler, J. Barker, R. Evans, R. Chantrell, The Univ. of York (United Kingdom); A. Tsukamoto, A. Itoh, Nihon Univ. (Japan); A. Kirilyuk, T. Rasing, A. Kimel, Radboud Univ. Nijmegen (Netherlands)

Revealing the ultimate speed limit at which magnetic order can be controlled, is a fundamental challenge of modern magnetism having far reaching implications for magnetic recording industry. Exchange interaction is the strongest force in magnetism, being responsible for ferromagnetic or antiferromagnetic spin order. How do spins react after being optically perturbed on an ultrashort timescale pertinent to the characteristic time of the exchange interaction?

Here we demonstrate that femtosecond measurements of X-ray magnetic circular dichroism provide revolutionary new insights into the problem of ultrafast magnetism. In particular, we show that upon fs optical excitation the ultrafast spin reversal of GdFeCo - a material with antiferromagnetic coupling of spins - occurs via a transient ferromagnetic state [1]. The latter one emerges due to different dynamics of Gd and Fe magnetic moments: Gd switches within 1.5 ps while it takes only 300 fs for Fe. Thus, by using a single fs laser pulse one can force the spin system to evolve via an energetically unfavorable way and temporary switch from an antiferromagnetic to ferromagnetic type of ordering. These observations supported by atomistic simulations, present a novel concept of manipulating magnetic order on different classes of magnetic materials on timescales of the exchange interaction.

Funding from European Union through UltraMagnetron and FANTOMAS programs is gratefully acknowledged.

[1] I. Radu et al., Nature 472, (2011) 205.

8260-59, Session 14

Terahertz magneto-optics in the quantum Hall system

R. Shimano, The Univ. of Tokyo (Japan)

I guess the invited talk can skip this part.

8260-60, Session 14

THz time domain spectroscopy of quantum cascade lasers

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THz time-domain measurements of loss and gain in THz QCL are presented. The broad band THz pulses generated from fs lasers are ideally suited to study the spectral gain and the waveguide properties of QCLs. Electro-optic sampling allows amplitude and phase resolved measurements of the THz response. We will present the results for different active region designs and cavities. A coupled cavity geometry allows the generation of broadband THz pulses at the first waveguide section and the study of amplification in the second section. For QCLs with LO phonon depopulation design in double metal waveguides we observe a steep increase of the gain at threshold and gain clamping at quite low values.

8260-61, Session 14

THz time-resolved investigation of a Cu/CuxO Schottky barrier

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By utilizing phase-dependent THz pump - THz probe spectroscopy, we investigate the terahertz frequency plasmonic characteristics of a Cu/CuxO) interface. The sample provides a platform for exploring the fundamental characteristics of material interfaces. The high-frequency transmission of THz radiation through dense ensembles of subwavelength Cu/CuxO microparticles via near-field coupling of localized plasmons is shown to be phase dependent. By utilizing in-phase and out of phase THz probe pulses, we show that the transmission properties of the ensemble changes depending on the orientation of polarization of the particles relative to the polarization of the THz radiation. The findings are interpreted in terms of interaction of the space charge region to the THz time-varying plasmonic electric field which perturbs the built-in potential barrier and results in alteration of transmission of the THz probe radiation. This finding introduces a physical groundwork for the integration of plasmonic circuits with traditional semiconductor electronics.

8260-62, Session 14

Terahertz spectroscopy of Ni-Ti alloy thin films

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We investigate the charge transport in nickel-titanium (Ni-Ti) alloy thin films using terahertz (THz) transmission spectroscopy. Ni-Ti alloys have peculiar mechanical properties such as shape memory effects. Electrical conductivity can be a good measure to characterize the alloy phase transitions, yet the carrier transport properties of this material are relatively unexplored in the thin film regime. We grew 60-80-nm Ni-Ti alloy films of various Ti concentrations (0-100%) on intrinsic Si substrates by Ar plasma sputtering. We carried out THz transmission spectroscopy of the samples using broadband THz pulses. The broadband THz pulses were generated by optical rectification of femtosecond laser pulses in a 1-mm ZnTe crystal. The light source was a 1-kHz Ti:sapphire amplifier producing 800-nm femtosecond pulses (pulse energy, 1 mJ; pulse duration, 90 fs). The transmitted THz pulses were measured by either a L-He-cooled Si:Bolometer (sensitive to time-averaged THz power) or by electro-optic (EO) sampling using a 1-mm ZnTe crystal. Analyzing the power transmission data and the transmitted waveforms, we obtained the alloy resistivity as a function of Ti concentration. Sharp changes in the resistivity were observed at the Ti fractions of 22%, 44% and 62%, indicating that structural disorder is greatly enhanced when the alloy undergoes a phase transition.

8260-63, Session 15

Terahertz near-field imaging of electric and magnetic resonances in plasmonic microstructures

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The electromagnetic near-fields of plasmonic systems, not only carry the signature of their resonant behavior, but also play an active role in determining their optical properties, e.g. by mediating coupling between individual plasmonic resonators. Hence, experimentally visualizing the near-fields of resonantly driven plasmonic structures is highly desired in order to get insight into the underlying microscopic mechanisms. While conventional SNOM-type near-field imaging techniques are able to capture field intensities with the required spatial resolution, they are typically not able to provide detailed information on the time- and frequency-dependence or polarization of local fields, as well as on their magnetic field components.

Here we utilize terahertz near-field imaging [1] to measure the amplitude, phase and polarization of the electric near-fields in the vicinity of resonant plasmonic microstructures. By this approach we can trace the electric field vectors after excitation close to the structures on sub-ps time scales with sub-wavelength spatial resolution. From the measured in-plane electric vector fields we are able to reconstruct the out-of-plane magnetic field vectors. Using our approach we have investigated various plasmonic systems operating at terahertz frequencies ranging from sub-wavelength hole arrays [2] over plasmon waveguides to uncoupled and coupled resonators in metamaterials [3].

References:

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8260-64, Session 15

Nanofocusing of mid-infrared light

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Mid-infrared spectroscopy is a powerful tool for highly sensitive material analysis. Its application, however, is limited by diffraction to the micrometer scale. Here we show that mid-infrared light can be focused to nanoscale spots (“hot spots”) by employing antennas and transmission lines. Employing scattering-type scanning near-field microscopy, we are able to map the vectorial field distribution of nanoscale hot spots in antenna gaps, as well as mid-infrared energy transport and compression in tapered transmission lines. We furthermore discuss applications in infrared nanoimaging and nanospectroscopy.

8260-65, Session 15

Experimental demonstration of an offset-apertured near-field scanning optical microscope probe

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Traditional near-field scanning optical microscope (NSOM) tip designs are typically based on one of two principals: (1) A sub-diffraction aperture at the tip of the probe that couples light into or out of the structure of interest for subsequent detection; or (2) An apertureless tip that scatters the near-fields of a structure, where some of this scattered radiation propagates to the detector. The resolution of an apertured tip is limited by the diameter of the aperture. However, the signal decreases in proportion to (d/λ)4, which makes it very difficult to detect a signal from a tip with a small aperture. The fraction of light that is scattered by an apertureless tip and propagates to the detector can be very small, making it difficult to detect a signal from this type of tip as well. In this investigation, we combine principals of both of these classes of NSOM tips to obtain high-resolution scans with a strong signal-to-noise ratio. We separate the aperture from the probe tip and couple the two with the pyramid ridge of the tip which accommodates surface plasmon polariton propagation. In this way, a strong signal can be obtained because the aperture diameter can be as large as one likes so long as it is sub-diffraction. Furthermore, the resolution of such a tip is limited only by the diameter of the apex of the tip. In our work, we demonstrate a resolution of 45nm or /14 with a relatively dull tip, indicating that a substantially higher resolution is possible with a sharp tip.

8260-66, Session 15

Bethe-hole magnetic polarization analyzer

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We study the coupling between the magnetic field component of light and the nano-size hole punctured on the metal surface. Oblique angle incidence of electromagnetic wave to a hole generates non-perpendicular tangential electric and magnetic fields. By resolving polarization angle of the scattered field, we can resolve the contribution of the incident magnetic field to the scattering. In three different hole-size/wavelength ratio, the polarization-resolved-transmission study shows totally different coupling mechanism between the hole and electromagnetic field. At a 10λ size hole, the polarization of the transmitted field follows the polarization of the incident electric field and the hole couples predominantly with the incident electric field. When the hole size is comparable to the wavelength the incident tangential magnetic field starts to couple. And at λ/10 size hole, the hole couples only with the incident tangential magnetic field component, as Bethe predicted. Our results enable the determination of the magnetic field orientation even for such cases where the electric and magnetic fields are parallel to each other, establishing the magnetic polarization of light as a separate entity from its electric counterpart.

8260-67, Session 15

Combining nanooptical fields and coherent spectroscopy on systems with delocalized excitons

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For a lot of nanostructures such as semiconductor quantum dot emitters or biological systems like light harvesting complexes (photosynthesis) the coupling between individual constituents leads to the formation of delocalized exciton states.

Whereas coherent two dimensional spectroscopy like photon echo or double quantum coherence is a versatile tool to investigate the internal coupling of nanostructures, nanoplasmonics provides techniques to localize optical field on a nanoscale.

We combine these two techniques in a theoretical study and propose new experiments.

First, we show, that it is possible to localize the electric field at a quantum dot so that it is 10 times stronger than on another neighbor quantum dot. Second, using this result, we show that the two dimensional spectra with localized fields contain valuable informaton regarding spatial resolution of delocalized states. This allows to experimental verify, how strongly a specific exciton is localized or delocalized. The utilization of nanofields and coherent spectroscopy also opens a wide range of post processing on standard and coherent 2D optical spectra: We show, that using postprocessing of different spectra with localized field, we can enhance certain spectroscopic features in standard coherent spectroscopy, e.g. suppress certain resonances.

The combination of coherent spectroscopy and nanooptics will open new possibilities in retrieving information from spectra especially in case, where states are not well separated in energy.

8260-68, Poster Session

Laser initial chirp effect on femtosecond optical Kerr effect measurement

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In the past few decades, many researchers concentrated on the optical Kerr effect (OKE) due to its applications in many fields. Recently, people tend to use shorter laser pulses in the optical Kerr measurements, as they can obtain the material's temporal responses in shorter time domain and reduce some influences on optical Kerr measurements. However, using the shorter laser pulses (e.g. femtosecond laser), because of their wider spectrum and more serious pulse chirp, will introduce new measurement errors like the Laser initial chirp effect. In this work, we investigated the laser pulse wavelength dependence of ultrafast time-resolved optical Kerr effect in CS2 with the influence of laser initial chirp condition. By adjusting the distance between prism pairs of laser compressor to get different compression characteristics and chirp condition of laser source, corresponding wavelength components dependence of OKE was studied. Special attentions were paid to the peaks temporal-shift of optical Kerr signals at different wavelengths of the probe laser pulses in typical Optical Kerr experiment which we contributed to femtosecond laser initial chirp condition. And the optimized signals were achieved. From the results it is reasonable to say that laser chirp condition plays a great role in ultrafast optical Kerr measurements and this influence on optical Kerr measurements can be reduced by adjusting the laser chirp conditions.

8260-69, Poster Session

A nanoplasmonic contour bowtie antenna for nanoscale confinement of mid-infrared radiation

S. Sederberg, A. Y. Elezzabi, Univ. of Alberta (Canada)

A new type of nanoplasmonic antenna is proposed and simulated. Rather than a standard bowtie antenna, we consider the contour of a bowtie antenna. This geometry allows us to include an additional dimensional parameter in the simulation space: the contour outline thickness. Through finite-difference time-domain simulations, we explore the behavior of these antennas. We show that it is possible to tune the resonant wavelength of these antennas over a broad spectral range by varying the contour thickness and that these antennas operate at wavelengths that are red-shifted when compared to a standard bowtie antenna with the same dimensions. These new antennas allow for an increase in the gap enhancement by 28% and a factor of 3.6 reduction in the antenna footprint. We draw an analogy between a three-dimensional plasmonic nanoshell and the present planar antenna. Two other variants of this antenna are simulated in order to understand the behavior better.

8260-70, Poster Session

A dual-mode terahertz metallic resonator

C. J. Straatsma, A. Y. Elezzabi, Univ. of Alberta (Canada)

A metallic resonator fabricated on silicon capable of dual-mode operation at terahertz frequencies is presented. The resonator exhibits a notch plus stop band filter response or a notch filter response depending on the orientation of the incident electric field with respect to the structure. The notch plus stop band response results in two resonance features: one at 0.69 THz with a Q-factor of 3.7 and the other at 0.91 THz. The notch only response results in a resonance feature at 0.63 THz with a Q-factor of 5.7. Using 3D finite-difference time-domain simulations, the device is designed to operate between 0.1 and 1.4 THz. Experimental verification is performed using a free space terahertz time-domain spectroscopy system, and agreement with our simulations is realized.

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8261-01, Session 1

Critical comparison of GaAs and InGaAs THz photoconductors

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Arguably ultrafast photoconductors have been the most enabling device technology in the THz field during the past decade. And their implementation is now worldwide in time- and frequency-domains systems of various types. While the technological push is towards InGaAs or similar photoconductors operating at 1550 nm, the GaAs-based devices operating around 800 nm still provide superior performance and robustness in most cases. This talk contrasts the GaAs and 1550-nm devices in terms of materials design and solid-state metrics such as e-h lifetime, carrier mobility, and breakdown electric field. It also summarizes THz performance metrics such as average power and bandwidth, and addresses the issue of reliability in these devices which can be problematic because of the high junction temperature and bias field that they must endure.

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8261-02, Session 1

Portable terahertz spectrometer with InP related semiconductor photonic devices

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We demonstrate the several beat sources based on 1.55 μm photonic devices. Broadband antenna integrated low-temperature-grown (LTG) InGaAs photomixers are also verified for widely tunable continuous-wave (CW) THz generation and detection. The novel optical beat sources show a beat frequency tuning range of 0.26 to over 1.07 THz. The dual-mode laser diode (DML) consists of one phase and two active sections. The micro-heaters are used to independently tune the wavelengths of the two laser modes of the DML. Wavelength tuning with the micro-heaters is preferable to optical beat sources because it maintains the spectral linewidth of lasing modes and the optical beat frequency can be continuously tuned without mode hopping. Broadband antenna integrated LTG InGaAs photomixers are used as THz wave generators and detectors. For the fabrication of the LTG-InGaAs photomixers, 1.2 μm-thick Be-doped InGaAs layers were grown on semi-insulating InP substrates at 250 using a molecular beam epitaxy (MBE) system. The use of 1.55 μm photonic devices could bring the connection between the THz and InP-based communication technologies since the well-developed InP-based optoelectronic technologies are expected to enable the integration of tunable laser diode (LD) sources with other optical components such as semiconductor optical amplifiers (SOAs), electro-absorption modulators, and waveguide-type THz photomixers. Besides realization of optical fiber-coupled THz time-domain spectroscopy (TDS) system, we are also successfully achieved continuous frequency tunings of the CW THz emissions from 0.315 THz to over 1 THz. Our results show that photomixing using the photonic devices is very promising for the realization of a compact and cost-effective portable THz spectrometer.

8261-03, Session 1

High-speed three-dimensional terahertz tomography using electronically controlled optical sampling

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We demonstrate 3-dimensional high-speed tomography using a terahertz (THz) pulse. High-speed THz tomography has been implemented based on electronically controlled optical sampling (ECOPS). The ECOPS system employs two femtosecond lasers for generation and detection of THz pulses, respectively. The time delay of the probe pulse from one laser is repetitively scanned at 1 kHz against the pump pulse from the other laser. Thus, the ECOPS system enables us to measure the time-domain waveform of the THz pulse at 1 kHz.

The A scan can be obtained at 1 kHz by measuring the time-domain waveform of the THz pulse reflected from a sample. The A scan range is limited to ~10 mm in free space due to the time delay window of the ECOPS system. It can be extended at a lower scan rate. XY translation stages are used to scan a sample, which move in a zig-zag trajectory. While scanning a sample, we acquire the THz time-domain signal and the position information of the XY translation stages, simultaneously. For C scan images, we interpolate the zig-zag grid into the uniform rectangular grid by use of the triangle-based linear interpolation method. Also, the deconvolution is performed for the A scan. Resultantly, we can acquire a 3-dimensional tomographic image with 140X100X700 pixels for 10 mm x 10 mm region in 14 seconds. The acquisition time is limited by the motion of the XY translation stages. We will be able to reduce the acquisition time by using THz beam scanning.

8261-04, Session 1

Terahertz dynamic scanning reflectometry of soldier protective material

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Ballistic characterization of improved materials for Soldier personal protective equipment is an ever challenging task, requiring precise measurement of materials during ballistic impact. Current dynamic deformation technologies, such as high speed digital image correlation and laser velocimetry, are only able to provide surface measurements. However, there is a need to measure the dynamic delamination and mass loss of composite material, thus allowing calculation of available kinetic energy remaining in the material. A high sensitivity terahertz scanning reflectometer may be used to measure dynamic surface deformation and delamination characteristics in real-time. A number of crucial parameters can be extracted from the reflectometer such as dynamic deformation, propagation velocity, and final relaxation position. As a proof of principle, an acrylic plate was struck with a blunt pendulum impactor and the dynamic deformation was captured in real time. Reflectance kinetics was converted to deformation and the velocity calculated from the kinetics spectrum. Kinetics of a focused pendulum impactor on a steel plate was also acquired, characterizing plate relaxation from maximum deformation to equilibrium with discernible vibrations before reaching stable equilibrium.

8261-05, Session 1

Towards monolithically integrated CMOS cameras for active imaging with 600 GHz radiation

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Progess in terahertz (THz) imaging has been impeded by the lack of cost-efficient, room-temperature cameras. Plasma-wave-stimulated rectification in field-effect transistors has been identified and demonstrated as a promising detection concept [1]. Distributed phenomena sustain the resistive mixing process well above the transistor's cut-off frequency.

Antenna-coupled field-effect-transistors have been implemented as detectors entirely using commercial CMOS technology [2]. Improved detectors reach an average maximum responsivity of 970 V/W and achieve an average minimum noise-equivalent power (NEP) of 43 pW/sqrt(Hz) [3]. A high yield, the low performance variations of less than 8 % between pixels of different chips and a good uniformity of the array suggest, that CMOS detectors are suitable candidates for commercial cameras [3].

Firstly, this contribution discusses the design of a fully-scalable CMOS THz camera and addresses straightforward strategies to meet the challenge for read-out and multiplexing imposed by a high detector output impedance. Secondly, a 100x100-pixel virtual camera has been simulated by scanning a single pixel detector in the image plane over the beam spot of 2x2 cm^2 both in power detection and heterodyne mode. Example images are shown, which have been acquired with an integration time of 10 ms (30 fps) and using active illumination with 150 µW power. Images show a dynamic range of 20 dB and achieve sub-millimeter resolution limited by the optics.

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8261-06, Session 1

Liquid crystals for terahertz technology

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Liquid crystals (LCs) have been studied for various applications such as display, tunable optical elements, communications, and signal processing because it has relatively large birefringence. In order to develop efficient optical devices based on LCs, it is essential to understand the optical and mechanical properties of LCs such as the extraordinary and ordinary refractive indices, and viscosity. In recent decades, terahertz (THz) studies have been widely explored from investigations of spectroscopy data in chemicals and explosives to bio-medical imaging of breast cancers and skin diseases. For these and practical applications using THz waves, THz optical devices such as waveplates and polarizers are essential components. THz optical devices based on LCs are especially attractive because LCs have relatively large birefringence and moderate absorption in the THz range. Furthermore, the optical properties of LCs can be conveniently controlled using electric or magnetic fields. Several different THz optical devices based on LCs like phase shifters have been already demonstrated successfully.

In this paper, we have investigated terahertz properties of a set of LCs: E7, BL037, RDP-97304, and RDP-94990. Refractive indices and absorption coefficients of ordinary axis and extraordinary axis of LCs were acquired from the measurements using conventional THz time-domain spectroscopy. We found that RDP-94990 has the comparably large and flat birefringence and small absorption in the THz range. It is a good candidate to design fast and efficient THz optical devices.

8261-07, Session 2

Miniature self-aligned external cavity tunable single frequency laser for THz imaging

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We report on the unique highly-configurable wavelength tuning and switching properties of a tunable external cavity laser based on multiplexed volume holographic gratings (VHGs) and a digital micromirror device. The ultra-compact (3x3x3 cm3) laser exhibits single mode operation in either single or multiple wavelengths with narrow linewidth , 50ms rise/fall time constant, and maximum switching rate of 0.66KHz per wavelength. A prototype laser exhibited 37 mW of output power in wavelengths from 776 - 783 nm.

The unique discrete-wavelength-switching features of this laser are well suited as a source for CW Terahertz generation, as the laser can access any sequence of discontinuous frequency points, in any order, without needing to tune continuously in a sweep from one frequency to the other. This ability to "frequency hop" is a distinct advantage when compared to thermally-tuned DFBs or grating-tuned semiconductor lasers for THz photomixing applications, improving the agility of the system and enabling access to frequencies from 100GHz to 3THz.

The design also provides several distinct advantages over conventional Littrow or Littman/Metcalf designs, including size, cost, stability and discrete, rapid wavelength control.

The novel self-aligning optical configuration greatly reduces assembly tolerances and package size, while the micro-mirror switching allows discrete access to multiple wavelengths.

8261-08, Session 2

Evaluation of terahertz spectra using chemometric methods

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Many crystalline substances like explosives, drugs or chemicals can be identified using terahertz time-domain spectroscopy. The measurements can be done either in transmission or reflection mode with spectral features being more distinctive in transmission. 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, e.g. water vapor lines or the roughness of sample surface. Therefore a reliable method for the automatic identification of real-world spectra has to be developed.

Our approach is the use of chemometric methods for the extraction of information from terahertz measurements. These chemometric methods are known from the evaluation of infrared spectra, but they have to be adapted to the specific features of the broadband terahertz spectra. In most cases, it has to be decided how the substance-specific information is hidden within the various environmental influences to the 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 (pipeline of filters) is essential for the discrimination of the measurements in this so-called "feature room". Based on such a reliable mathematical model, methods of pattern recognition can be used for automatic identification of substances. We also show that data derived from measurements in the reflection mode demand a much higher effort than those retrieved in transmission mode.

8261-09, Session 2

Application of graphene membrane in micro-Golay cell array

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We report the design, simulation, and fabrication of a miniaturized, uncooled Golay cell array, implemented with monolayer graphene suspended over thin TEM foils as the deflecting membrane. Currently, ultra-thin polymer membranes for Golay cell applications are prone to increased flexural rigidity as the lateral dimensions are reduced to the microscopic range, and monolayer growth has not been achieved. We examine how graphene's unique material parameters, such as low flexural rigidity, atomic layer thickness, broadband optical conductance, high electrical conductance and negligible gas permeability, can potentially improve performance over existing polymer membrane approaches. Chemical vapour deposition of large-area, high quality graphene enables large scale fabrication of graphene membranes required for Golay cell arrays. Simulations of deflection versus temperature are presented, with analysis of the optimal geometry for maximum sensitivity.

Cavities with all spatial dimensions under 10 µm are predicted to provide sensitivities of approximately 10 nm/K, in good competition with devices hundreds of times larger. We present simulations of the visible optical reflection response of graphene Golay cells under thermal irradiation.

8261-11, Session 3

THz lasing in InAs/GaSb broken-gap heterostructure devices and quantum-dot pillar arrays

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An efficient man-portable and powerful radiation source is of great potential importance for terahertz (THz) frequency spectroscopy in future field applications, because the long wavelength regime (wavelength range 1000-100 µm; frequency range 0.3-3.0 THz; photonic energy range 1.24-12.4 meV) offers promise for probing the unique spectral fingerprints of many biological and chemical molecules. However, achieving robust and highly efficient THz sources has long proven to be a formidable challenge in physical electronics. While useful and viable solid-state THz sources exist (e.g., Schottky diode harmonic multipliers; two-wave photomixers, Auston Switch type emitters, and quantum cascade lasers (QCLs)) their operating power levels, power efficiency and/or bandwidths remain somewhat limited across at least portions of the THz regime and motivates the investigations of new and novel device concepts. This presentation will discuss ongoing research into a novel approach for the generation of THz radiation that utilizes "interband" transitions and tunneling processes occurring simultaneously within double-barrier (DB) GaSb/InAs/GaSb broken-gap (BG) resonant-tunneling-diodes (RTDs). The key innovations are the use of ultra-fast heavy-hole (HH) interband tunneling to realize depopulation of the lower valence-band (VB) well-state, and spatially-delocalized (SD) interband transitions (i.e., arising from electrons resonantly injected into the upper conduction-band (CB) well-state) to realize robust THz lasing with significant suppression of the degrading nonradiative recombination processes. An analysis of the major electronic and photonic processes occurring within InAs/GaSb broken-gap heterostructure devices will be given, along with full architectural and cavity designs for realizing coherent vertical emission from single large-aperture DB-BG-RTD devices and quantum-dot pillar arrays. Design techniques useful for mitigating CB drive current (& the associated thermal heating) while at the same time optimizing output power and power efficiency will be the major emphasis of the presentation.

8261-12, Session 3

Energy conversion efficiency calculation model for direct-bonding planar-waveguide THz emitters based on optical rectification effects in GaAs

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The generation of terahertz (THz) pulses based on optical rectification effects in gallium arsenide (GaAs) has become more and more attractive and practical due to advances in high power ultrashort pulse fiber lasers. However the energy conversion efficiency between the THz pulses and ultrashort optical pulses is low and is sensitive to the phase-match conditions for the optical rectification process. Normally the coherence length is a parameter introduced for judging how the phases match by comparing the group velocity of optical pulses with the phase velocity of one of the frequency components, like a component at 2 THz, of THz pulses. It is obvious that the coherence length can not characterize the THz pulse generating process well because it can not include the contribution to all components in the spectrum band of the THz pulses. An energy conversion efficiency calculation model is proposed in this paper by integrating the energy of all THz components generated by the optical rectification process in a planar waveguide device in which the GaAs wafer is direct-bonded with a silicon wafer to form an asymmetric waveguide with air as its cover layer. Under the condition of long coherence length, which could be obtained by designing the configuration of the asymmetric waveguide, we found the spectrum bandwidth of THz pulses generated by the waveguide devices quite narrow and some approximations can be made in an acceptable way for deducing the integral results of the energy in the THz band. The best duration of input optical pulses and the center wavelength of THz pulses at which the energy conversion efficiency has a maximum, can be calculated by this calculation model.

8261-13, Session 3

Long-term frequency and amplitude stability of a solid-nitrogen-cooled continuous wave THz quantum cascade laser

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The Submillimeter-Wave Technology Laboratory (STL) is engaged in the development of compact coherent THz transceivers using Schottky diode mixers and THz QCLs as transmitters and local oscillators. Efforts have been focused on obtaining continuous wave (CW) operation, ultra-stable frequency and amplitude QCL performance and sufficient output power to drive state-of-the-art Schottky diode mixers1. Identifying the simplest approach to achieving these goals motivates this work. As growth and fabrication techniques have improved2 the operating temperature of CW THz QCLs has increased and enabled solid nitrogen to be employed as the coolant. The hold time compared to liquid helium has thereby increased approximately 30-fold, and at a greatly reduced cost.

A roughing pump was used to solidify liquid nitrogen, and when the residual vapor pressure in the nitrogen reservoir reached the maximum thru-put of the pumping system, the temperature equilibrated and remained constant until all the nitrogen sublimated. The QCL was operated CW at solid nitrogen temperature (59K at the QCL mount when biased at ~ 1A and 5V). To measure the long-term frequency, current, and temperature stability, the free-running 2.31 THz QCL signal was heterodyned with a CO_2 pumped far-infrared gas laser line in methanol (2.314 THz) in a corner-cube Schottky diode and the IF frequency, QCL current, and temperature were recorded. Under these conditions the performance characteristics of the QCL, which will be reported, exceeded that of a device mounted in a mechanical cryocooler.

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8261-14, Session 3

Plasmonic response of grating-gated InGaAs/InP HEMT device to terahertz and millimeter wave radiation

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Plasmons can be generated with photons in the two dimensional electron gas (2DEG) of high electron mobility transistors (HEMTs). Because the plasmon frequency at a given wavevector depends on sheet charge density, a gate bias can tune the plasmon resonance. This effect allows a properly designed HEMT to be used as a voltage-tunable detector or filter. This work describes characteristics of such a device and its possible response to millimeter wave radiation.

In previous works, values of different parameters of HEMT such as sheet charge density ns, mobility μ and relaxation time   were obtained [2]. Using these values, plasmon resonance spectrum was also calculated based on the theory developed for MOSFETs by Schaich, Zheng, and McDonald [1]. The effect of differences in each of parameters of HEMT devices were studied and analyzed [2], on studying of plasmon spectrum of these devices free electron laser [3] and a Fourier far infra-red spectrometer [4] were used to reveal the frequencies of plasmon absorption resonances.

In present work, we are using a FTIR microscope interfaced with a He-cooled IR bolometer and cryostat to measure the frequencies of plasmon resonances. Also, we are using ultrastable BWO radiation source operating in range 40-110 GHZ with frequency modulation and synchronous lock-in detection to detect very weak photoresponse effects of the HEMT device.Using BWO radiation source and modulating the frequency of the BWO with modulation amplitude Δf, we synchronously amplify the measured source-drain current ISD. Supposing that there is some effect on channel conductance due to the absorption by plasmons, whose absorptance A = 1-T-R, then the lock-in output is proportional to $|(\delta T/\delta f)|\Delta f$. This allows detection of resonant changes that depend on gate-voltage, even though the resonances are broader than the tuning range of the BWO in the mm-wave range.

8261-15, Session 3

New developments in waveguide mode matching techniques for far-infrared astronomy

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In this paper we consider new developments in waveguide mode matching techniques applied to the efficient modeling of the radiation characteristics of cavity coupled detectors. This approach is useful in far-infrared astronomical instrumentation and cosmic microwave background experiments (e.g. QUAD) in which bolometers, cavity coupled to a horn antenna or Winston cone structure, are often employed for high sensitivity, good control of stray light and a well behaved predictable beam pattern. When calculating the radiation patterns of such systems the cavity is often assumed to be perfect and modeled as a black body radiator, which is equivalent to assuming perfect absorption by the bolometer and no reflections from the cavity of the incoming radiation. While it is possible to model such systems using full wave FEM techniques it would also be desirable, especially for large structures in term of the wavelength, to exploit more efficient mode matching techniques, particularly for the design optimisation phase. This would also be particularly useful for cavities feeding over moded-horn waveguide structures or Winston cones. The advantage of the mode matching approach is that it is straightforward to model the complete pixel including horn, waveguide cavity and the bolometer in the form of a thin absorbing layer. The absorbing layer is included as a thin resistive sheet and is incorporated into the mode matching code. We will discuss the examples of a cavity coupled bolometer feeding both a corrugated single mode feed horn and a smooth walled Winston cone geometry that illustrate the effectiveness of the technique to predict beam patterns and optical efficiencies.

8261-16, Session 4

Spoof plasmon analogue of metal-insulator-metal waveguides

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Metallic surfaces with corrugations have been previously studied as guides for surface electromagnetic modes with the corrugation providing additional control over electromagnetic fields. Recently, terahertz modes on subwavelength-corrugated conductors have been identified as 'spoof' surface plasmons (SSPs), which emulate optical frequency surface plasmons on flat metallic surfaces and enable the concentration of terahertz radiation at a metal/dielectric interface.

In this report, we analyze the guided modes of a parallel plate waveguide with subwavelength corrugations on both surfaces. These corrugations significantly alter the electromagnetic modes on both sides of the light line compared to both the non-corrugated parallel plate waveguide and the single corrugated interface. The geometrical parameters of the corrugations provide a large degree of control over dispersion properties and field distributions of light in such a waveguide. We analytically derive the dispersion relations of these modes and elucidate their unique properties. Because our structure is closely related to non-corrugated metal-insulator-metal (MIM) waveguides in plasmonics, we will refer to the doubly-corrugated geometry as a spoof-insulator-spoof (SIS) waveguide.

SIS waveguides have numerous design parameters and can be engineered to guide modes with very low group velocities and adiabatically convert light between conventional photonic modes and plasmonic ones. Analytical calculations and finite element simulations are used to demonstrate this new approach to mode conversion.

8261-17, Session 4

Wide-range broadband terahertz emission from high chi(2) dendrimer

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The electro-optic (EO) route for terahertz (THz) generation is advantageous, because, pump-THz conversion is not limited either by emission saturation or by heat dissipation. In EO route, the main mechanisms include: EO rectification (EOR), difference frequency generation (DFG) and optical parametric oscillation (OPO). Of these, EOR depends on a femto-second pulsed laser (femto-laser): when an ultra-fast laser pulse is introduced in to the lattice of an electro-optically active material, the lattice acts as a grating to convert the very high frequency derived from the femto-laser in to a relatively lower frequency pulse, that falls in to the terahertz range; this is the so-called rectification effect. The difficulty here is, not only the process is depended on the availability of a femto-laser, but two vital parameters of the terahertz radiation - the output power and the terahertz range - are completely dependent on the characteristics of the femto-laser. As such, only low average power has been produced and a range of a few terahertz has been possible. Because of its low available THz range (~5THZ), many materials system can not be effectively characterized by such THz source. A wider THz source, therefore, is important. In contrast, difference frequency generation (DFG) uses two-photon excitation that eliminates the use of a femto-laser and allows for producing both continuous wave (CW) and pulsed terahertz radiation. This report outlines a two-photon excitation technique that has been developed to obtain wide band terahertz emission from an EO Dendrimer. This source is suitable for spectroscopy and imaging applications.

8261-18, Session 4

Thin-film platinum nanowires as sub-wavelength bolometers

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We fabricated nanoscale bolometers made of platinum wires framed by four contact pads, using state-of-the art ebeam lithography and metal deposition on SiO2/Si wafers. The thin-film platinum wires have a fixed width of 300 nm and thickness of 50 nm, and their length ranges from 300 nm to 20 µm. By illuminating the bolometers with a NiCr-Ni blackbody infrared source (1200 K, peak wavelength at 2.4 µm), we monitor the change in resistance in the structures depending on length and bias current. The relationship between resistance and temperature is given by :

$R=R0*(1+\alpha\Delta T)$

Where R0 is a constant and α is the temperature coefficient of resistance (TCR) of platinum. Following this equation we are able to characterize accurately the temperature change in the bolometers. From this data we extract two figures of merit for our devices, the responsivity R [V/W] and the detectivity D* [cmHz^(1/2)/W].

By decreasing the wire length, we observe a steep rise in R and D*. Increasing the bias current leads to improved responsivity but the detectivity soon levels off to a plateau. We demonstrate that such simple strutures can have performances comparable to advanced bolometers : our smallest structures reach a responsivity R of 4.5x10^5 V/W and a detectivity D* of 2.3x10^10 cmHz^(1/2)/W. Finally, numercial simulations suggest response times of nanoseconds for our smallest samples. In summary, we present here sub-wavelength bolometers of a simple design, highly efficient with low-power requirements and fast reponse time.

8261-10, Poster Session

Aberrations of the large aperture attenuating THz lenses

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The elements for manipulating THz beams can be designed both on the basis of the microwave and on the optical technology. Similarly to typical optical components, refractive lenses and diffractive structures including high order kinforms can be used in the THz range.

For many practical applications the passive THz systems (e.g. concealed weapon scanners) require sophisticated optical elements with a large numerical aperture (NA). In the case of the mentioned scanners the expected resolution of the whole optical setup is close to the diffraction limit. Therefore the aperture diameter of such optical elements is mostly in the range between 100 and 250 mm or even more and their focal length is often equal to the diameter.

A standard refractive high NA spherical lens for the THz range shows no chromatic aberration due to very weak dispersion. However such lenses exhibit high signal attenuation due to significant thickness. For typical converging lenses their attenuation is higher near the optical axis (low geometrical aberrations) than in the peripheral regions (high geometrical aberrations). This additionally "boosts" geometrical aberrations of the lens.

The authors propose to improve the overall performance of the imaging element by designing a sophisticated Fresnel-type structure. It should be thin enough to provide a low attenuation and thick enough (high order kinoform - phase retardation must be a multiplicity of 2π) to avoid chromatic aberration. Due to special design process the spherical aberration of the structure can be significantly decreased.

Computer modeling and experimental results are presented.

8261-19, Poster Session

Terahertz transmission enhancement through GaN quantum wells controlled by DC voltage

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In the last years, there has been a growing interest in using the terahertz (THz) radiations as a powerful tool to investigate materials/devices/ structures in chemistry, biology, medicine... [1].

In this communication we will present both experimental results and results of an analytical model showing the possibility to control the intensity of THz radiations transmitted through GaN-quantum wells [2] by applying a dc voltage. The devices have interdigitated contacts (IDF) with a distance of Ls = 19 µm in the short region and Ll = 39 µm in the long region, respectively. The width of the device is 500 µm. The experimental set-up uses a commercial electronic source to generate continuous harmonic waves in the 0.22 - 1.1 THz frequency range. The beam is focused in a He-free cryostat by a first spherical mirror. The transmitted beam through device is extracted from the cryostat and focused with the help of a second spherical mirror on a Si-bolometer for measurement. A lock-in amplifier system is used to extract the part of the bolometer signal corresponding to the transmitted beam.

A better understanding of involved physical phenomena responsible of the transmission enhancement in sub-THz frequency range will bee given by a specially developed phenomenological theory of a light transmission via devices under electrical bias [3]. The evolution of transmission coefficient - modelled following the standard procedure as described in [4] - as a function of applied voltage (Fig. 1) will be consequently related to weak changes of the differential mobility µU.

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8261-20, Session 5

Real-world applications of terahertz pulsed technology

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Over the past twenty years terahertz sensor technology has been looking for a "killer" application since the first demonstration of free-space radiation following exposure of a GaAs co-planar strip line to an ultrafast pulsed laser. In the early years, research groups rapidly looked first at dental applications and then skin cancer; however these applications are driven by cost and regulation which make these areas difficult and expensive to penetrate. Early in this century, applications in non-destructive testing began to come to the forefront. This paper discusses the new exciting applications of terahertz pulsed technology in solving real world problems.

8261-21, Session 5

One-half milliwatt 2.33 THz CW QCL operating at 77K

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During the last decade, terahertz quantum cascade lasers (TQCLs) have been rapidly developed due to their potential applications as a compact, coherent THz source. Recently, researchers have devoted their efforts to developing high temperature, high power TQCLs to eliminate the use of either helium cryostats or power hungry cryo-pumped base-plates. Most of the demonstrated high temperature TQCLs have been based on resonant-phonon depopulation designs and fabricated using metal-metal (MM) waveguides, that require complex fabrication procedures. In this work we report a 2.33 THz semi-insulating surface plasmon (SISP) waveguide QCL based on bound-to-continuum (BTC) design with an output power of ~0.5 milliwatt from a single facet, an input power of ~5 watts, and a threshold current density of 123A/cm2 at 77 K. Based on a recent survey of TQCL performance [1], this represents the lowest frequency device with a maximum operating temperature above 77 K in the CW mode from a BTC, SISP waveguide laser. These results were achieved by optimizing the fabrication processes, such as depositing alloy metal on both contact layers, only annealing the bottom metal layers, and thinning the substrate thickness to ~170 µm to assure a better thermal dissipation. With further improved device processing, we expect to achieve 1 mW output power at 77 K in CW mode with less than 5 Watts input power. This work is instrumental to the development of portable, very sensitive coherent heterodyne THz transceivers operating at liquid nitrogen temperature.

8261-22, Session 5

Backwards wave oscillators combined with solid state frequency multipliers extend spectral coverage of electronic sources to 2.2 THz

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For 3 decades millimeter wave sources in the 100-300 GHz spectral range have been used by the global research community. These devices, some generating up to 100 mW CW power, coupled to solid state multipliers with optimized output coupling efficiency have demonstrated that more power can be extracted from a BWO by improving the output impedance matching. Impedance matching the multipliers and BWOs one can improve conversion efficiency from 10 % at low frequencies or.01-1% at higher frequencies by a factor of two on average. Evidence supports that this is actually the improved impedance matching between the BWO and the multiplier compared to free space out-coupling resulting in higher BWO output. These hybrid systems generate smooth coverage across the tuning range. This is an additional indication of poor impedance matching between free space and the BWO internal cavity resulting in their typically spiky power spectra. With additional continued development of nonlinear solid state diodes in frequency multipliers we have developed several different product lines of millimeter wave BWO/multiplier hybrid sources covering from.1 THz to 1.5 THz,.18 to 2.2 THz and.2 to 1.1 THz. We have demonstrated that sub-millimeter wave BWO's can also be extended by tripling the 500-710 GHz QS1-710 BWO to the 1.6 to 2.1 THz range doubling the available power to as much as 20 microWatts from the power level in the QS1-260-2100 MMW BWO/hybrid. Combined with improvements in Golay cell detectors or bolometers this enables more powerful spectroscopic and imaging instruments.

8261-23, Session 5

Upper band operation of active photonic crystal terahertz lasers

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The terahertz (THz) spectral region offers unique potential for applications such as spectroscopy, real-time imaging or sensing. The energy of rotational and vibrational transitions of molecules lies typically in this frequency regime resulting in a chemical fingerprint. Up-to-now the only compact and coherent sources of THz radiation are quantum-cascade lasers (QCLs). The unipolar nature of QCLs allows the realization of various, unconventional resonator geometries.

Here, we present the design, fabrication and characterization of active photonic crystals (PhCs) lasing in the first and second photonic band. The resonator consists of an array of isolated pillars which are embedded in a metallic waveguide. The devices are fabricated with a ratio of pillar radius ‘r’ to PhC period ‘a’ of 0.3 and 0.35 respectively. These THz-QCLs show stable single mode emission around 2.2 THz, purely defined by the PhC geometry and not the gain maximum.

Active PhCs in higher bands have a significant advantage over the previously published devices operating in the first photonic band. The optical mode is pushed out of the pillars and into the surrounding media. This opens a simple path to directly manipulate the lasing mode during operation or to sense variations in the environment. The amount of mode leakage is again defined by geometry.

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8261-24, Session 5

Portable real-time THz imaging setup based on QC lasers

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THz imaging systems are interesting both for research and commercial applications. The unique transitions of molecules in THz range can be exploited to study specific functions of the samples or as fingerprint for security reasons. Thanks to the non-ionizing, low photon energies, the use of THz radiation in biomedical applications is also pursued. The good transparency to THz of non metallic materials such as plastics, ceramics and polymers and the high penetration depth makes this radiation valuable for non destructive material testing and homeland security. In this paper we present the TERASCOPE, a completely portable setup for real-time THz imaging , operating both in transmission and reflection modes and based on quantum cascade lasers. The Terascope is based on laser illuminators constituted by third order distributed-feedback quantum cascade lasers operated either at high duty cycle or in continuous wave mode and cooled down to 40K by a compact Stirling crycooler. The low power consumption and the high efficiency displayed by these photonic-wire lasers is a key factor that allows the realization of a compact and light system with reduced cooling needs. The detector is constituted by an uncooled, micro-bolometer camera operating at video rates The optical system is reconfigurable and based on refractive elements. It allows quick switching from transmission to reflection modes. The footprint of the system is 100 x 60 cm for a total weight of 20 Kg. Real-time imaging of different specimens is realized and, using high NA optics, a resolution of 2.5 times the wavelength (220 micrometer at 3.4 THz) is demonstrated.

8261-25, Session 5

Exploring performance limits of silicon CMOS FET detectors for THz frequencies

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Plasma waves excited in the channel of field-effect transistors can be used for the detection of terahertz radiation [1]. Efficient detection can even be achieved in the nonresonant (overdamped) plasma-wave regime [2], which can equally be understood as the distributed resistive self-mixing model of electronics [3]. An equivalent circuit model properly describing the physical processes is of practical importance and was used for device implementation of monolithically integrated antenna-coupled detectors in a standard 250-nm CMOS process [3]. By going to a 150-nm CMOS technology, by optimizing device impedances, and reducing losses, we recently achieved a 6-fold improvement in sensitivity for radiation close to 600 GHz [4].

This study addresses the effects, which limit the high-frequency performance of THz detectors based on distributed resistive self-mixing in silicon CMOS field-effect transistors. We discuss on the interplay between device impedance, derived by a physical model for rectification, parasitic capacitances, defined by technological node, and integrated antenna characteristics. We present experimental data on detectors implemented with standard 150-nm CMOS technology and optimized for discrete frequencies up to 4.25 THz. Detectors operating at 600 GHz show average maximum responsivity (average noise equivalent power) values of 970 V/W (43 pW/sqrt(Hz)) whereas performance drops to 11 V/W (4 nW/sqrt(Hz)) at 4.25 THz.

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8261-26, Session 6

Propagation loss optimization in dielectric/metal coated hollow flexible terahertz waveguides

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The Terahertz (THz) frequency range, located midway between the microwave and infrared region, is a rapidly developing area for source and detection technologies. For many applications like invivo medical imaging it is necessary to transport and guide THz radiation with minimal transmission loss. A flexible THz waveguide is an essential tool for these applications.

Low loss, hollow, flexible dielectric/metal coated waveguides have been designed and fabricated for the maximal transmission of Terahertz (THz) radiation. Polycarbonate (PC) was chosen to be the base material due to its lowest surface roughness. THz radiation can be guided by coating the inner surface of PC tubing with a high reflective metal like Silver (Ag) or Gold (Au). Attenuation characteristics of Terahertz radiation in Ag and Au coated waveguides with bore diameters 4.1mm, 3.2mm, 2 mm were studied at 215μm wavelength. Minimal Propagation loss of 2dB/m was obtained by coupling the lowest loss TE11 mode from an optically pumped terahertz laser into Ag coated waveguide. Transmission loss can be reduced substantially by creating corrugation in metal coated waveguides and by coupling linearly polarized Hybrid (HE) mode into it. Corrugation can be achieved in waveguides by the addition of a dielectric layer to the metal coating. Polystyrene (PS) was chosen to be the dielectric, due to its lowest extinction coefficient, which enhances the transmission through the waveguide. By coupling HE11 mode into PS/Ag coated waveguides a minimal propagation loss of less than 1dB/m was achieved. The results will be presented during SPIE conference.

8261-27, Session 6

Thin Film Lithium Tantalate (TFLT(TM)) pyroelectric detectors

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Pyroelectric thermal detectors are excellent candidates for detection of broadband radiation. Such detectors utilize permanently poled ferroelectric single crystal lithium tantalate to generate a charge as the crystal heats up by absorbing radiation. The charge, which results in a current output when connected to an external electrical circuit, is directly proportional to the rate of change of temperature of the crystal. The fundamental approach toward enhancing pyroelectric detector response is to form the pyroelectric material into a thin film. An elegant approach for producing bulk quality thin films of pyroelectric materials is by crystal ion slicing. In this paper, we report on the formation of thin film lithium tantalate (TFLT™) pyroelectric detector devices using the ion slicing process. The devices incorporate films less than 9 microns thin and feature apertures as large as 5 mm in diameter. To make functional detectors, ion sliced films were transferred to ceramic carriers in TO-type can test packages. Test results have shown improvement in room temperature detectivity about 20 times higher than the state-of-the-art lithium tantalate pyroelectric detectors.

8261-28, Session 6

Metamaterial-based tunable absorber in the infrared regime

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In this paper, we present a design for a narrowband perfect absorber based on metamaterials in the long wave infrared (LWIR) wavelengths (8-12 μm) for wavelength-selective uncooled hyperspectral imaging systems. Particularly, the proposed narrowband perfect absorber integrated with microbolometer focal plane arrays has the potential to increase the detection sensitivity of the microbolometers. The design of the metamaterial unit cell consists of a resonant metallic ‘cross’ structure which has a resonance in the LWIR wavelengths and is placed on a dielectric substrate with a metal back plate. In order to achieve a very high absorption of the electromagnetic radiation, the designed metamaterial needs to have minimal transmission and reflection within its spectral response window. Minimal reflection is achieved through impedance matching of the metamaterial with the free space whereas zero transmission is ensured through the metal back plate. Moreover, for the purpose of hyperspectral imaging, the metamaterial structure is combined with a tunable electro-optic material, namely, liquid crystal. Tunability can be achieved upon applying a voltage across the combined liquid crystal and metamaterial structure which in turn can change the dielectric constant, thus bringing about a shift in the resonant frequency. In our simulated model, where losses of metal and dielectric substrate materials were taken into account, we noted more than eighty percent of absorption can be achieved with near zero transmission for the designed metamaterial structure.

8261-29, Session 6

Changing growth of neurites of sensory ganglions by terahertz radiation

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Now all over the world workings out on creation of techniques of application terahertz radiations for medicine and biology problems are conducted. From this point of view, the influence of THz radiation on the nerve fibers is of primary concern. Thus, several studies indicated both stimulating and depressive effect on nerve cells. However, the mechanism of this effect has not yet been studied, including defined dose and exposure time. In this regard, our work explore the possibility to change the growth of neurites of sensory ganglion. It demonstrates the experimental setup of model. The generated THz radiation had a frequency band from 0.05 to 2 THz. As object we used sensory ganglias of 10-12 days chicken embryos in organotypic tissue-culture. Time of exposure was a 3 minutes.

After three days the growing of neurites was investigated in vivo. Morphometric method was used to quantify the effect of THz radiation on the growing of neurites in sensory ganglia. In order to unify finite exponents of the growing of neurites, evaluation relative criterion was used - area index (AI), which was calculated as the ratio of whole explant, including the peripheral zone of growth to the original area of the ganglion. AI values were expressed as percentage, the reference value AI taken for 100%. The results were processed with the help of t- Student’s test. Dependence of changes in functional responses of cells from the average output power has been found out. Increasing of stimulating effect in the time of reduction of power density was observed.

8261-30, Session 7

Advances in biomedical imaging using THz technology

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No abstract available

8261-31, Session 7

Generation and detection of broadband THz pulses (>10 THz) with organic nonlinear optical crystals OH1 and DSTMS as alternatives to DAST

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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 relatively 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. Compared to poled polymers, the advantage of organic crystals is the high stability and possibility for relatively large thicknesses (several mm) and therefore high conversion efficiency at the phase-matched conditions. However, most of the efforts in the past have focused only on the generator crystal DAST (4-N,N-dimethylamino-4'-N'-methyl-stilbazolium tosylate), because of the lack of alternative crystals with similarly high figures of merit and possibilities for growth of high-quality single crystals.

We investigate THz interactions using recently developed materials, stilbazolium salt DSTMS (4-N,N-dimethylamino-4'-N'-methyl-stilbazolium 2,4,6-trimethylbenzenesulfonate), which is a derivative of DAST with superior processing and THz figures of merit, as well as phenolic polyene OH1 (2-(3-(4-hydroxystyryl)-5,5-dimethylcyclohex-2-enylidene) malononitrile), which is a hydrogen bonded crystal and an important alternative for stilbazolium salts due to the low absorption at around 1 THz. Best phase-matching properties of these materials for pump optical wavelengths in the range of 800-1600 nm and for THz frequencies in the range of 0.1-12 THz have been determined. We demonstrate efficient generation and detection of very broadband THz pulses (0.1-12 THz) using these materials, pumped by fs fiber lasers at telecommunication wavelengths.

8261-32, Session 7

Terahertz generation from quasi-phase matched gallium arsenide using a type II ring cavity optical parametric oscillator

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We demonstrate generation of 120 micro-Watts at 850 GHz CW power from a 4 layer gallium arsenide quasi-phase matched crystal in stable long term product level performance from 75 W intracavity power using a type II doubly-resonant ring optical parametric oscillator (OPO) with periodically-poled lithium niobate (PPLN) as the gain medium. In previous work a linear cavity type II PPLN OPO produced 1 mW pulsed power at 2.8 THz with a 30% duty cycle. The current OPO was synchronously pumped by 5W from a mode locked 1064 nm fiber laser with 110 MHz repetition rate and 6 ps duration. The pump beam waist is focused to 60 microns in the 10 mm long PPLN crystal. The OPO had 65% pump depletion for a round trip cavity loss of 4%. Signal and idler pulse timing was adjusted to.2 ps separation. The 2.1 micron signal and idler pulses, spectrally separated by the desired THz frequency, are focused to a 330 micron beam waist inside the GaAs. Passive locking with thermal self-stabilization in gallium arsenide (GaAs) alone produced >6 minutes of stable 117 microwatt CW power at 750 GHz. Long term active locking with >100 microwatts has been demonstrated. Additionally, a 15 layer gallium arsenide sample produced 55 microwatts with 42 W intracavity power. This was done with a.5 ps pulse separation. Pump depletion with the 15 layer sample is typically 50-55% for a 6% round trip cavity loss. The THz beam profile is a TEM00 25 mm diameter collimated beam.

8261-33, Session 7

Log periodic antenna coupled microbolometer using low temperature VOx for the mm-wave detection

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Imaging techniques have been developed at various electromagnetic wave frequency bands including X-ray, UV, and infrared. Image sensors with millimeter-wave (MMW) are necessary due to its several characteristics. MMW can pass through some objects and propagate with significantly less attenuation under low-visibility conditions than infrared and visible radiation. So, it is less affected by atmospheric conditions. For these reasons, MMW image sensors can be applied in a variety of areas including radio astronomy, atmospheric radiometry, concealed weapon detection, all-weather aircraft landing, through-wall imaging. In this paper, we suggest a new MMW image sensor using vanadium oxide as a thermal detector.

The new millimeter-wave image sensor using vanadium oxide thin film as a thermal detector was developed. The sensor consists of a micro bolometric detector, a micro heater and a micro antenna. The thermal detecting material is vanadium oxide thin film which has large temperature coefficient of resistance (TCR). Polysilicon was used for the micro heater. The micro log-periodic bow-tie antenna was designed and simulated. The designed antenna has planar structure and resonance frequency of 140GHz. As a result of simulation, It showed broadband characteristic of 31.6GHz and high gain of 14.21dBi at 140GHz. Fig. 1 and Fig. 2 show the new designed antenna and the result of frequency simulation, respectively. The antenna coupled image sensors was fabricated on a 4inch silicon wafer by MEMS technology. The size of the sensor is 3mm by 3mm. LPCVD was used for making polysilicon heater and the vanadium oxide thin film was deposited by reactive DC magnetron sputter. The antenna and electrodes are fabricated using a gold layer. Backside-etched silicon substrate and a silicon nitride membrane were used for thermal isolation structure. The single cell of fabricated sensors is shown in Fig. 3. The fabricated MMW image sensor showed large sensitivity (larger than 550 v/w).

8261-34, Session 8

Continuous wave terahertz reflection imaging of ex vivo nonmelanoma skin cancers

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Continuous wave terahertz imaging has the potential to differentiate between nonmelanoma skin cancers and normal skin. Contrast between cancerous and normal tissue in transmission mode has already been demonstrated using a continuous wave terahertz system.

The aim of this experiment was to demonstrate both reflection and transmission imaging of nonmelanoma skin cancers. A CO2 optically pumped far-infrared molecular gas laser was used for illuminating the tissue at 584 GHz. The reflected and transmitted signals were detected using liquid Helium cooled Silicon bolometers. Fresh skin cancer specimens were obtained from Mohs surgeries at Massachusetts General Hospital. The samples were processed and imaged within 24 hours after surgery. During the imaging experiment the samples were kept in pH balanced saline to prevent tissue dehydration. For evaluation purposes, Hematoxylin & Eosin (H&E) histology was processed from the imaged tissue.

The waist of the terahertz beam in the imaging plane was 0.57 mm and the system's signal to noise ratio was measured to be 65 dB. The terahertz reflection and transmission images were found to correlate well with each other and with sample histology. Our results indicate the reflection based continuous wave terahertz imaging of nonmelanoma skin cancers shows promise for in vivo applications in intraoperative assessment of skin cancer margins.

8261-35, Session 8

THz time-domain spectroscopy in different carbon nanotube and graphene thin-films

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Carbon nanotubes (CNT) have been widely investigated because of their unique properties in view of applications in electronics and mechanics (Dresselhaus, et al., Springer, 2000). THz spectroscopy of CNT samples is nowadays subject to intense researches. The THz time-domain spectroscopy (TDS) is certainly the best tool to perform these studies, as it leads to the simultaneous determination of this material over 0.1 THz to several THz (Mittleman, Springer Series in Optical Sciences, 2003, Duvillaret et al., Topics in Quant. Electron., 739, 1996). The quick fast relaxation time of less than 1ps and slow recombination time greater than 1ps of graphene carriers as well as gapless energy spectrum in THz time-domain emission mixture pumped optical-probe energy hΩ can be archived for studying intraband and interband process (H. Karasawa, et al.,Journal of Infrared, Millimeter and Terahertz Waves, 2010). Recent works have permit to define precise physical models to describe the THz properties of CNT films (T.-I. Jeon, et al., J. Appl. Phys. 98, 2005, C. Kang, et al., Phys. Rev. B 75, 2007, Kim, et al., J. Korean Phys. Soc. 50, 2007, E. P. J. Parrott, et al., Adv. Mat.21, 2009). We will report on the optical and electrical properties of single-walled and multi-walled CNT (SWNT and MWNT) as well as graphene thin-films which are deposited on quartz substrate. We will present corresponding experimental results as well as fitting modelling results by combination of the Maxwell-Garnett and extended Drude-Lorentz models. The results show that by increasing frequency, the power absorption and refractive index of the CNT thin-films are increased and decreased, respectively.

This work is supported by MITEPHO project (www.uc3m.es/portal/page/portal/grupos_ investigacion/optoelectronics/european_ projects/mitepho) which is coordinated by GOTL research group in Carlos III de Madrid University with foundation grant agreement number 238393 (EU-FP7) in order to develop compact tunable dual-mode diode lasers and terahertz spectroscopy in sensing and biomedical applications.

8261-36, Session 8

Laser driven generation of intense single-cycle THz field

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We report on laser-based, high-power single-cycle source operating in the THz gap. Two approaches are currently investigated in our laboratory at the Paul Scherrer Institute: four wave mixing and optical rectification. The temporal and spectral THz pulse characteristics are measured by electro-optical sampling technique. The value of the electric field is crosschecked by calibrated Golay cell measurement.

The four-wave mixing is driven by a TW Ti:Sapphire laser delivering <50 fs, 10 mJ pulses. The laser fundamental and second harmonic are tightly focused in plasma. This setup delivers electric field of several hundreds of kV/cm at central frequency of 0.7 THz.

The optical rectification is carried out in organic salt crystals (DAST, OH1) pumped by powerful optical parametric amplifier. The generated THz spectrum is peaked at 2 THz. Using 0.2 mm DAST and infrared pump of 0.85 mJ at 1.5 microns, we recorded electric field exceeding MV/cm with a corresponding magnetic transient of 1 Tesla. The resulting unprecedented conversion efficiency is larger than 2%.

Both the setups provide sub-ps THz transients with wavefront and transverse beam profile, which allows for near diffraction-limited focusing and the realization of highest fields. Single-cycle TW fields are reconstructed with electro-optical sampling in GaP or ZnTe crystal. The electric field generated with the two techniques is intrinsically carrier-envelope phase stabilized. The presented sources represent a versatile tool for time resolved THz experiments such as ultrafast magnetic switching, nonlinear phenomena and dynamical imaging.

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8262-01, Session 1

High growth rate of AlGaN for buffer structures for GaN on Si to increase throughput

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One of the bottlenecks of GaN on Si by MOVPE is the low growth rate of AlGaN and AlN which is used for the buffer structures on Si. Sometimes the growth rate of AlN is limited to an order of 0.1μm/hr in a large scale production MOVPE reactor. On the other hand, the cycle time for the growth of GaN on Si should be less than 4 to 5 hours for the low cost production. The minimum required growth rate of the buffer structures on Si depends on the total thickness, in other words, the break down voltage (VB). Assuming 1kV of VB, the growth rate of the buffer structure should be more than 1.5μm/hr in average.

In the attempt of growing GaN on Si, we have tested a production scale high flow speed MOVPE reactor (UR25k) for 6 inch X 7 wafers. Al0.58Ga0.42N was grown with the growth rate of 1.95μm/hr at 30 kPa. AlN was grown with the growth rate of 0.9μm/hr at 13kPa. AlN/GaN SLS (5nm/20nm) was grown at the growth rate of more than 1μm/hr. An excellent uniformity of aluminum concentration of less than 0.5% was also obtained for Al0.58Ga0.42N.

Above results is, however, just one step to mass production of GaN electron device on Si. To keep on track the competition with Si technology, we must further increase the growth rate and develop a novel device structure with smaller stacks of layers.

8262-02, Session 1

Low temperature growth of group III nitrides by pulsed sputtering and its applications to large area devices

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It is generally believed that group III nitride devices exhibit high performance but they are quite expensive because their fabrication process involves low throughput high temperature epitaxial growth by MOCVD or MBE. It is quite natural to believe that group III nitride devices prevail quickly among various new application fields once low cost fabrication process is established. Large area nitride devices such as solar cells and displays are among these applications. For this purpose, we have recently developed a new growth technique named PSD (pulsed sputtering deposition). PSD has already attracted much attention of industry engineers because its productivity is much higher than that of MOCVD. In this technique, surface migration of the film precursors is enhanced and, therefore, the temperature for epitaxial growth is dramatically reduced. This reduction allows us to utilize various large area low cost substrates such as metal sheets or mica sheets that have not been used for growth of semiconductors so far due to their chemical vulnerability. In this presentation, we will discuss feasibility of large area nitride devices such as LED displays or solar cells fabricated with PSD on various low cost substrates. We will also show that PSD is quite promising for growth of high In concentration InGaN which is necessary for fabrication long wavelength optical devices.

8262-03, Session 1

Reduction of threading dislocation density by regrowth on In-polar InN

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InN films grown on sapphire by RF-MBE still show high density of threading dislocation in the order of 10^9-10/cm^2. Previously, we demonstrated a regrowth method to reduce dislocation density in InN regrown on N-polar micro-faceted InN template [1]. Recently, successful reduction of dislocation density was also reported by selective area growth of InN using Mo mask [2]. In this study, we report on reduction of the threading dislocation density by regrowth on In-polar InN.

In-polar InN was grown on MOCVD-grown GaN template by RF-MBE. Then, the In-polar InN was etched by KOH solution with 10 mol/l at 70°C for 15 min. The etched In-polar InN surface showed many hexagonal pits compared to the N-polar InN with hexagonal pyramids [3]. InN was regrown on the etched In-polar InN at 400°C for 2h. Cross-sectional TEM study revealed that the regrowth region showed relatively low dislocation density. Especially, density of edge-type dislocations was reduced from about 10^10/cm^2 to 10^9/cm^2. This is due to the bending and merging of the edge-type dislocations at the regrowth interface, which is similar to the mechanism of dislocation reduction by regrowth on N-polar micro-faceted InN [1].

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[1] Muto et al., PSS(a) 203, 1691 (2006).

[2] Kamimura et al., APL 97, 141913 (2010).

[3] Muto et al., PSS(a) 202, 773 (2005).

8262-04, Session 1

Pyramid nano-voids in GaN and InGaN

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We report a new nano-size void defect in InGaN on GaN based light emitting diode structures, revealed by aberration-corrected scanning transmission electron microscopy (STEM) and conventional TEM. The voids are pyramids with {10-11} side facets, symmetric hexagonal (0001) base facets, and a dislocation at the peak which continues up along the [0001] growth direction towards the surface. Some of the dislocations are {10-10} faceted hexagonal open core dislocations with varying lateral widths and varying degrees of hexagonal symmetry. The void density within each sample varies, with some regions of the sample having no voids while other regions having densities up to ~1015 cm-3. STEM electron energy loss spectroscopy (EELS) spectrum imaging revealed a large carbon concentration inside or on the facets of the void, as well as a larger carbon concentration in the GaN (or InGaN) below the void than above the void. Because carbon contamination is known to cause irregular growth during deposition, we propose that carbon contamination during MOCVD growth acts as a mask, locally stopping the GaN deposition. When subsequent layers of GaN are deposited around the carbon contaminated region, the overhanging {10-11} facets of the void are created. The meeting of the six {10-11} facets at the pyramids peak is not perfect, forming the dislocation cap.

8262-05, Session 1

Effects of tensile strain on GaN nano- and micro-rods growth on Si (111) substrates

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We report the optical and structural properties and effects of tensile strain on GaN nano- and micro-rods (NMRs) on Si (111) substrates. Strong tensile strain is applied on their N-terminated (000-1) top surface due to the lattice mismatch between GaN and Si (111) and coalescence between GaN islands during NMRs growth. According to Wulff plot (γ-plot), without considering the effect of the diffusion kinetic of Ga and N adatoms, the thermodynamic equilibrium shape is determined by a procedure of minimizing the total free energy of creating interfacial boundaries. Therefore the growth rate of the certain crystallographic orientation is proportional to the surface energy of the plane normal to its orientation. In case of N-terminated GaN NMRs, they have only (000-1) and {1-100} crystallographic planes due to the lower surface energy than that of the other facets. Since we found that strain on {1-100} planes of GaN NMRs is weaker than that on (000-1) plane from Poisson's ratio and transmission electron microscopy (TEM) results, we only considered the change of surface energy of (000-1) planes. Moreover we experimentally confirmed that the growth rate of the tensile stressed (000-1) top surface is faster than that of the unstrained- or compressive-stressed surface due to its higher surface energy. By using this mechanism, we successfully grew the GaN NMRs on Si (111) substrate. The direction and strength of strain on the (000-1) top surface are investigated by TEM, scanning electron microscopy (SEM), and cathodoluminescence.

8262-06, Session 2

Reduction of dislocation density and strain by three-dimensional islands growth on TiC buffer layer in HVPE-GaN crystal

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Freestanding GaN crystals are fabricated by hydride vapor phase epitaxy using a random-islands facet-initiated epitaxial overgrowth(r-FIELO) technique. In this method,micron-size GaN islands were firstly formed on the thin TiC layer deposited on sapphire substrate. Successively, thin low-temperature buffer layer and thick GaN layer at high temperature of 1040ºC were grown. Freestanding GaN crystals were successfully obtained by self-separation from the sapphire substrate during the cooling down. Dislocation density was drastically reduced by three-dimensional growth(3DG) with well-developed facets formed in the initial stage of high temperature GaN layer. The reduction ability of dislocations in r-FIELO was greater than that of stripe-FIELO we have reported[1]. 2-inch-diameter GaN wafers with dislocation density as low as 3×10^6 cm^-2 are produced using this method. We also have succeeded in the development of 4-inch-diameter GaN wafer using the same method. The thickness of 3DG layer affected the radius of curvature. By controlling the 3DG layer thickness within 150-200 micron, the radius of curvature was suppressed in the range of 5-10 m. The wafer bending is considered to be related to the strain in grown crystals. We evaluated residual and intrinsic strain by measuring a low-temperature micro-reflectance spectrum[2]. Energy shifts of free excitons, which are very sensitive to induced strain, was precisely measured along the growth direction. From obtained data with the radius of curvature observed, intrinsic strain was deduced. It is found that the intrinsic strain, the driving force of wafer bending, can be greatly reduced by the introduction of the 3DG layer.

[1]A.Usui et al.,Jpn.J.Appl.Phys., 36(1997)L899.

[2]A.A.Yamaguchi et al.,.J.Appl.Phys., 83(1998)4542.

8262-07, Session 2

GaN substrates with variable vicinal angle for laser diode applications

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It has been well known that during Metalorganic Vapor Phase Epitaxy (MOVPE) of InGaN layers on the c-plane GaN the indium content decreases with increasing vicinal angle of the substrate. In this work we show that this also holds for several micrometer sized regions of the GaN substrate. In our case the vicinal angle of the c-plane GaN substrate was locally changed by special patterning technique (photolithography and ion etching). We also show that emission wavelength of InGaN/GaN Multiquantum Wells (MQWs) depends on local vicinal angle of these patterned GaN substrates, corresponding to local indium content variations.

Initially we discuss basic properties of InGaN/GaN MQWs grown on patterned GaN substrates with variable vicinal angle: the local bandgap variation and defect density distribution. Next, we exploit the patterned GaN substrates in design of edge emitting ridge waveguide laser diodes (LDs) demonstrating interesting new features. The first practical example is an electrically pumped LD with lower indium content at the mirror facets. This approach could eventually be used to suppress the catastrophic optical mirror damage (COMD) effect in future ultra-high power LDs. The second example is an electrically pumped LD lasing at multiple wavelengths separated by 5-20 nm at the same time.

8262-08, Session 2

Molecular beam epitaxial growth and characterization of nearly intrinsic and Si-doped InN nanowires

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InN nanowires have emerged as a promising candidate for a range of nanoelectronic and nanophotonic devices. However, the achievement of nearly intrinsic InN nanowires, and a detailed understanding of their fundamental surface charge properties have remained elusive. In this context, we have investigated the epitaxial growth and surface electronic properties of both nearly intrinsic and Si-doped InN nanowires. In this experiment, non-tapered InN nanowires were formed on Si(111) substrates using a self-catalytic growth process by RF plasma-assisted molecular beam epitaxy. The nanowires are nearly free of dislocations and are oriented along the [0001] polar direction, with their sidewalls being non-polar m-planes. Such InN nanowires can exhibit an extremely narrow photoluminescence (PL) spectral linewidth (~ 8 meV) at 5 K. From the detailed analysis of the excitation power dependent PL spectral linewidth, a residual electron density of ~ 2x10e15 cm-3 was derived, which is nearly three orders of magnitude smaller than the previously reported values for InN nanowires. The surface charge properties of InN nanowires were further studied using angle-resolved x-ray photoelectron spectroscopy. It is measured that the surface Fermi-levels are located below the conduction band minimum (CBM) in intrinsic InN nanowires and 0.6-1.0 eV above the CBM for Si-doped InN nanowires, depending on the growth conditions. We have also observed the phonon sideband (~ 0.61eV) in the PL emission spectra of InN nanowires. The evolution of the phonon sideband emission with temperature, excitation power, and doping concentration is being analyzed, which can provide additional insight on the surface charge properties of InN nanowires.

8262-09, Session 2

Growth of less bowed GaN/sapphire using low temperature GaN with nanocolumnar microstructure and InN interlayer

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Difference in thermal expansion coefficients between GaN and substrate causes significant wafer bowing problem. This problem, especially during the active layer growth, leads to non-uniform wafer temperature distribution that would deteriorates the uniformity of device properties. Furthermore, excessive bowing would make subsequent device processing difficult to obtain adequate yield. In this study, the structure to reduce the wafer bowing of GaN on sapphire was proposed. Firstly, InN layer and low temperature (LT) GaN layer with columnar nanostructure were grown on c-plane sapphire temperate. Subsequently, thick high temperature GaN layer was grown on the nanocolumnar LT GaN/InN/sapphire temperate.

Microstructure of LT GaN nanocolumnar structure and InN layer was investigated by transmission electron microscopy and scanning electron microscopy. We confirmed that InN layer was decomposed to indium (In) and In atom was diffused out through nanocolumnar LT GaN when LT GaN was grown on InN layer. Wafer bowing was measured by using optical methods and significant reduction of wafer bowing was observed for the sample with the nanocolumnar LT GaN layer compared to GaN layer grown on conventional LT GaN buffer layer. The effect of LT GaN with nanocolumnar microstructure on InN interlayer that compensates the compressive strain will be reported in detail.

8262-10, Session 3

Carbon-doped p-type (0001) plane AlGaN (Al= 0.06 to 0.55) with high hole density

H. Kawanishi, Kogakuin Univ. (Japan)

Wide band-gap AlGaN is one of the promising semiconductors for deep ultra violet (Deep-UV) light emitter applications. However, p-type conduction of the Mg-doped AlGaN with high Al composition has been extremely poor electrical-properties for the device applications such as light emitting diode (LED) and laser diode (LD).

P-type conduction has been achieved experimentally in the C-doped (0001) plane AlGaN with small to large Al compositions, but not GaN in our study. And, we have been demonstrated UV LED under current injection to the (Si-doped n-type AlGaN)/(un-doped GaN)/(C-doped p-type AlGaN (25% of Al)) double-hetero structure, for the first time. Maximum hole density (determined by the van der Pauw geometry Hall-effect measurement) that we have achieved for the AlGaN single layer with 10% of Al compositions was in the range of p= (1-3) x 10 18 cm-3.

“Maximum effective ionized acceptor density” (NA--ND+), which was determined by Capacitance-Voltage measurement for AlGaN with 10% to 55% of Al composition, was also around these values. Then, we have determined the electrical efficiency ((NA--ND+)/NA) to be around 55 65 %, where NA is the carbon density which was determined by SIMS analysis of carbon doped AlGaN with 27% of Al. And then, “acceptor level” of the carbon in the AlGaN with 27% of Al was estimated to be 26-30 meV at room temperature. This acceptor level is extremely small value compared with former’s theoretical and experimental one. As a result, we conclude that carbon is promising and extremely attractive new acceptor for the AlGaN.

8262-11, Session 3

Rare earth doping of III-nitrides: in situ doping vs. ion implantation

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III-nitride light emitters have shown a tremendous development in the last two decades with the commercialization of blue and UV LEDs and lasers. At longer wavelengths, however, the internal quantum efficiencies of conventional III-nitride LEDs are still very low. Rare earth (RE) doped III-nitrides provide an alternative route for the realization of all-nitride light emitters throughout the entire visible spectrum. First red emitting LEDs based on Europium doped GaN have been realized using in situ doping during OMVPE growth [1]. Ion implantation allows RE doping of planar substrates with the facility of lateral patterning. It is also well suited to doping low dimensional structures such as nanowires and quantum dots whereas incorporation of impurities in nanostructures during the growth process is challenging. However, the damage caused by ion implantation introduces defect levels in the band gap which can lead to nonradiative deexcitation and thus inhibit the RE emission. In this study we compare structural and optical properties of in situ doped and ion implanted GaN:Eu layers. Both show excellent crystalline quality, incorporation of Eu on substitutional Ga-sites and spectrally identical optically active centers. Finally RE implantation in GaN nanowires as well as self-assembled GaN quantum dots is discussed. Optical activation is achieved in these nanostructures during thermal annealing. Implantation damage is found to be lower in quantum dots than in thick layers.

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8262-12, Session 3

A local vibration mode in a carbon doped (1-101)AlGaN

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Carbon is believed to form a deep level in GaN to make the material semi-insulating. On the other hand, several reports have shown a possibility to from a shallow acceptor level and the doping behavior is still to be studied. In this paper, the carbon doping in a (1-101)AlGaN is investigated. The sample was grown on (1-101)GaN facets of GaN triangular stripes prepared by selective MOVPE on a (111)Si substrate. Intentional carbon doping was performed by using C2H2 during the growth. SIMS analyses showed the carbon density of 10E18-10E19 cm-3. Phonon modes were investigated by grazing incidence FTIR analyses at room temperature.

In the FTIR spectra, in addition to A1(TO), E1(TO) and A1(LO) phonons due to GaN, a new LVM mode was found out at 945 cm-1 which was associated with A1(LO) phonon mode of AlN at 888cm-1. The intensity was enhanced by increasing the carbon doping level suggesting that the new LVM mode is generated by carbon doping. And the fact that this mode is associated with the AlN-A1(LO) mode suggests that the carbon is doped in the AlN matrix.

Simple linear chain model with effective masses suggested that the LVM energy accelerated by an Al-C bond is at 929cm-1 which is a little bit lower than the experimental observation. Thus, the substitutional C doping on the N site might take place forming a kind of complex with additional elements.

8262-13, Session 3

AlGaN polarization doping for highly efficient LEDs

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The development and application of nitride-based light-emitting diodes (LEDs) is handicapped by the low hole conductivity of Mg-doped layers.

Mg-doping becomes increasingly difficult with shorter LED wavelength and higher Al-content of the p-AlGaN layers. As an alternative, polarization-induced hole doping in N-face graded AlGaN was recently demonstrated. This talk explains the concept of polarization doping and investigates its impact on the performance of ultra-violet LEDs using advanced numerical device simulation. The results show that the internal quantum efficiency can be strongly increased and the efficiency droop eliminated by using such graded AlGaN layer instead of the traditional AlGaN electron-blocker layer (EBL).

8262-14, Session 4

Natural band alignments of wurtzite InN/GaN/AlN heterojunctions

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Heterojunction band alignments for III-nitrides (InN, GaN, AlN, and their alloys) have always been a strong focus in both experimental and theoretical studies because of their importance in the design and characterization of optoelectronic and electronic devices based on III-nitride heterostructures. However, there are still large uncertainties in the reported valence band offsets (VBOs) due to the strong influence of polarization effects resulting from spontaneous and/or piezoelectric polarizations in wurtzite III-nitrides, which are pyroelectric materials with large macroscopic polarizations along the polar (c-) axis. Previous studies have found that the discontinuities of piezoelectric polarizations in coherently strained heterojunctions (ultrathin III-nitride epitaxial layers grown on lattice-mismatched III-nitrides) would result in a strong forward-backward heterojunction asymmetry (i.e., A/B versus B/A growth sequence). Furthermore, in our previous studies, we have confirmed that the measured VBO values are strongly affected by the spontaneous polarization discontinuities in nearly strain-free III-nitride heterojunctions. Therefore, determination of the “natural” (“intrinsic”) band alignments of III-nitrides unaffected by the polarization effects is very important towards a full understanding of III-nitride heterojunctions. In this study, we use a unique combination of nonpolar measurement technique and strain-free nanorod-array sample to determine the “natural” band alignments of III-nitrides, evidenced by the agreement with the expected transitivity rule.

8262-15, Session 4

Recombination and diffusion processes in polar and nonpolar bulk GaN investigated by time-resolved photoluminescence and nonlinear optical techniques

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The competition between nonradiative and radiative (excitonic and interband) recombination remains an open question for development of III-nitride materials even after decades of intensive studies. To address this very issue, we investigated optically-injected carrier dynamics in bulk polar and nonpolar GaN, combining single- and two-photon excitation conditions. The excitation decay was monitored by photoluminescence and free-carrier absorption techniques, while diffusivity was investigated by light-diffraction on transient grating technique. The measurements were performed on c-plane-200-mkm and m-plane-450-mkm thick freestanding HVPE GaN in a wide range of excitation densities and temperatures. Particular attention was paid to elaborate on the impact of carrier diffusion on nonradiative recombination and radiative emission dynamics.

For c-plane GaN, under two-photon excitation (10e15-to-10e17 cm-3 carrier density), the diffusivity was found to decrease with temperature (D ~ 1/T) whereas the carrier lifetime increased with temperature (~ T) in the entire 10 to 800 K range. A bulk lifetime value of 40 ns was measured at RT and attributed to diffusion-governed carrier flow to the interface defects at GaN hexagonal grain boundaries, acting as centers of nonradiative recombination. The data revealed a hexagonal column radius of 3.6 mkm and an effective interface recombination velocity of S = 9500 cm/s for the polar crystal with mid-105 cm-2 dislocation density. Under single-photon excitation of a 50-100 nm thick subsurface layer (1016-to-1019 cm-3 carrier density), the fast PL transients were fitted by using the determined D and lifetime values and revealed the strong impact of carrier depth redistribution due to diffusion, surface recombination, and reabsorption processes. Bimolecular recombination rate was determined in a wide temperature range by the nonlinear optical techniques. The dependences of exciton emission decay on temperature and excitation, as well the bimolecular carrier recombination rate were measured and analysed. Dynamic interaction between the exciton and electron subsystems will be discussed.

8262-16, Session 4

Absence of electron accumulation at the InN(11-20) cleavage surface

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InN opens the possibility to use only one ternary III-V semiconductor alloy (InGaN) in optoelectronic devices to cover the whole visible spectral range. However, key material properties of InN are still under debate. The intrinsic energetic position of the Fermi level is unclear, i.e., whether the Fermi level is located within the fundamental band gap or shifted into the conduction band. The latter case induces electron accumulation at the surfaces of the crystal, which is typically observed at InN surfaces upon air contact. This raises the pivotal question whether it is an intrinsic material property or not.

In order to probe bulk properties by STM and no contamination or surface effects, a clean and stoichiometric, cross-sectional surface is necessary. We recently achieved this by cleaving InN along the non-polar (11-20) cleavage surface and analyzing the origin of the different electronic states in detail by cross-sectional scanning tunneling microscopy (XSTM) and spectroscopy (XSTS). In XSTS spectroscopy measurements within the bulk band gap of Eg = 0.7 eV no intrinsic surface states could be observed. Furthermore, the Fermi level pinning at about 0.3 eV below the conduction band minimum indicates the absence of an electron accumulation layer. These results illustrate that electron accumulation at InN surfaces is not a universal property of InN. For clean stoichiometric cleavage surfaces no electron accumulation is observed. Consequently, electron accumulation results primarily from the details of the surface structure and is not an intrinsic property of the material InN.

8262-17, Session 4

Structural and electronic properties of Al2O3/InN heterointerfaces

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We have fabricated Al2O3 /InN heterostructures on yttria stabilized zirconia (YSZ) (111) substrates and investigated their structural and electronic characteristics, putting special emphasis on the effect of polarity of the InN films. InN films were grown on YSZ (111) substrates in a pulsed laser deposition apparatus with a KrF excimer laser. Polarity control of the InN was realized by surface treatments of YSZ (111). N- and In-polar InN films were grown at 550 and 450 oC, respectively. Amorphous Al2O3 was deposited on the cleaned InN surfaces at 200 oC by the ALD method. Al2O3/InN heterostructures were characterized by high resolution x-ray photoelectron spectroscopy and AFM. We found that In-polar InN(0001) films grow with atomically flat surfaces, which makes striking contrast to the case of N-polar where InN films show rough surfaces. High resolution XPS measurements have revealed that the Al2O3 /In-polar-InN interfaces were abrupt although InOx interdiffused layers are formed at the Al2O3 /N-polar-InN interfaces. We have also found that the valence band offset of Al2O3/In-polar-InN is 2.8 eV, while that for N-polar-InN is slightly smaller. This discrepancy can be probably explained by the fact that surfaces of In-polar InN are more resistant to oxidizing atmosphere of the ALD process for Al2O3 deposition.

8262-18, Session 4

Cathodoluminescence microscopy of polarization-reduced GaN directly grown on patterned (112) Si substrate

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Recently, there has been significant interest in the growth of semi- and nonpolar GaN. Conventional c-axis grown nitrides quantum wells are influenced by large internal electric fields causing both unwanted wavelength shifts and, even more important, a decrease of the oscillator strength in c-plane quantum wells (quantum confined Stark effect). However, heteroepitaxially grown nonplanar m-plane GaN films are characterized by the presence of high dislocation density due to the large lattice mismatch with the available substrates. In particular, stacking faults are commonly formed during m-plane growth with dramatic impact on the luminescence properties of the layers.

m-plane GaN is realized on Si substrates by initiating growth on the vertical (111) sidewalls of stripe-patterned Si(112) substrates using MOCVD. By masking the other Si{111} planes with SiO2, only the vertical Si (111) sidewalls participate in subsequent GaN growth - laterally advancing dominantly along the c+ direction. Fully coalescent m-plane GaN regions are obtained. Finally, a 6-nm thick InGaN double heterostructure LED sequence is completed. The structural and optical properties are characterized using spatially and spectrally resolved cathodoluminescence.

The integral spectrum at T = 5K is governed by (D0,X) emission of GaN mostly emitted from c-facets of non-coalesced regions. In addition, strong dominance of InGaN and (D0,X) emission is obtained from m-plane facets, although in certain regions forming characteristic growth domains, the BSF luminescence is most intense. In particular the -c ELO-wings reveal intense BSF emission with a striation like contrast along the [1120] direction.

8262-19, Session 4

Auger effect in nonpolar quantum wells

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Nitride based light emitting diodes suffer from a reduction of the quantum efficiency with increased current. The effect, commonly known as the efficiency droop, is intensively discussed. Possible origins of the efficiency droop are charge carrier leakage [1], Auger recombination [2], charge carrier density-activated defect recombination [3], and phase state filling [4]. For c-plane (Al,In)GaN laser diodes, the contributions of charge carrier leakage and Auger recombination could be separated by a combination of experiments [5].

Here, we investigate the droop curve of nonpolar InGaN quantum wells. The experiments were performed on InGaN quantum wells grown by MOVPE on free-standing GaN substrates. The active region of the samples is embedded in 200nm GaN and consists of three nominally 3.5 nm thick In0.15Ga0.85N quantum wells, each between 8nm In0.02Ga0.98N barriers. The substrates contain threading dislocation densities in the range of 10^7 cm^2.

For spectral analysis, the quantum wells are excited optically by the 363.8 nm line of an Ar-ion laser over a wide range of excitation densities. At low excitation of several hundred W/cm^2 and room temperature, the peak position of the spontaneous emission is around 410 nm. We compare the experimental results to theoretical calculations of the band structure. Furthermore, we evaluate the mechanisms suggested in the ongoing debate on the cause of the efficiency droop for pseudomorphic, nonpolar InGaN QWs. We come to the conclusion that Auger recombination is responsible for the reduction of the quantum efficiency in the regime of high charge carrier density.

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8262-20, Session 4

Electron paramagnetic resonance study of the Mg impurity in nitride films

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Although Mg is the accepted p-type dopant for nitrides, the impurity is one factor limiting optimization of LED output. Unfortunately, little is understood about the chemistry or structure of the dopant. We have extracted some unique information about p-type nitrides by studying the Mg-related signal detected by electron paramagnetic resonance (EPR) in a large selection of MBE and MOCVD nitride films. First, the data show that the EPR signal is readily detected and has similar characteristics in GaN and AlxGa1-xN (x=0.12, 0.28); however, no such signal is observed in InxGa1-xN:Mg (x=0.04,0.08) exhibiting a hole density of 1018 cm-3. Thus, although Mg is structurally similar in GaN and AlGaN, Mg may be incorporated differently in InGaN. Secondly, annealing studies indicate that the onset temperature for hydrogen passivation decreases with Mg concentration and, separately, Al mole fraction. Such results highlight one reason why CVD post growth procedures must be modified to maximize hole density and/or band gap. Finally, the Mg EPR data reveal a line shape that evolves from Lorentzian, typical of insulating materials, to Dysonian, typical of metals, as the sample is rotated in the plane of the magnetic field. The cause of this behavior is not yet clear, but the results suggest that Mg is influenced by a region of anisotropic conductivity such as may be created by an interfacial layer. The talk will highlight the details of each finding and emphasize their relevance to p-nitrides.

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8262-21, Session 5

Terahertz emitters based on GaN/AlGaN HEMTs

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The channel of High Electron Mobility Transistor (HEMT) can act as a resonator for the plasma waves propagating in 2D electron gas. The plasma frequency increases with reduction of the channel length and can reach the Terahertz (THz) range for nanometre size transistors. As it was predicted by Dyakonov and Shur, when a current flows through a transistor's channel, the steady state can become unstable against generation of plasma waves leading to the emission of an electromagnetic radiation at the plasma wave frequencies. In this work we present experimental results on THz emission by GaN/AlGaN nanotransistors.

We present recent results on THz emission obtained in different types of GaN/AlGaN nanometric HEMTs We show that depending on the transistor geometry different THz emission mechanism play role. In most of investigated HEMTs in agreement with the theoretical predictions i) the emission frequencies correspond to the estimated characteristic plasma wave frequencies and ii) the emission appears once the drain current exceeds a certain well defined threshold value - instability threshold. First results have been obtained at cryogenic temperatures, however recently it was shown that from the field plate geometry 150nm and 250nm gate length GaN/AlGaN HEMTs one can also obtain an efficient room temperature THz emission -for more details see Ref.1.

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8262-22, Session 5

Scaling of GaN single nanowire MOSFET with cut-off frequency 150GHz

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This work aims to provide experimental solution as well as theoretical analysis to resolve a long-standing issue, i.e., short channel effect, which hinders scaling-down of nano-electronics at gate length below 100nm. Taking advantage of our recent development of (i) horizontal and selective site growth of [11-20]-gallium nitride nanowires on sapphire, (ii) photo-enhanced oxidation to transform GaN to crystalline gallium oxide (Ga2O3), and (iii) polarization engineering to provide 2D electron gas confined at the {1-10-1} GaN/Ga2O3 interfaces and negative space charge at the {0001}GaN/sapphire back interface, we realize a new structure design of GaN NW-MOSFETs that possess superior DC and RF characteristics to its planar III-Nitride HEMT using complicated material design. This paper outlines further strategic development to reach GaN high gain NW-MOSFET with fT exceeding >100GHz at Lg=100nm gate length. The transport measurement from a 100nm gate length Ga2O3/GaN NW-MOSFET with 60nm size of isosceles triangular cross-section revealed the following characteristics: saturation current of 105uA, transconductance of 85uS, current on/off ratio of 10^4, and unity current/power gain bandwidth fT/fmax at 95/105GHz. Using a 3D diffusion and drift model analysis, we reconstructed the I-V characteristics which perfectly agree with the experimental observations. Our analysis suggests that for the Ga2O3/GaN NW-MOSFET with 100nm gate length and 10nm-thick Ga2O3 the short channel effect can be effectively suppressed due to polarization-induced negative space charge of -2.8×10^{12} cm^2 confined at the back interface between GaN NW and the sapphire substrate. The superior DC/RF characteristics can be ascribed the to polarization-induced 2D electron gas of 7×10^{12} cm^{-2} confined at the abrupt and atomic smooth semi-polar {1-10-1} GaN/Ga2O3 interfaces.

8262-23, Session 5

Hardened planar nitride based cold cathode electron emitter

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Low threshold electron emission from planar AlN/Silicon heterostructures is reported. The surface emitting ballistic electron structure consisted of an undoped AlN layer grown on Silicon by Molecular Beam Epitaxy, a Ti/Au Ohmic contact, and a thin Pt Schottky contact fabricated by e-beam deposition. The tunnel-transparent Pt Schottky contact was deposited on a 1 µm thick Silicon Dioxide layer with a 4 x 4 matrix of 50 µm diameter via. The measurements were performed in vacuum (~10-8 Torr) by using a metal grid separated from the structure by a 60 micron thick Kapton® polyimide film having an opening aligned with the via. Bias voltages in the range of 0-130 V were applied across the Schottky diode, while currents were recorded across the structure for grid voltages ranging from 0 to 50 V. The field emission nature of the measured currents was confirmed by plotting the Fowler-Nordheim dependence. Current density of at least 2.5x10-4 A/cm2 was achieved for a grid voltage of 50 V and a bias of 130 V. Degradation of the structure performance was observed at bias voltages exceeding 90 V as a result of Schottky barrier modification under the elevated temperature and high electric field operation. The solid-state electron emitting structure indicated a threshold field as low as 0.2 V/µm under applied grid voltage of 12 V.

8262-24, Session 5

Properties of (In,Ga)N/GaN single quantum wells on defect-free micro-crystals obtained by molecular beam epitaxial overgrowth of GaN nanowires on Si(111)

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We investigate the properties of (In,Ga)N single quantum wells deposited on pendeoepitaxially overgrown and thus laterally expanded GaN nanowires (NWs) on Si(111). In this approach, we first synthesize a GaN NW ensemble with a length of about 0.5 µm by self-induced epitaxial growth on a Si(111) substrate. By shifting the stoichiometry towards Ga rich conditions, lateral growth is promoted. The top areas of the GaN NW template (which has virtually zero dislocation density) thus undergo coalescence by pendeoepitaxy [Jpn. J. Appl. Phys. 40, L192 (2001)]. The surface of the coalesced GaN NWs reveal the presence of hexagonal GaN micro-crystals of a size between 1 to 3 µm embedded in a network of smaller grains. These GaN micro-crystals are free of threading dislocations and exhibit an atomically smooth surface (roughness of 0.2 nm). Photoluminescence spectra of these micro-crystals are dominated by an intense donor-bound-exciton transition at 3.471 eV with a width of 1 meV reflecting strain-free GaN of exceptional structural quality. To go further, we deposit an (In,Ga)N single quantum well on the laterally expanded GaN NWs. Integral photoluminescence spectra of the heterostructure are dominated by a strong green luminescence band located at 2.48 eV. Spatially resolved luminescence maps obtained by cathodoluminescence spectroscopy exhibit dual-color production of the blue and green regions which are correlated to the morphology observed by scanning electron microscopy. We propose that the bottom-up approach based on the pendeoepitaxial expansion of threading dislocation free GaN NWs is very attractive for producing high-efficiency micro-sized light emitting diodes (LEDs).

8262-25, Session 6

Molecular beam epitaxy growth of InGaN nanowires and InGaN/GaN nanowire heterostructures

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InGaN nanowires are considered today as a promising material in the field of visible light-emitting diodes: the presence of free surfaces, intrinsic to nanowires, is expected to favor the strain relaxation and extend therefore the In composition range available, leading to green and yellow emission. It will be shown that this is partially true, although real situation is NOT as ideal as foreseen.

InGaN nanowires were grown by Plasma-Assisted MBE on Si(111). They consisted of a GaN NW base having a typical diameter of 30nm covered with a thick InGaN part on the top, about 30-70 nm long. The nominal In composition was varied between 0 and 0.5 by changing the In flux.

Based on SEM and HRTEM studies, it has been found that the morphology of the InGaN section was multiple, corresponding to several modes of elastic strain relaxation: plastic, elastic or a combination of both, depending on In content. In clustering correlated to strain relaxation process has been observed and estimated by energy dispersive Xray analysis (EDX).

By performing spatially resolved cathodoluminescence (CL) experiments in a Scanning Transmission Electron Microscope (STEM) with an home-made high throughput CL detector, it has been demonstrated that the spontaneously formed GaN shell, when present, efficiently passivates the InGaN core. CL mapping at the nm scale has been performed, putting in evidence a strain gradient along the radius of the NW.

Structural properties of quantum dots-in-nanowires will also be presented, as a paragon of a system very well suited to single dot spectroscopy studies.

8262-27, Session 6

Reduction of dislocation density in GaN nanorods

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Growth of GaN nanorod (NR) can reduce the threading dislocation (TD) density. In the patterned growth on a GaN template with metalorganic chemical vapor deposition, it has been discovered that a TD cannot penetrate through the patterned hole into a NR when the hole size is small. This behavior is supposed to be due to the built strain distribution around the hole. When the hole size becomes large, such strain distribution covers only the regions near the hole edges. In this situation, a TD near the hole center can still penetrate into the NR. To improve such a result, we develop a technique for forming a ring-shape opening on the silicon dioxide mask. In other words, in a patterned hole, its central part is still covered by silicon dioxide. This central-part mask can stop the penetration of TD into an NR when the hole size is large. The growths of GaN NRs based on such ring-patterned masks and those with hole patterns are compared. Also, the results of different hole and ring sizes are demonstrated. The comparisons are based on the measurements of transmission electron microscopy, photoluminescence, and cathodoluminescence. Meanwhile, the coalescence overgrowths of such GaN NRs to form GaN templates are preformed to show the overall reduced TD density. In addition, blue light-emitting diode structures are grown on such templates to observe the enhanced emission efficiency.

8262-28, Session 6

Helium temperature scanning transmission electron microscopy cathodoluminescence for nano-characterization of nitrides

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Luminescence techniques belong to the most sensitive, non-destructive methods of semiconductor research. The combination of luminescence spectroscopy - in particular at liquid He temperatures - with the high spatial resolution of a scanning transmission electron microscopy (STEM) (Δx < 1 nm at RT, Δx < 5 nm at 10 K), provides a unique, extremely powerful tool for the optical nano-characterization of semiconductors. Our STEM-CL -detection unit is integrated in a FEI STEM Tecnai F20 equipped with a liquid helium stage and a light collecting parabolic mirror. Panchromatic as well as spectrally resolved CL imaging is used. In CL-imaging mode the CL-intensity is collected simultaneously to the STEM signal at each pixel. The TEM acceleration voltage is optimized to minimize sample damage and prevent luminescence degeneration under electron beam excitation. Typical results which will be presented include nm-scale correlation of the optical properties and strength and appearance of structural defects in: strain engineering AlN interlayers (thickness = 12 nm) in GaN-on-Si structures, lattice matched AlInN/GaN distributed Bragg reflectors (DBRs) and complete VCSEL structures with all-epitaxial as well as hybrid DBRs for blue (InGaN QWL cavity) and UV (GaN cavity) emission. 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 visible. The individual λ/4 layers of the epitaxial DBRs and the nanoscale properties of their mutual interfaces are clearly resolved.

8262-80, Session 6

Analysis and control of emission properties of InGaN-on-GaN nanocolumns grown by molecular-beam epitaxy on Si(111) substrates

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Self-assembled InxGa1-xN nanocolumns (NCs) were fabricated by plasma-assisted MBE on Si(111) substrates. The samples were analyzed by continuous-wave and time-resolved photoluminescence (PL) in order to gain control about the emission characteristics by changing the growth parameters. NCs were grown on Si (111) in a two-step procedure: (i) growth of GaN NCs at 800 ºC and (ii) growth of InGaN NCs on top of the GaN NCs at different sample temperatures (from 650 ºC to 750ºC) with the same nominal flux of In and Ga. This growth approach was chosen due to a drastic suppression of non-radiative recombination centers inside the NCs, a significant enhancement of the internal quantum efficiency and a superior light extraction efficiency.

Within the growth temperature range of 650 to 750 °C, an increase in incorporation for decreasing temperature is observed. This effect allows tailoring the InGaN nanocolumns emission line shape by using temperature gradients during growth. Depending on the gradient rate, span, and sign, broad emission line shapes are obtained, covering the yellow to green range, even yielding white emission.

8262-29, Session 7

Photonic cavities with high quality factors embedding nitride quantum dots

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III-N materials have become the dominant materials for UV to blue-green semiconductor light sources. Besides these conventional light emitters, III-N materials are also attracting candidates for less conventional emitters and for new applications (integration with electronics, integration wit lab on chip, array of microsources...). In order to better control the light emission, realizing photonic nanostructures with large quality factors in the UV range is especially challenging due to the larger scattering losses compared to similar structures in the visible and IR spectral ranges.

In this work we study the spectroscopy of Al(Ga)N photonic resonators embedding GaN quantum dots (QDs). For room temperature operation, nitride QDs are promising candidates due to their large radiative efficiency [1]. We have studied the spectroscopy of single photonic membrane cavities as well as microdisks, by microphotoluminescence. The recent progresses of the fabrication techniques allowed us to reach state of the art quality factors for both photonic structures, i.e. Q=1800 for a L3 nanocavity [2] and Q=7300 for microdisks [3]. In both systems, photonic modes are modelled, allowing to determine the processes limiting the quality factor. These results are compared to state of the art nitride microdisks and photonic crystal cavities.

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8262-30, Session 7

3D GaN for core-shell LEDs

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3D GaN based core-shell structures have attracted considerable attention in the recent past. The large increase of active LED area per wafer is the main advantage in comparison to planar LEDs. The characterisation as well as processing of 3D LEDs, however, turns out to be difficult. Here, we report on the MOCVD growth and characterisation of 3D GaN LEDs with core-shell geometry. It turns out that the GaN polarity plays an important role during MOCVD growth. Kelvin probe force microsopy is used to analyse the polarity with spatial resolution. Multi-polar GaN structures have been identified, and strategies to avoid multi-polarity are discussed.

In this talk, an overview on potential advantageous and challenges of the exciting new approach to a new type of LED will be discussed.

8262-31, Session 7

Electronic and thermal tuning of violet GaN coupled cavity laser

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Tunable violet and blue laser diodes are of increased interest for wide range of applications, which includes chemical or biological hazard detection, laser-induced fluorescence spectroscopy, combustion diagnostics, photobiology and atomic physics. Although external cavity tunable lasers were reported for the violet-blue region, their main disadvantage for the applications is precise mechanics and alignment, making these devices expensive, complex and bulky. Contrary, for the most of the applications portable and low-cost lasers are desirable. By introducing an integrated coupled cavity design to a GaN semiconductor laser one can obtain similar tuning range and higher reliability, while keeping device size, cost and complexity low.

AlGaN/GaN/InGaN multiple quantum well lasers with central wavelength at 400-415nm were studied. Two air slot coupled, Fabry-Perot cavities were fabricated using Ga+ focus ion beam milling of a subwavelength air slot. Laser was electrically driven with 200ns pulses at 50 kHz repetition rate. Both laser and superluminescent diode regimes were shown experimentally by variation of the angle of the air slot. Tunablity of GaN lasers were studied by forward and back cavity current scans. Wavelength tuning maps show difference in lasing modes selection before and after processing due to the Vernier effect, which enhance the tunable range of laser. Our results show dependence of tuning range, power and mode profile on air slot position and reflectivity of laser facets. We demonstrate electronic and thermal tuning range of 3nm and 2.4nm, respectively. Measured thermal tuning coefficient is 0.06nm/K.

8262-32, Session 7

Lasing action in gallium nitride photonic quasicrystal nanorod arrays

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There have been great research interests in gallium nitride material due to its promising applications in UV to blue optoelectronic devices and strong emission properties. Conventionally, devices are built in two dimensional thin film structures. Recently, devices incorporating additional micro or nano structures have gained substantial attention for their interesting properties and potential applications. Here we report the observation of lasing action from room temperature optically pumped GaN photonic quasicrystal nanorod arrays. The nanorod arrays were fabricated from a GaN epitaxial wafer by nano imprint patterned etching, followed by epitaxial regrowth. The imprint patterned etching created nanorod arrays in a 12-fold symmetric quasicrystal pattern. The epitaxial regrowth formed {10-10} M-plane facets on nanorod side walls and hexagonal pyramid on top. The regrowth also grew InGaN/GaN multiple quantum wells on nanorod side wall and pyramid facets, forming a core shell structure. The cathodoluminescent (CL) emission of quantum wells red shifts from the bottom to top portion of nanorods. Under optical pumping, multiple lasing peaks were excited. The lasing mode distribution did not show obvious regularity. The linewidth of laser peaks was in the range of 0.2-0.3 nm, indicating strong resonant feedback oscillation. The excited lasing modes in the photonic quasicrystal nanopillar arrays will be discussed.

8262-33, Session 8

Nitride semiconductor based photo-chemical cells

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Nitrides can split water into H_2 and O_2 without any extra bias, because this material system has very high external quantum efficiency (EQE) in photocatalysis compared with other conventional oxide materials. We found out that NiO co-catalyst makes higher efficiency and better chemical stability of GaN photocatalyst significantly.

Hydrogen is promising clean energy. Direct photoelectrolysis by solar power is a promising method for H_2 evolution from water. The major problems of a semiconductor photo-electrode are efficiency and corrosion of semiconductor.

We found out that nitride (AlN-GaN-InN) system is promising for photocatalysis [K.Ohkawa, Jpn Patent 3730142 (2001); K.Fujii, K.Ohkawa et al., Jpn. J. Appl. Phys. 44, L543 (2005).]. Nitride semi-conductors have the following 3 merits compared to oxides; (1) bandgap control in the range of 0.65-6.2 eV (200-2000 nm in light wavelength), (2) p- and n-type amphoteric doping, and (3) chemical sta-bility. The point (1) indicates that InGaN has a potential to use solar energy efficiently. The doping level optimized has made possible to produce H_2 gas without extra bias [Y.Iwaki, K.Ohkawa et al., phys. stat. sol. (c) 5, 2349 (2008).].

EQEs of GaN photocatalyst achieved 74 and 65 % at 300- and 350-nm lights, respectively. Responsiv-ity of InGaN extended up to 540 nm (EQE over 1 %) so far. We succeeded to enhance stability of ni-tride photocatalyst using NiO co-catalyst. There was no photo-corrosion after photo-irradiation for several ten hours. The state of the art of Nitride photocatalyst will be shown in this paper.

8262-34, Session 8

Concentrating properties of nitride-based solar cells

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The bandgap of GaInN ternary alloys covers a broad range from 0.65 to 3.43 eV, therefore these alloys are suitable for solar cell applications. When a multi-junction solar cell is designed, the material with a wide-band-gap range exhibits a high degree of freedom. Performances of the solar cells using other material systems, such as AlGaInP and GaAs, are improved by concentrating the light. However, a few papers reported the concentrated irradiation properties of nitride based solar cells. In this paper, we investigated the concentrating properties of nitride based solar cells up to 200 suns. In addition, we also discuss the dependence of concentrating ratio on solar cell performances.

The device structure is a GaInN-based solar cell with GaInN/GaInN superlattice active layer on a freestanding GaN substrate. The conversion efficiencies of the devices were measured using a solar simulator (Asahi Spectra HAL-302). Both irradiation areas and light intensities were changed for concentrating the light. The current density versus voltage characteristics of the device were measured from 1 to 200 sun at room temperature. The open circuit voltage and efficiency of the cells were found to increase with increasing light intensity. We obtained solar cells with up to 3.4% conversion efficiency by irradiating the concentrated sun light up to 200 suns. The open-circuit voltage is 1.9V, the fill factor is 70%, and the short-circuit current density is 513 mA/cm2.

8262-35, Session 8

High efficiency InGaN solar cell with a graded p-InGaN top layer

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In spite of high flexibility in the design of InGaN p-n junction solar cells, the performance is still to be improved. The main issue is the short diffusion length of the photo-excited carriers, which is attributed to the poor crystalline quality as well as to the fast band to band recombination process. In this paper, the enhancement of the carrier drift motion is attempted in the p-type top layer by introducing built-in electric field.

Our model device structure consists of a 1-2 micron thick n-type $In_xGa_{1-x}N$(X=0.56) base layer grown on an Si or a sapphire substrate, followed by a 0.5-1.0 micron thick graded p-type $In_xGa_{1-x}N$ top layer and an $In_xGa_{1-x}N$ (x>0.55) wider gap cap layer. The cap layer is intended to suppress the surface recombination of photo-excited electrons in the p-type layer. The In composition x in the p-type top layer was reduced from 0.56 up to 0.55 to induce the built-in electric field up to 100V/cm in the p-type layer.

By solving drift-diffusion equation using conventional materila parameters, the photo-current was investigated numerically under sunlight of AM1.5 as a function of the built-in electric field. It was found that, by introducing the cap layer to prevent surface recombination, the photocurrent across the p-n junction is enhanced as expected. By introducing built-in field as low as 100V/cm, 3.5 times higher photocurrent was achieved. The effect of the built-in field was more enhanced in devices with lower surface recombination velocity.

8262-36, Session 8

Efficiency enhancement of InGaN multi-quantum-well solar cells via antireflective SiO2 nano-honeycombs

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Periodic sub-wavelength SiO2 nano-honeycombs are fabricated on GaN-based multiple quantum well (MQW) solar cells by self-assembly polystyrene (PS) nanosphere lithography and reactive ion etching with the attempt to boost conversion efficiencies. The nano-honeycombs result in improved impedance match between air and GaN, and thus effectively suppress the undesired surface reflections over a wide range of wavelengths. Under the illumination of air mass 1.5G solar simulator, conversion efficiency of the solar cell is enhanced by 24.4 %. The improved performances indicate that optical absorption by the active region is enhanced due to the excellent light-trapping effect on the device surface. Simulations based on finite-difference time-domain method support the experimental results.

8262-37, Session 8

Optimization of electrode structure in GaInN based solar cells

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Since the bandgap of GaInN ternary alloys has a broad range from 0.65 to 3.43 eV, they are suitable for high-efficiency multi-junction solar cells. To improve a conversion efficiency of GaInN-based solar cells, optimization of electrode pattern to achieve an increase of light incorporation without an increase of the resistance is essential. In this study, we optimized the electrode pattern for GaInN based solar cells.

We fabricated solar cells on GaN substrates with Ga0.83In0.17N (3nm)/Ga0.93In0.07N (0.6nm) superlattice in active layer and Si doped Ga0.90In0.10N (3nm)/GaN (3nm) superlattice beneath the active layer. Ti/Al/Ti/Au was deposited by electron beam evaporation as ohmic contacts to the n-type GaN layers. Semitransparent Ni/Au (5nm/5nm) ohmic contacts to the p-type GaN layers were deposited by electron beam evaporation. The grid electrode was patterned with a combination of photolithography and lift-off technique. After the deposition, rapid thermal annealing was also performed at 525 °C in O2 for 5 min.

To optimize the efficiency of light incorporation, we have applied eight different grid electrodes for p-type contact. As the results, the energy conversion efficiency of the GaInN based solar cell with the optimized semitransparent grid electrode is approximately 2.8 % under AM1.5G. This efficiency corresponds to 14% improvement compared to that with conventional uniform semitransparent contact. We will also compare the experimental results with the theoretical results based on a simple equivalent circuit model.

8262-38, Session 8

Temperature dependent behavior of the surface photovoltage for GaN

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Due to excess surface negative charge, n-type GaN is known to exhibit upward surface band bending that can impact device performance. The amount of band bending can be calculated indirectly using the surface photovoltage (SPV) technique, where the surface potential is measured during illumination using a Kelvin probe setup. If the surface is illuminated with above-bandgap light, then electron-hole pairs are generated and holes are swept to the surface, resulting in a less negative surface potential and decreased band bending. Previously, we have shown that room-temperature data of the steady-state SPV and its restoration behavior are consistent with a thermionic model.[1] In this study, the SPV and its restoration are measured for n-type HVPE GaN as a function of both excitation intensity and temperature up to 500 K. Such temperature-dependent measurements provide information about the bulk-to-surface flow of electrons in dark, Ro, over the near-surface barrier. As expected from our thermionic model, the value of Ro increases with increasing temperature from 9x10^8 cm-2s-1 at 296 K to 1.6x10^11 cm-2s-1 at 500 K, corresponding to band bending values of 0.83 eV at 296 K and 1.1 eV at 500 K. The restoration rate of the SPV is accurately predicted by the thermionic model to be logarithmic in time with a temperature-dependent slope. Experiments are in progress to also examine the temperature-dependent behavior of p-type GaN.

[1] M.A. Reshchikov, M. Foussekis, A.A Baski, J. Appl. Phys., 107, 113535-1,13 (2010).

8262-39, Session 9

Absorber bias dependence of self-pulsation in GaN-based multi-section laser diodes

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GaN-based laser diodes with integrated saturable absorbers are compact and inexpensive short-pulse laser light sources in the near-UV to blue spectral range. In the group-III-nitride material system, such devices are realized by fabricating separate electrical p-contacts on a Fabry-Perot-type ridge laser to define multiple sections, where one section is operated as a saturable absorber by applying a constant negative bias voltage. These multi-section laser diodes are useful for biomedical lifetime imaging and optical data storage.

We analyze the tuneability of the repetition frequency and pulse width of self-pulsation in GaN-based multi-section laser diodes with an undoped active region via the absorber bias. The observed frequencies and pulse widths range from 1.5 to 4.5 GHz and 90 to 18 ps, respectively. The maximum achieved peak power is 0.6 W, which corresponds to a pulse energy of 11 pJ. Additionally, the charge carrier lifetime and the absorption coefficient of the absorber section are measured as functions of applied bias to understand their influence on the pulse properties.

The observed behavior is explained by a fast optical switching of the absorber from an unsaturated to a partially saturated state, which causes a stabilization of the relaxation oscillations of the laser diode and thus a self-pulsating operation.

8262-40, Session 9

Analysis of the deep level responsible for the degradation of InGaN-based laser diodes by DLTS

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Despite the excellent potential of InGaN-based laser diodes, the reliability of these devices can be limited by a number of factors. Recent studies demonstrated that degradation of laser diodes can be due to an increase in non-radiative recombination rate within the active layer of the devices, due to the generation of defects. However, the defects responsible for degradation have not been identified up to now.

The aim of this paper is to show that the degradation of InGaN-based laser diodes is strongly correlated to the increase in the concentration of a deep level located within the active region of the devices. The properties of this deep level are described in detail in the paper. The analysis is based on combined optical measurements and Deep-Level Transient Spectroscopy (DLTS) investigations, carried out on devices with multi-quantum well structure grown on GaN-substrate by MOCVD.

More in detail, we show that: (i) constant current stress induces a remarkable increase in the threshold current of the devices; (ii) threshold current increase is correlated to an increase in non-radiative recombination rate; (iii) during stress time, the concentration of a deep level located within the active region increases with the same kinetics of the threshold current increase; (iv) the activation energy of the detected deep level is 0.35-0.45 eV. Hypothesis on the nature and origin of this deep level are presented in the paper.

8262-41, Session 9

Highly doped GaN: a material for plasmonic claddings for blue/green InGaN laser diodes

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Highly n-doped GaN is a material of a reduced refractive index which may substitute AlGaN as a cladding layer in InGaN laser diodes. However better knowledge of its optical properties and their dependence on the doping level are needed for the proper design of the plasmonic cladding device. In this study we show the measurements of the optical absorption and the refractive index of GaN:O having the electron concentration between 1x1018 - 8 x1019 cm-3. Though the measured absorption coefficient for the highest doped GaN are rather high (200 cm-1) we show using an optical mode simulation that you can design a InGaN laser diode operating in blue/green region with decent properties and low optical losses. We propose to use relatively thin AlGaN interlayer to separate plasmonic GaN from the waveguide and thus to dramatically reduce the optical losses.

8262-42, Session 9

Estimation of the recombination coefficients in aged InGaN laser diodes

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In order to determine recombination processes in InGaN laser diodes and their evolution during aging we analyzed subtreshold light-current characteristics of these devices. We believe that in the properly chosen current range we can model the recombination processes by using a simple A, B generation-recombination formula. Here, A coefficient corresponds to inverse of the nonradiative recombination lifetime and can be directly determined from standard electroluminescence measurements made on ready device. We compare various experimental geometries to avoid the influence of both the “droop” and stimulated emission effects which can mask the “real” light-current characteristic. By choosing the low current range we can avoid tunneling effect and the influence of the process of screening piezoelectric fields at higher currents. We performed the aging of InGaN laser diodes and we observed very pronounced increase of nonradiative recombination -expressed by A coefficient. This process dominates the initial stage of aging. For the heavily degraded devices we observe stabilization of nonradiative recombination and decrease of the injection efficiency. These results may suggest the increase of the leakage current. We compare the obtained results with these deduced from photoluminescence measurements.

8262-43, Session 10

Polarization of eigenmodes and the effect on the anisotropic gain in laser structures on nonpolar and semipolar GaN

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The performance of InGaN-based laser diodes is strongly affected by the crystal orientation. The layer orientation defines the strength of the polarization field across quantum wells with largest fields on polar (0001), reduced fields in semipolar directions and no fields in the case of nonpolar planes. These fields separate electron and hole wave function, leading to increased radiative lifetimes and reduced gain.

For lasers on semipolar and nonpolar substrates the resonator orientation is of great importance. We have previously shown that eigenmodes of a laser resonator oriented along the projection of the c-axis onto the plane of growth (called c’) show linear TE/TM polarization. Resonators along nonpolar directions show ordinary and extraordinary eigenmodes with the electric field vector parallel or perpendicular to the c-axis, caused by the birefringence of the GaN crystal. This polarization tilt together with the anisotropic band structure leads to a reduced material gain along the nonpolar directions compared to the c’-direction.

In this work we present gain measurements of semipolar laser structures with differently oriented resonators and for various polarization states. We compare thresholds for lasers on semipolar (10-12), (11-22), (10-11), (20-21) planes and on nonpolar (10-10) m-plane. For waveguides on semipolar (20-21) the waveguide design is optimized and the ASE threshold in dependence on waveguide thickness and composition is evaluated.

The experimental results are accompanied by numerical calculations of the material gain as well as investigation of the surface morphology and resulting waveguide losses in dependence of the used crystal orientation.

8262-44, Session 10

Effect of ridge waveguide etch depth on laser threshold of InGaN MQW laser diodes

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The laser thresholds and lateral mode confinement of blue InGaN multiple quantum well (MQW) laser diodes have been investigated. Ridge-waveguide (RW) laser devices with different ridge etch depth ranging from 80 nm above the active region (deep-ridge waveguide) to 200 nm above the active region (shallow-ridge waveguide) as well as purely gain-guided devices have been fabricated. The comparison of devices with the same resonator length shows that the threshold current densities are significantly lower for deep-ridge waveguide laser diodes.

For deep-etched and 10 µm-wide ridge waveguide laser diodes the threshold current density is about 7 kA/cm² compared to shallow-etched devices with lasing thresholds of 13 kA/cm². The threshold current densities of shallow-ridge devices do not differ significantly from gain-guided laser devices with the same contact width.

The difference in lasing threshold becomes even more eminent for narrow ridges, which are required for single mode operation. For shallow-ridge devices the threshold current density increases by a factor of three when the ridge width is decreased from 20µm to 1.5µm (corresponding to threshold current densities of 8.6 kA/cm² and 25 kA/cm², respectively). However, for the deep-ridge waveguide devices the lasing threshold is almost independent of the ridge waveguide width, with threshold current densities as low as 9 kA/cm² for 1.5µm wide ridges.

This behavior can be explained by the improved lateral mode confinement and reduced current spreading for deep-ridge waveguide devices. For shallow ridge waveguide devices the optical mode experiences significantly higher absorption losses, due to widening of the optical mode beyond the gain region. The experimental results will be discussed in the context of 2D-simulations of the optical mode confinement and lateral current spreading in RW laser diodes.

8262-45, Session 10

Modeling gallium-nitride-based semiconductor blue lasers for data storage of information technology

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GaN-based semiconductor blue lasers can produce wavelengths at 405nm and provide more data storage capacity than red lasers in information technology. With proper designs in periodic structures and materials, the output wavelengths and performance can be more stable. This work demonstrates the process of utilizing periodic waveguide structures to model InGaN/AlGaN semiconductor quantum lasers with built-in corrugated metal gratings in order to calculate the coupling coefficients of these devices. The numerical results show how the optical, geometrical, and material parameters in models affect the coupling coefficients. Physical interpretations provide insights into the models and results.

8262-46, Session 10

Comparison of gain formation in polar and nonpolar/semipolar laser diodes from violet to green

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Experimental gain spectra at CW operation of laser diodes (LDs) fabricated from c-plane and nonpolar/semipolar GaN-based materials emitting in violet, blue and green spectral regions are presented. Gain spectra were taken from the measured amplified spontaneous emission using the Hakki-Paoli method at high resolution. The ability of the setup to resolve the sharp Fabry-Perot longitudinal peaks of the lasers at all injection currents allowed us to accurately measure the current density to reach transparency on the devices characterized in this work, and determine both total losses and differential modal gain curves up to threshold. We present a detailed comparison of transparency current density and modal gain for nonpolar/semipolar and c-plane LDs in violet and blue. The main parameters for the analysis are the internal electric fields (for c-plane lasers), hole effective masses, and valence band splittings assuming, in a first order approximation, that carrier recombination is dominated by the radiative and Auger recombination processes. In a preliminary analysis, we investigated the gain and spontaneous emission spectra of nonpolar/semipolar green LDs and observed a significantly lower total linewidth (homogeneous plus inhomogeneous) than reported elsewhere, which seems to indicate that inhomogeneous broadening is not a main unavoidable issue governing the evolution towards high performance green LDs.

8262-60, Session 10

Polariton lasers based on GaN microcavities

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In 1992 Weisbuch, Arakawa and co-authors have demonstrated the strong exciton-light coupling in semiconductor microcavities with embedded quantum wells. This discovery triggered a series of experimental studies of exciton-polaritons in microcavities which resulted in a number of remarkable successes. On of the most interesting effects discovered in 2006 by Le Si Dang, Deveaud an co-authors is the Bose-Einstein condensation of exciton-polaritons. Accumulation of 1000 or more polaritons in the same quantum state results in the polariton lasing, i.e. spontaneous emission of a coherent and monochromatic light. Contrary to conventional lasers, polariton lasers do not require inversion of the electronic population and have therefore an ultralow threshold. In 2007 room temperature polariton lasing in GaN-based microcavities has been demonstrated by Baumberg et al. In this talk I will address the most essential characteristics of polariton lasers and comment on the perspective of realisation of electrically pumped polariton lasers based on GaN microcavities.

8262-63, Poster Session

Impact of carrier localization, recombination, and diffusivity on excited state dynamics in InGaN/GaN quantum wells and double heterostructures

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For a comprehensive investigation of photoexcitation energy relaxation pathways, carrier recombination and transport processes in InGaN heterostructures we applied spectrally- and temporally-resolved techniques of photoluminescene (PL), picosecond light-induced transient grating (LITG), and differential absorption (DA). A comparative study of localized and extended states and internal field effects was undertaken by analyzing carrier dynamics in structures with different In content and well width, at photoexcitation carrier densities of 1016 to19 cm-3 and temperatures 10 to 300 K.

Spectrally-resolved PL and DA kinetics in InGaN multiple quantum wells (MQWs) with 10% -15 % of In revealed slow 3-5 ns decays for energies lower than the peak emission, whereas faster DA transients (~0.5 ns) at higher energies were consistent with energy transfer to lower states. Localization effects were verified directly by the decreasing diffusion coefficient, D, with increasing In content, down to 0.1 cm2/s at 15 % of In, but linearly increasing with excitation and temperature before saturating at a ~1.5-2 cm2/s RT value. The decrease in D correlated well with increase of localized carrier lifetime, thus providing the localized carrier low-level injection mobility of ~5 cm2/V.s and diffusion length of ~200 nm (at 15 % of In). Dependencies of lifetime and mobility on temperature and injection level revealed conditions (In content, injection level, temperature) under which the localization and piezoelectric field effects gradually vanish and pave the way to the determination of nonlinear recombination rate. Complementary data of carrier relaxation rate vs temperature and excitation density provided insight into processes leading to nonexponential transients in PL, LITG, and DA decays.

8262-64, Poster Session

Impact of indium surface segregation on optical properties of ultrathin InGaN/GaN quantum wells

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We investigate theoretically the influence of indium surface segregation in InGaN/GaN single quantum well on its optical properties. Obtained results show that the influence of the surface segregation on the dipole matrix element is not equal for all optical transition. This effect results from the joint action of the piezoelectric polarization and indium surface segregation which change selection rules. In addition, surface segregations at each interface of the quantum well have different impact on optical characteristics depending on the direction of the piezoelectric polarization. The effect of the surface segregation has been estimated applying the global sensitivity analysis in the frame of six-band approximation for the valence band and parabolic approximation for the conduction band.

8262-65, Poster Session

Measurements of off-state electrical stress in InAlN/AlN/GaN heterostructure field-effect transistors with varying In compositions

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We report on the electrical stress results in GaN-based heterostructure field-effect transistors (HFETs) with InAlN barriers. We monitored the DC characteristics and particularly much more sensitive the low-frequency phase noise behavior for the devices at pre- and post-stress conditions for five different wafers with In compositions varying from 12% to 20% in the barriers of the structures. The devices were stressed under off-state conditions with a gate bias of -10V (pinch-off condition), zero drain bias for 10hr. From the acquired data we observed that at higher In composition, HFETs became less sensitive to the stress. At lower In composition we noted up to 30 dBc/Hz higher low frequency noise for stressed devices over the entire frequency range of 1 Hz-100 kHz. The absolute drain current and noise differences decrease as the In composition in the barrier increases. The most relevant stress effect is revealed by a drain current reduction which is consistent with higher noise level measured. It was found that the HFET degradation is minimum for nearly InAlN/AlN/GaN lattice matched condition, i.e., 17.5% In composition, at which HFET the sheet electron density (channel current) is comparable with lower In composition. This latter result is promising for power applications in which reliability of devices functioning at higher drain current is crucial. The results may be valuable to decouple the off-state stress effect from the hot -electron and self heating effects.

8262-66, Poster Session

AlGaN/GaN based field effect transistors for terahertz detection and imaging

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As terahertz applications emerge, the need for sensitive fast operating detectors is becoming crucial, especially at the room temperature. Amongst these detectors, emerging plasma wave electronic devices such as field effect transistors (FETs) offer performance comparable to commercially available devices with the advantages of easy array focal plane integration. AlGaN/GaN FETs have great potential because of their material advantages such as high breakdown voltage, high electron mobility, and high saturation velocity. These advantages could be exploited for resonant and non-resonant terahertz detection.

We have designed, fabricated, and characterized different AlGaN/GaN FETs as single pixel terahertz detectors. This work focuses on non-resonant detection and imaging using GaN field plate FETs. To evaluate their performance as terahertz detectors, we have measured the responsivity as a function of i) the voltage applied on the gate ii) the azimuthal angle between the terahertz electric field and the source-to-drain direction of the structure, and iii) the temperature. This work gives prospects for electrical simulation of field effect transistors as terahertz detectors.

The imaging performance of the detectors was evaluated by scanning objects in transmission mode and an example of application of terahertz imaging as new non-destructive technique for the quality control of materials is given. Results indicate that AlGaN/GaN based FETs can be considered as promising devices for terahertz detection and imaging applications.

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8262-67, Poster Session

Degradation in InAlN/AlN/GaN heterostructure field-effect transistors using low-frequency noise and current-transient methods: hot phonon effects

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Low-frequency noise and current transient measurements were applied to analyze the degradation of nearly lattice-matched InAlN/AlN/GaN heterostructure field-effect transistors caused by electrical stress. Almost identical devices on the same wafer were stresses 7 hr. at a fixed DC drain bias of VDS=20 V and different gate biases. We noted up to 32 dB/Hz higher low-frequency noise for stressed devices over the entire frequency range of 1 Hz- 100 kHz. The measurements showed the minimum degradation at a gate-controlled two-dimensional electron gas density of 9.4x10^12 cm-2. This result is in good agreement with the reported stress effect on drain-current degradation and current-gain-cutoff-frequency measurements, and consistent with the ultrafast decay of hot-phonons due to the phonon-plasmon coupling. Moreover, the current transient (gate-lag) measurements were also performed on pristine and highly degraded devices at 430K for up to 5 ms pulse durations. Drain current is almost totally lost in degraded HFETs as opposed to a very small drop for pristine devices and no recovery observed for both indicating that generation of deep traps in GaN buffer.

8262-68, Poster Session

Efficiency enhancement of GaN/In0.11Ga0.89N solar cells grown on strain release sapphire substrate and biomimetic anti-reflection surface

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In this work, we successful fabricated the p-i-n double-heterojunction GaN/In0.11Ga0.89N solar cells grown by metal-organic chemical vapor deposition and grown on nano pattern c-plane sapphire substrate for reduced strain release. The solar cell with standard process was grown 2µm n-GaN, 300nm In0.11Ga0.89N and 400nm p-GaN. The conversion efficiency of the devices with standard process is 3.1%, which corresponds to a fill factor of 58%, short circuit current density of 2.86 mA/cm2, and open circuit voltage of 1.87 V under AM1.5G illumination. For further improvement of the conversion efficiency, utilized two-dimensional closely packed polystyrene nanospheres as a self-assembled monolayer mask in the anisotropic inductively coupled plasma reactive ion etching process to form a biomimetic surface texture. The surface morphology of the solar cell shows a periodically hexagonal nipple pattern and the nipple are formed in a diameter/height are 200/160 nm with a period of 250 nm. It is found that an increase of 3.87% in conversion efficiency cause by the 15% improvement of short circuit current density in the biomimetic surface cell. Considering the p-GaN layer thickness limit, we optimize the nipple structure for 180 nm of the height and 375 nm of the period, which can be expected to earn a 10% of the short circuit current gain.

8262-69, Poster Session

Investigation of emission polarization and strain in InGaN/GaN multiple quantum wells on nanorod epitaxially lateral overgrowth templates

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Conventional c-plane InGaN/GaN multiple quantum wells (MQWs) structure suffers from the quantum confinement stark effect (QCSE) due to the existence of spontaneous and piezoelectric polarization fields, leading to spatial separation of the electron and hole wave functions and to restrict the electron-hole recombination rate. Growth along the non-polar and semi-polar oriented direction has been proved to be an effective approach to ease or eliminate the influence of polarization field in nitride-based materials. On the other hand, Due to the anisotropic in-plane strain in the non-polar (In, Ga)N material system, the original $|X \pm iY\rangle$ valence band states are not degenerate any more. Additionally, $|Y\rangle$-like and $|Z\rangle$-like states will split larger to enhance the polarization ratio of light. The strong polarized light emission, resulted from the different energy state transitions, can be measured. Therefore, under the influence of the strong in-plane strain, the valence-band states will separate large enough to raise the emission polarization ratio. In this study, we grow the a-plane InGaN/GaN MQWs on the high crystal quality nanorod epitaxially lateral overgrowth (NRELOG) GaN templates. While keeping the a-plane InGaN-based MQW parameters (Indium composition and well thickness) the same, the optical polarization properties grown on the different nanorod height templates with different strain-induced effects were investigated and compared with the as-grown MQWs structure. In summary, the polarization ratio of the emission from InGaN MQWs varies from 85 % to 53 % along with the increase of the GaN nanorod height. The reduction of polarization ratio could be attributed to the partial strain relaxation within the epitaxial structures as a result of growth on the GaN nanorod templates and the micro-size air-voids observed in the nanorod templates.

8262-70, Poster Session

Free-standing a-plane GaN substrates grown by HVPE

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In this work, 225-µm-thick non-polar a-plane GaN substrates are fabricated. The process includes growing a-plane GaN thick films on MOCVD-grown templates by hydride vapor phase epitaxy (HVPE), separating the GaN thick films from the underlying sapphires by laser lift-off, followed by another regrowth of GaN on the free-standing GaN films by HVPE. Low-temperature photoluminescence (PL) measurement shows that, with increasing GaN film thickness, the intensity of near-band-edge (NBE) emission increases, while the intensity of the PL emission related to the basal-plane stacking

faults (BSFs) decreases. It is deduced that the density of BSFs

decreases with increasing film thickness. It is also found that the intensity of the NBE emission is stronger than that of the emission related to the BSFs when the thickness of the film is greater than 200 um. Cross-sectional SEM images show that voids are formed in the thick a-plane GaN films during HVPE growth and it is believe that they are helpful in releasing stress. A growth mechanism is developed to explain the formation of these voids. By optimizing the HVPE process, nonpolar a-plane GaN substrates thicker than 200 um can be achieved.

8262-71, Poster Session

Homoepitaxial growth of GaN on nonpolar and semipolar free-standing substrates

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GaN-based devices grown along the polar [0001] c-direction have large polarization, leading to the quantum confined Stark effect (QCSE) and a reduced radiative recombination rate within the quantum wells. To decrease these effects of polarization, the growth of devices on nonpolar and semipolar GaN substrates has been demonstrated. In this work, homoepitaxial GaN films were grown on nonpolar and semipolar GaN substrates to investigate their surface morphology. Moreover, we fabricated LED structures on these substrates and characterized their optical properties.

The GaN substrates were sliced from c-plane bulk GaN grown by hydride vapor phase epitaxy (HVPE). GaN films grown at 1090°C and LED structures with InGaN/GaN (3 nm/7 nm) multi-quantum wells for active regions were fabricated by metal-organic vapor phase epitaxy. The samples were evaluated using X-ray diffraction (XRD), atomic force microscope (AFM), and electroluminescence (EL).

In our experiments, high-quality GaN films with different surface morphologies were obtained. Some samples had a smooth surface with very low RMS values. With increasing current, whereas LEDs on a c-plane sapphire exhibit a shift of approximately 50 nm over 20 mA, there was hardly any shift of the peak emission wavelength on nonpolar and semipolar GaN substrates. This indicates a significant reduction of the effects of polarization.

8262-72, Poster Session

High performance 375 nm ultraviolet InGaN/AlGaN light-emitting diodes by using a heavily Si-doped GaN growth mode transition layer

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High performance 375 nm ultraviolet (UV) InGaN/AlGaN light-emitting diodes (LEDs) with a heavy Si-doped GaN growth mode transition layer (GMTL) were fabricated by metal-organic chemical vapor deposition (MOCVD). From transmission electron microcopy (TEM) image, the dislocation densities are reduced significantly by using the GMTL technique. The threading dislocation (TD) value of AlGaN grown on GMTL was significantly decreased from the control sample value of 8×108 to 8×107 cm-2. Furthermore, the internal quantum efficiency (IQE) of the LEDs with GMTL was measured by power-dependent photoluminescence (PL) to be 40.6% higher than ones without GMTL. After vertical-type (size:1mm×1mm) LED chips were fabricated, the output power were measured by integrating sphere detector under 350 mA injection current driving. The output powers of the LEDs with and without GMTL were measured to be 286.7 and 204.2 mW, respectively. As much as 40.4% increased light output power was achieved. The GMTL leads to the superior IQE performance of the LEDs not only in decreasing the carrier consumption at non-radiative recombination centers but also in partially mitigating the efficiency droop tendency. Therefore, forming the GMTL between un-doped GaN and n-AlGaN to reduce dislocations would be a promising prospective for InGaN/AlGaN UV-LEDs to achieve high IQE.

8262-73, Poster Session

Reduction of efficiency droop in InGaN-based UV light-emitting diodes with InAlGaN barrier

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In this study, we fabricated and compared the performance of LEDs of InGaN-based UV MQWs active region with ternary AlGaN and quaternary InAlGaN barrier layers. HRXRD and TEM measurements show the two barriers are consistent with the lattice, and smooth morphology of quaternary InAlGaN layer can be observed in AFM. The electroluminescence results indicate that the light performance of the InGaN-based UV LEDs can be enhanced effectively when the conventional LT AlGaN barrier layers are replaced by the InAlGaN barrier layers. Furthermore, simulation results show that InGaN-based UV LEDs with quaternary InAlGaN barrier exhibit higher radiative recombination rate about 62% and low efficiency droop about 13% at a high injection current. We attribute this change to a drastic improvement from increasing of carrier concentration and redistribution of carriers, because of reduction of scatterings due to better morphology in the transverse carrier transport through the InGaN/InAlGaN MQWs.

8262-74, Poster Session

Thermally stable low-resistance Ohmic contacts to N-polar n-type GaN for high-power vertical light-emitting diodes

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Vertical-type GaN-based LEDs have attracted a great deal of interest because of their applications in solid-state lighting. In this type of LEDs, the formation of low resistance and thermally stable Ohmic contact to N-polar n-type GaN is critical. Unlike Ohmic contacts to Ga-polar n-GaN that are easily formed using metal schemes with a small work function, such as Ti and vanadium, Ohmic contacts to N-polar GaN are very difficult to form. For example, it was shown that unlike Ti/Al-based contacts to Ga-polar GaN, N-polar contacts exhibited electrical degradation after annealing at 700 °C. These results indicate that the formation of reliable Ohmic contacts to N-polar n-GaN is very important for the fabrication of high-performance vertical LEDs. It should be stressed that unlike top-emission LEDs, the fabrication of vertical LEDs requires low processing temperatures below 400 °C not to damage the conductive supporters. In this work, we used a laser-annealing process to form thermally stable and low resistance Ohmic contacts to N-polar n-GaN for high-performance vertical LEDs. It is shown that unlike the untreated sample, the laser-annealed samples exhibit Ohmic behaviors after annealing 250 °C, which remain stable up to 60 min at 300 °C. On the basis of the XPS and STEM results, Ohmic mechanisms are related to the formation of N vacancies due to the formation of interfacial TiN/b-AlN phases.

8262-75, Poster Session

Effect of MOCVD growth conditions on the optical properties of semipolar (1 -1 0 1) GaN on Si patterned substrates

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A strong internal electric polarization fields in the c-direction of wurtzite GaN leads to spatial separation of electron and hole wavefunctions in active regions of c-plane light emitting diodes (LEDs) providing the basis for GaN-based solid-state lighting. The elimination of the polarization fields by exploring nonpolar or semipolar GaN orientations has great promise for the production of high efficiency and high power LEDs as well as new material physics.

Recently we have found that optical quality of (1 -1 0 1)GaN grown by metal-organic chemical vapor deposition (MOCVD) on patterned Si(001) substrates is comparable to that of c-plane GaN films grown on sapphire. In this work, the dependence of optical properties of (1 -1 0 1)GaN and (1 -1 0 1)GaN/InGaN/GaN LED structures on MOCVD growth conditions were examined by steady-state and time-resolved photoluminescence (PL) and correlated with the distributions of extended defects studied by spatially resolved cathodoluminescence (spatio-CL) and high-resolution transmission-electron microscopy (HRTEM). We have found that reactor pressure is the major parameter that has a dramatic effect on the carrier decay dynamics in (1 -1 0 1)-GaN/Si(001). The (1 -1 0 1) GaN layers grown at high reactor pressure and high V/III ratios show bright luminosity and very long carrier decay times (~1.8 ns). To gain insight into possible effects of strain and defects caused by coalescence of stripes on carrier decay dynamics in ( )GaN on patterned Si(001), we have compared time-time-resolved PL, spatio-CL, and HRTEM data for the fully coalesced films and free-standing (1 -1 0 1)GaN stripes.

8262-76, Poster Session

Degradation mechanism of InAlN/GaN based HFETs under high electric field stress

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The degradation of InAlN/GaN based HFETs under high electric field stress for four bias points, namely, on-state high field stress (hot phonon, hot electron and self heating effect), off-state high field stress (hot phonon and hot electron effects but with much lesser intensity), on-state low field stress (self heating effect only), and reverse piezoelectric field stress (lattice strain effect) has been examined. The degradation is characterized by several electrical properties, such as, drain current reduction, gate lag, and low frequency noise. On-state high field stress has been shown almost a 50% reduction in the drain current and approximately 25dB increase in low frequency noise after 25 hours of stress, while other stress conditions lead to much lesser degradation. It will be argued that the degradation can be mainly ascribed to the hot phonon and hot electron effects.

8262-77, Poster Session

Electrical properties of ZnO:Ga as a transparent conducting oxide in InGaN-based light emitting diodes

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ZnO heavily doped with Ga or Al (GZO/AZO) has been studied as transparent electrodes in InGaN based light-emitting diodes (LEDs), which was proved to greatly improve the current spreading on p-side, light extraction efficiency and consequently the external quantum efficiency. Due to the small lattice mismatch ~1.8% between ZnO and GaN, it was thought the properties of ZnO grown on the p-GaN contact layer of the InGaN LEDs will be improved compared to other substrates such as a-plane sapphire substrates and glass substrates. However, few studies regarding the properties, especially the electrical characteristics, of GZO/AZO grown on GaN templates are available in literatures. Previously, we found that the surface morphologies of underlying p-GaN templates considerably affected the surface morphologies, growth modes, and structural properties of GZO layers grown on p-GaN templates. In this work, we mainly focused the effects of GaN templates on the electrical properties of GZO layers grown by plasma-enhanced molecular-beam epitaxy (MBE) for LEDs' application. Temperature-dependent Hall measurements combined with theoretical simulations have been used to gain insight into carrier-scattering mechanisms governing electron mobility and the relationship between the crystal structure and electrical properties of GZO layers. The electrical properties of GZO/GaN are compared with those of GZO/a-sapphire in terms of pecularities of their crystal structures and different growth mechanisms. Application of GZO layers as transparent electrodes in InGaN based LEDs will be discussed in details.

8262-78, Poster Session

Effects of polarization fields on avalanche breakdown of AlGaN quantum-well photodiode

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Current-voltage (I-V) curve and electroluminescence (EL) spectra of an Al0.1Ga0.9N/Al0.15Ga0.85N multiple-quantum-well (MQW) avalanche photodiode (APD) were measured and investigated. The effect of polorization fields to avalanche breakdown of AlGaN quantum well photodiode is studied. This carrier blockade effect induced by strong polorization fields starts to disappear if the applied field overcomes the polarization-induced fields within the barrier layers. This turning point is observed at about 11.6 V in conductance-voltage curve. This indicates that the threshold voltage for current breakdown is larger than the threshold voltage for carrier impact ionization in the AlGaN MQW APD, which is 10.0 V. Another effect of polarization fields is that carriers generated by impact ionization accumulate at the Al0.1Ga0.9N/Al0.15Ga0.85N interfaces and produce strong screening effect within the well layers. This is verified by seeing unusual Stark shift of the EL peaks with increasing of reverse bias. The changing rate of Stark shift shows a minimum at about 10.8 V, which indicates the voltage position that holding the strongest carrier screening in the well layers.

8262-79, Poster Session

Balancing intrinsic polarization and external fields in AlN/GaN heterostructures

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The large band-offset in AlN/GaN heterostructures makes them attractive candidates for fabricating quantum-cascade lasers operating in the mid-infrared frequency range, for instance for telecommunication. However, several challenges remain, like the scarcity of high-quality substrates and the need for mono-layer control of the layer thicknesses. In this presentation, we identify another key challenge, namely the formation of wide depletion regions between the GaN leads (cladding layers) and the active region. The additional barrier generated by this

depletion region can seriously inhibit current injection into the active structure. These depletion regions arise, together with a quantized inversion layer, to compensate for the large internal voltage drop stemming from the electric field of spontaneous and piezoelectric origin.

A systematic polarization-balance approach is developed. Here we match the internal voltage drop with the operational bias by using Al(x')Ga(1-x')N cladding layers of a specific alloy concentration x'. For structures with efficient emptying of the active region, this design approach secures flat-band in the leads. For AlN/GaN structures strained to the AlGaN leads, a simple relation between x' and the average alloy concentration of the active structure x guides our design. A large parameter study based on the Schrödinger-Poisson equation for a simple two-level quantum-cascade structure shows that good control over the lead composition is necessary to fulfill multiple design targets for polarization-balanced heterostructures.

We furthermore discuss and evaluate several specific designs of AlN/GaN quantum cascade structures aimed for lasing. We demonstrate that waveguides can be designed to provide good confinement of the optical mode for structures with ALGaN cladding layers. Finally, we show the results of our characterization of our grown samples.

8262-81, Poster Session

Optical properties of a hybrid nitride-ZnO microcavity

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ZnO is a wide bandgap semiconductor with strong excitonic properties. Due to its large exciton binding energy (larger than 60meV) and large oscillator strengths ZnO microcavities are expected to provide robust excitons and large non-linearities, which should facilitate the demonstration of polariton lasers at room temperature, as recently observed with GaN microcavities.

The microcavity investigated here consists in a 5[lambda]/4 ZnO active layer grown by molecular beam epitaxy embedded between a bottom (Ga,Al)N/AlN DBR and a top (Si,O)/(Si,N) DBR. The 13 pairs nitride DBR is grown by MBE on a Si(111) substrate. The dielectric DBR is realized by PECVD. This design leads to a cavity with a local quality factor of 450 and presents a large Rabi splitting of 120 meV at 10K. The quality factor is enhanced by a factor of 4 compared to previous ZnO cavities based on nitride DBRs.

In the linear regime, this microcavity exhibits a strong exciton-photon coupling regime both at low and room temperature. The emission of the microcavity has been studied under strong excitation density. When the carrier density is increased and for temperatures between 80 and 300 K, laser operation in the weak coupling regime is observed, with the laser emission line at an energy close to the bare cavity mode. At the laser threshold, the cavity switches from the strong coupling to the weak coupling regime. Below a temperature of 240 K, there is a coexistence of the strong coupling regime and a gain-related transition. The gain mechanism leading to lasing is attributed to an exciton-scattering process which is enhanced in II-VI semiconductors and well-known for bulk ZnO samples. This is a novel mechanism compared to VCSEL, which relies usually only on gain in a degenerate electron-hole plasma. Our interpretation supports the recent one of gain mechanism in ZnO nanowires in terms of exciton scattering processes.

8262-47, Session 12

Highly efficient InGaN/GaN blue LED on 8-inch Si (111) substrate

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We have grown LED structures on top of a robust n-type GaN template on 8-inch diameter silicon substrates achieving both a low dislocation density and a thick crack-free thickness even at a sufficient Si doping condition. The n-type GaN template consisted of AlN layer, which acts as a nucleation layer and barrier layer of Ga-Si eutectic reaction. The transition layer which consists of AlGaN layers and the unique epitaxial structure which consists of the dislocation reduction layer and stress compensation layers were then grown to control the stress and reduce the dislocation, simultaneously. After that, over 3.5 μm-thick Si doped GaN layer with 4.5×1018 cm-3 doping concentration has been grown successfully without any cracking. The full width at half maximum (FWHM) values of GaN (0002) and (10-12) ω-rocking curves were 220 and 320 arcsec, respectively. The dislocation densities were measured about 2~3×108/cm2 by atomic force microscopy (AFM) after in-situ SiH4 and NH3 treatment. On top of n-GaN layer, 20 pairs of InGaN/GaN layers for the effective current spreading, a five-period multi-quantum-well active region consisting of 3 nm-thick InGaN wells and 5 nm-thick GaN barriers, AlGaN layer for blocking electron overflow and p-GaN cap layers were grown. The measured relative internal quantum efficiency of 8-inch InGaN/GaN LED on Si was measured about 90% based on the intensity dependent photo-luminescence method. The standard deviation of dominant emission wavelengths measured from the mapping of whole 8-inch LED wafers was kept as small as 1.8 nm with median wavelength of 434 nm.

Under the un-encapsulated measurement condition of vertical InGaN/GaN LED grown on 4-inch Si substrate, the overall output power of the 1.4×1.4 mm2 chips representing a median performance exceeded 504 mW with the forward voltage of 3.2 V at the driving current of 350 mA. The measured internal quantum efficiency was 90 % at injection current of 350 mA. The efficiency droops of vertical LED chips on Si between the maximum efficiency and the efficiency measured at 1A (56.69 A/cm2) input current was 5%. In our measurement, the crystalline quality of InGaN/GaN LED on 8-inch Si was similar with that on 4-inch Si. World first results of InGaN/GaN LED on 8-inch Si substrates will be presented at conference.

8262-48, Session 12

Roles of the radiative and nonradiative recombination rates on the efficiency droop in InGaN-based quantum-well light-emitting diodes

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We investigated roles of the radiative and nonradiative recombination rates on the internal quantum effieicny (IQE) on both the temperature and the carrier density, the so-called ‘efficiency droop’, in InGaN/GaN blue and green multiple quantum well (MQW) light emitting diodes (LEDs).

In our model, the saturation of the radiative recombination rate is a trigger increasing the carrier density at the In-rich active areas of an InGaN QW. Once the radiative recombination rate begins to saturate there, the carrier density as well as the nonradiative recombination rate increase rapidly due to their small volumes. Eventually the IQE droop appears from much larger increase in the nonradiative recombination rate than that in the radiative one.

The radiative recombination rate tends to saturate with increasing carrier density and decreasing the active volume and temperature, which mostly originates from the imbalanced distributions of electrons and holes in the electron momentum k-space.

A nature of the dominant nonradiative recombination process in the IQE droop depends on the maximal carrier density containable in a QW, which is determined by a trade-off between the total carrier recombination rate and the electron escape rate in a QW.

Three shapes of IQE droop curves (i.e. convex, straight, and concave) are experimentally obtained. With an aid of the proposed model, we successfully explain the relation between a shape of the IQE droop curves and a dominant nonradiative recombination process among the SRH recombination in a QW, carrier escapes from active QWs to p-(Al) GaN clad layer via thermionic emission or tunneling transports.

8262-49, Session 12

Device characteristics of InGaN quantum well light-emitting diodes with AlInN thin barrier insertion

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The efficiency of InGaN quantum well (QW) LEDs suffers significantly at high operating current density, which leads to great limitation for the development of low-cost and high-power solid state lighting. Although the origin of the efficiency-droop phenomenon is still controversial, several carrier-density dependent possible reasons have been proposed to explain this issue.

In this paper, we present the MOCVD growths and characteristics of 500-nm emitting InGaN QW LEDs employing thin (~1.5 nm) AlInN barrier layers for efficiency droop suppression. The use of thin large-bandgap AlInN barriers leads to suppression of thermionic carrier escape at high carrier density, which in turn leads to reduction of the efficiency droop in nitride LEDs. In addition, the optimized growth condition for lattice-matched AlInN alloy (with 17% In-content) is compatible with those of InGaN QW and GaN barrier layers. The InGaN QW LEDs employing three different barrier configurations were grown as follow: 1) direct 1.5 nm thin AlInN barriers + GaN barriers, 2) 1 nm GaN spacer + 1.5 nm thin AlInN barriers + GaN barriers, and 3) GaN barriers. The characteristics of InGaN QW LEDs were measured by power-dependent cathodoluminescence and electroluminescence measurements at room temperature under CW operation. The efficiency droop was not observed for InGaN QW LEDs with direct AlInN barrier layers (structure #1) up to current density of 80 A/cm2, while the conventional InGaN QW LEDs shows efficiency droop phenomena at high current density. The finding indicated the possible suppression of efficiency droop in nitride LEDs employing thin AlInN barrier layer.

8262-50, Session 12

The quantum efficiency of InGaN light emitting diodes: effects of active layer design, electron cooler, and electron blocking layer

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A recurring problem in InGaN based LEDs is that efficacy falls sharply with rising current known as “droop”. Therefore, the efficiency and efficiency retention in InGaN LEDs has attracted considerable attention recently. In this realm, we investigated internal quantum efficiency (IQE) and relative external quantum efficiency (EQE) of c-plane InGaN LEDs with various active region including multiple quantum wells (MQWs) of different barrier height (either In0.01Ga0.99N or In0.06Ga0.94N barriers) and thickness (3 nm and 12 nm) as well as a 9-nm double heterostructure (DH). Pulsed electroluminescence (EL) and laser excitation power-dependent measurements indicated that both the relative EQE and the IQE were enhanced due to the incorporated two-layer InGaN staircase electron injector (SEI) as compared to the conventional AlGaN electron blocking layer (EBL). Furthermore, the lowered In0.06Ga0.94N interwell barriers (LB) improved the EQE and the IQE of MQW LEDs. The DH LEDs showed 30% higher EQEs compared to MQW LEDs, albeit at a relatively higher injection current density of 150 A/cm2. IQE and relative EQE of LEDs with various thickness of active region, i.e., 3nm, 6nm, 9nm and 11nm have also investigated and compared in order to understand the underlying mechanism of quantum efficiency versus injection. Since electrons must have holes with which to recombine for photon generation, increase of hole concentration is imperative and cannot be circumvented by any design of the active region. This paper also discusses means to increase the hole concentration.

8262-51, Session 12

High-voltage thin GaN LEDs array

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Recently, GaN-based semiconductors are attractive materials for light-emitting diodes (LEDs) and Laser diodes in the blue-ultraviolet spectral region. These devices make new display technology or high-density data storage on compact disks be realized. Due to the lack of native substrates, films of GaN and related nitride compounds are commonly grown on sapphire wafers. The use of a sapphire substrate also complicates processing steps, such as formation of cleaved-edge facets and electrical backside contacts. The extraction of heat from an operating device through the sapphire substrate is also hampered. Therefore, free-standing GaN optoelectronics without sapphire are most desirable. Thin-film laser lift-off (LLO) technique has recently been established as an powerful tool for GaN-based heteroepitaxial structures, eliminated the sapphire constraint. With the advancement of process, high efficiency has became the most popular issue of LEDs, hoever, the efficiency has a dropping phenomenon at high current injection. In this study, we fabricated small size (10 mil×23 mil) chips, which were using Laser lift-off techniques transfering epi-layer to Si substrate with mirror, then connecting 64 chips to a 8×8 array, which is shown in Fig. 1, each 10mil×23mil chip was operated at 3 mA to keep high efficiency. The high-voltage LEDs were 64 chips array , under a 24 mA current injection, the voltage were 21.60 V, and the output powers of thin GaN high-voltage LEDs and original sapphire-based high-voltage LEDs were 216 mW and 170 mW respectively. The output power of high-voltage thin GaN LEDs reached 27% higer than original sapphire-based LEDs, and the luminance efficiency reaches 28.8% higher than original ones.

8262-52, Session 12

InGaN/GaN quantum-well light-emitting diodes with a reversed piezoelectric polarization field

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Reducing the efficiency droop and turn on voltage of InGaN/GaN multi-quantum well (MQW) light-emitting diodes (LEDs) have been the subjects under intensive investigations lately. Piezoelectric polarization mismatch, which induces polarization sheet charge at InGaN/GaN interfaces and impacts electron transport, is considered an important factor in the efficiency roll-off behavior of these LEDs. For typical p-side up InGaN MQW LEDs grown by metal-organic chemical vapor deposition, the polarization-induced electric field in the last barrier layer is responsible for the enhanced electron spillover toward the electron blocking layer (EBL). In this work, we investigate by simulation the electrical characteristics of p-side down single quantum well LEDs. Compared to its p-side up counterparts, p-side down LEDs exhibit higher internal quantum efficiency and lower turn-on voltage as well as less droop effect due to the reduced electron spillover. These properties can be well accounted for by the reversed piezoelectric field in the InGaN quantum well. Besides, the operating voltage of these LEDs is reduced when an AlGaN electron blocking layer (EBL) is added to the LED structure. This is attributed to the formation of a 2-dimensional hole gas at the GaN/AlGaN interface. Simulation shows that the use of an $Al_{0.12}Ga_{0.88}N$ EBL results in an operating voltage of 2.74 V, compared to 2.93 V for the LED without an EBL. This work indicates that the p-side down devices are very promising and deserve further development.

8262-53, Session 13

VLED for Si wafer-level packaging

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In this paper, we introduced the advantages of Vertical Light emitting diode (VLED) on copper alloy with Si-wafer level packaging technologies. The silicon-based packaging substrate starts with a double-side polished p-type silicon wafer, then anisotropic wet etching technology is done to construct the reflector depression and micro through-holes on the silicon substrate. The operating voltage, at a typical current of 350 mill-ampere (mA), is 3.2V. The operation voltage is less than 3.7V under higher current driving conditions of 1A. The VLED chip on Si package has excellent heat dissipation and can be operated at high currents up to 1A without efficiency degradation. The typical spatial radiation pattern emits a uniform light lambertian distribution from -65° to 65° which can be easily fit for secondary optics. The correlated color temperature (CCT) has only 5% variation for daylight and less than 2% variation for warm white, when the junction temperature is increased from 25°C to 110°C, suggesting a stable CCT during operation for general lighting application. Coupled with aspheric lens and micro lens array in a wafer level process, it has almost the same light distribution intensity for special secondary optics lighting applications. In addition, the ultra-violet (UV) VLED, featuring a silicon substrate and hard glass cover, manufactured by wafer level packaging emits high power UV wavelengths appropriate for curing, currency, document verification, tanning, medical, and sterilization applications.

8262-54, Session 13

Large-scaled fabrication of InGaN Nanowire LED using economic nano-crack lithography

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Low-dimensional nano-electronics, such as quantum-dots and nanowires, have been important research topics in the fields of Nanophotonics. Despite the rapid research achievements for nanowire-based devices, these devices have never been major players in current market due to limitations from current fabricating methods. Electron-beam Lithography (EBL) and Focused-Ion-Beam (FIB) can produce nanowire precisely at the desired location, but the high fabrication cost has limited these methods for prototype fabrications.

In this study, fabrications of III-nitride nanowires were demonstrated using Nano-Crack lithography. Nanoscale fractures occur when pre-patterned photoresist subjects to significant thermal stress, such as liquid nitrogen immersion. The cracked photoresist pattern was used as the etch mask to etch the underneath SiO2 thin film and creating SiO2 nano-trenches with width about 300 nm after stripping off the photoresist. The samples were subsequently loaded into a metal-organic chemical-vapor-deposition (MOCVD) reactor and a full InGaN multiple-quantum-wells (MQW) light-emitting diodes (LED) structure was grown into the nano-trenches. The fabricated nanowire LED is long (15 μm) and is also very narrow (> 300 nm). Regular photoluminescence and dark-field microscopy were used to analyze the optical properties of the nanowire structure. Electrical characteristics were also analyzed after fabricating contact electrodes. The proposed method can fabricate III-nitrides nanowire optoelectronic devices economically and cover large-area. Future fabrication optimization can leads to new types of nanoscale light emitters or nanolasers.

8262-55, Session 13

Improved performance of 375 nm InGaNAlGaN light-emitting diodes by incorporating a heavily Si-doped transition layer

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High performance 375 nm ultraviolet (UV) InGaN/AlGaN light-emitting diodes (LEDs) were developed using a heavy Si-doping technique with metal-organic chemical vapor deposition (MOCVD). From transmission electron microcopy (TEM) image, the dislocation densities were reduced after inserting a heavily Si-doping transition layer (HSTL), which results in residual stress relaxation and 3D growth. The internal quantum efficiency (IQE) of the LEDs with HSTL was measured by power-dependent photoluminescence (PL) to be 40.6% higher than ones without HSTL. The HSTL leads to the superior IQE performance of LEDs not only in decreasing carrier consumption at nonradiative recombination centers but also in partially mitigating the efficiency droop tendency. When the vertical-type LED chips (size: 1 mm × 1 mm) was driven with a 350 mA injection current, the output powers of the LEDs with and without HSTL were measured to be 286.7 and 204.2 mW, respectively. A 40.4% enhancement of light output power was achieved. Therefore, using the HSTL to reduce dislocations would be a promising prospective for InGaN/AlGaN UV-LEDs to achieve high IQE.

8262-56, Session 13

Improved performance of nonpolar a-plane GaN light emitting diodes by controlled integration of silica nano-spheres into GaN buffer layers

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Due to the process complexity, and hence high cost of conventional epitaxial lateral overgrowth (ELO)-based nonpolar GaN epitaxial layers, the use of ELO process for nonpolar GaN LED fabrication is not yet widely accepted. In order to improve the performance of nonpolar a-plane GaN light emitting diodes (LEDs) by a simple process, we propose a controlled integration of silica nano-spheres (CIS) into the a-plane GaN epitaxial layer grown on r-plane sapphire by metal-organic chemical vapor deposition. First, we intentionally grew the 3-dimensional shaped a-plane GaN buffer layer by using the anisotropic growth nature of a-plane GaN on r-plane sapphire. Then, the silica nano-spheres with diameter of 250 nm were preferentially integrated in the valley of the buffer layers by using a spin coating method. The silica nano-spheres integrated in the valley act as the SiO_2 mask layers in the subsequent ELO process and threading dislocations originated from the GaN and sapphire interface were blocked by the integrated silica nano-spheres. Therefore, the laterally overgrown a-plane GaN layers on the silica nano-spheres were dislocation-free epitaxial layers with improved crystalline quality. In addition to the crystalline quality improvement, increased random scattering of light by silica nano-spheres resulted in the improvement light extraction efficiency of a-plane GaN LED with CIS process.

An on-wafer measurement has shown that the output power of a-plane GaN LED with CIS process was 2.5 times higher than that of reference LED. More detailed characteristics of a-plane GaN LEDs with CIS process will be reported.

8262-57, Session 14

Production technology of high power LED grown on 6" sapphire substrate for general illumination

M. Oh, LG Innotek (Korea, Republic of)

At present, LED industry has been grown by display application such as Note PC and TV backlight. LED Lighting is the fast growing segment of LED industry. Though still in the early stage with 5% penetration rate in overall lighting market, the growth potential is considerable due to its long life, power saving advantage, and the rising awareness of environmental concerns. In 2013, LED Lighting market will be expected to grow rapidly.

For LED lighting market to be more active, LED device cost should be decreased more because initial price for LED lighting is too expensive to replace general lighting. LG Innotek has developed large substrate to increase the productivity for cost down. LG Innotek were applied 6" sapphire wafer mass-production the world's first.

In this presentation, when using large substrates, it caused wafer crack and poor wavelength uniformity due to wafer bowing problems and a large amount of strain. LG Innotek has developed epitaxial growth process and the design of the heat transfer mechanism for mass production.

We will introduce mass production technology with large sapphire wafer.

8262-58, Session 14

Nitride- and oxynitride-based phosphors for LED lighting devices

Y. Tian, Lightscape Materials, Inc. (United States)

A novel class of nitride/oxynitride phosphors have been devised for LED lighting devices. The design of the phosphor materials was guided by a bottom-up protocol based on a configuration coordinate and Frank-Condon principle. Targeting superior thermal stability of the fluorescent emission, we examined a group of Si-containing chemical bonds as candidate backbone of the building block of the host crystal, whose hardness and thermal expansion coefficients were used as primary criteria in the screening. As a result, a red-emitting (RED) and green-emitting (GREEN) phosphors have been prepared through solid state reactions. The phosphor materials were characterized by fluorescent excitation and emission spectroscopy, optical diffuse reflectance, thermal quenching measurements and XRD crystallography. The RED phosphor emits at a peak wavelength in a range of 645-658 nm depending on the formulation variation. A typical deep red emitter, its chromaticity coordinates (CIE 1931) fall in a range of x=0.60-0.64, y=0.34-0.36. The emission peak of the GREEN phosphor, on the other hand, can be adjusted in 535-560 nm by altering the formulation, changing the emission color from green to yellow-green, and to yellow. The quantum yield of both the RED and GREEN phosphors is slightly higher than 90% at room temperature with lumen maintenance better than 93% at 150 °C. A white LED was built by integrating the RED and GREEN phosphors onto a GaN-based blue LED. It is demonstrated that a white light of CRI higher than 85 can be achieved with CCT in 2800-6500 K.

8262-59, Session 14

High-efficiency phosphor-free InGaN/GaN dot-in-a-wire white-

light-emitting diodes on silicon

H. P. Nguyen, K. Cui, S. Zhang, S. Fathololoumi, R. Wu, Z. Mi, McGill Univ. (Canada)

High efficiency phosphor-free white-light-emitting diodes (LEDs) are in demand for the emerging solid state lighting. The realization of such devices, however, has been limited by the poor performance of conventional GaN-based LEDs in the green and red wavelength range. In this context, we have developed InGaN/GaN dot-in-a-wire white-light LEDs, which can exhibit a record high (~60%) internal quantum efficiency and negligible efficiency degradation at high injection levels (~2,000A/cm2).

Self-organized InGaN/GaN dot-in-a-wire LED heterostructures are grown on Si(111) substrates by RF plasma-assisted molecular beam epitaxy. The GaN nanowires are vertically aligned to the substrate, and each wire consists of ten vertically aligned InGaN quantum dots. The dot widths and heights are in the range of 20-40 nm and 3-10 nm, respectively. White light emission is achieved by varying the dot heights/compositions in a single epitaxial growth step. Each quantum dot layer is modulation doped p-type using Mg to enhance the hole transport. Additionally, an AlGaN electron blocking layer in incorporated in the device active region to effectively reduce the electron overflow. The devices are fabricated using standard photolithography, polyimide surface passivation, dry etching, and contact metallization techniques. The resulting phosphor-free white-light LEDs exhibit a record-high internal quantum efficiency of ~60%, extremely stable emission characteristic with increasing current, and virtually no efficiency degradation at current densities up to ~2,000 A/cm2, which are attributed to the superior carrier confinement provided by the quantum dots, the nearly-defect free GaN nanowires, the reduced electron overflow, and the enhanced hole transport due to p-type modulation doping.

8262-61, Session 15

III-nitride intersubband photonics

F. H. Julien, Univ. Paris-Sud 11 (France)

III-nitride heterostructures in the form of quantum wells or quantum dots are subject of extensive studies for optical devices relying on intersubband transitions between electron quantum confined states. The spectral domain spans from the near-infrared spectral range, including the wavelengths of interest for fibre-optics telecommunications, up to the THz frequency domain. In this talk, we will review the latest achievements in terms of short infrared wavelength ultrafast quantum cascade detectors and electro-optical modulators. We will also discuss the recent progress towards GaN/AlGaN quantum cascade lasers operating at THz frequencies. Because of the large LO-phonon energy in GaN, nitrides offer prospects for THz lasers operating above room temperature in a broad emission frequency range of 1-15 THz. We will focus on the observations of THz intersubband transitions as well as reproducible quantum-cascade like resonant tunnelling transport in GaN/AlGaN superlattices and discuss recent electroluminescence experiments.

8262-62, Session 15

Second harmonic generation in GaN-based photonic crystals for single molecule investigations

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One of the most exciting issues for the application of planar photonic crystals (PhCs) is the possibility of large enhancement of the nonlinear optical response.

For non-centrosymmetric crystalline materials, the phase-matching conditions are very difficult to fulfill - a problem that can be solved by using PhC structures. For second harmonic generation (SHG), PhCs act in two ways: i) firstly their periodicity provides quasi-phase matching conditions for the fundamental and the SH fields and ii) secondly, PhCs produce strong spatial confinement of the fields. Both effects enhance the SHG.

III-Nitride semiconductors are promising nonlinear materials for optical wavelength conversion - having nonlinear susceptibility (2) comparable to conventional nonlinear crystals such as LiNbO3. They also have a wide electronic bandgap that eliminates absorption of the fundamental (near infrared) and generated (near UV) SH waves. However SHG in bulk GaN is weak because GaN is strongly dispersive.

We show that appropriate PhC patterning in GaN helps to overcome dispersion and provides quasi-phase matching conditions, resulting in substantially increased conversion efficiency obtained in a flexible manner. Enhancement factors of more than five orders of magnitude can be achieved.

Use of PhCs makes it possible to reduce the effective observation volume, thereby opening new opportunities such as the study of single-molecule dynamics, even in high concentration solutions. We have demonstrated sharp enhancement of the excited emission of single molecules immobilized on the surface of a GaN PhC, when quasi-phase matching conditions are fulfilled.

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8263-01, Session 1

Making highly conductive ZnO: creating donors and killing acceptors

D. C. Look, Wright State Univ. (United States); K. D. Leedy, Air Force Research Lab. (United States)

We have grown 278-nm-thick Ga-doped ZnO layers on Al2O3 by pulsed laser deposition in 10-mTorr of pure Ar at 200°C and have obtained resistivity rho = 1.96 x 10-4 ohm-cm, carrier concentration n = 1.14 x 1021 cm-3, and mobility μ = 28.0 cm2/V-s, at room temperature. From Hall-effect modeling we have obtained donor ND and acceptor NA concentrations of 1.45 x 1021 and 1.71 x 1020 cm-3, respectively. By means of SIMS and positron annihilation measurements we have shown that the donors and acceptors are mainly GaZn and VZn2-, respectively [1]. To improve the conductivity, we have annealed in forming gas (FG: 5% H2 in Ar) at various temperatures (TA) from 300 - 600 C; at TA = 500 C, rho = 1.46 x 10-4 ohm-cm, n = 1.01 x 1021 cm-3, and μ = 42.2 cm2/V-s, with ND = 1.10 x 1021 and NA = 0.45 x 1020 cm-3. Annealing in Ar alone gives a similar decrease in NA, but a much larger decrease in ND, at least for TA > 450 C. Thus, the H in the FG appears to have little effect on NA, but a large, favorable effect on ND, most likely due to restriction of the formation of Ga2O3 and other neutral oxides. Prominent low-temperature photoluminescence features include a donor-bound exciton line at 3.366 eV and the so-called "A line" at 3.31 eV.

1. D.C. Look, K.D. Leedy, L. Vines, B.G. Svensson, A. Zubiaga, F. Tuomisto, D. Doutt, and L.J. Brillson, submitted for publication.

8263-02, Session 1

Optical characterization of high mobility polycrystalline ZnO:Al films

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Many optoelectronic devices require contact layers which offer a high electrical conductivity and optical transparency simultaneously. In thin film photovoltaics, where such films serve as front contacts, optical losses have to be minimized over a wide spectral range. For cells based on crystalline or microcrystalline silicon, this applies to photon energies extending down to 1.1 eV.

The materials used for this purpose are highly doped, transparent and conductive oxides (TCOs), e.g. aluminium-doped zinc oxide. In PV applications it is necessary to limit the doping level of these materials to lower values in order to prevent cell current losses due to free carrier absorption. It is therefore beneficial to raise conductivity by maximizing the carrier mobility rather than carrier concentration. Using capping layers to protect ZnO:Al films from degradation in high temperature treatments it was possible to raise the carrier mobilities to over 65 cm2/Vs.

In order to optimize the films a deep understanding of the connection between electrical and optical properties of TCOs is needed. While the Drude theory gives a good understanding of the general relationships, the optical analysis of films is often hindered by deposition related inhomogeneities and shortcomings of the Drude theory.

The talk will present recent results on the synthesis of ZnO films with high carrier mobilities, exceeding 65 cm2/Vs for carrier concentration in the range of 4e20 cm-3, and discuss their optical analysis. The current status and limitations of optical modelling for the determination of electrical transport properties of TCO films will be presented.

8263-03, Session 1

First-principles investigation of unusual electronic structures of oxides

S. Wei, National Renewable Energy Lab. (United States)

Post-transition metal oxides (ZnO, In2O3, SnO2, etc.) and their alloys comprise a group of materials that have many unique physical properties such as simultaneously high electron conductivity and optical transmission. Therefore, they are widely used in optoelectronic applications such as photovoltaic and LEDs. They have also been proposed as ideal hosts for high TC spintronic materials. In this talk, I will discuss our recent first-principles theoretical study of the oxides, demonstrating that the properties of the binary and multinary oxides are more complex than previously thought. We find that (i) many oxides (In2O3, Cd2SnO4, etc.) have non-equivalent fundamental and optical band gaps, arising from parity forbidden band edge transitions; a good transparent conducting oxide should have small fundamental band gap but a large optical band gap. (ii) The band gap renormalization in degenerate n-type doped oxides arises from the nonparabolic nature of the conduction band (i.e., not a rigid shift as previous thought), and is highly sensitive to the electronic states of the dopants. (iii) The ground state crystal structure of the non-isostructural (InMO3)m(ZnO)n (M=In, Ga, Al) alloy should satisfy several fundamental rules such as the octahedron rule and the octet rule. The formation of the layer quaternary structure or amorphorous structure also results in some interesting changes in the electronic and optical properties of the alloy. We have also analyzed the doping asymmetry problem in the wide-gap oxides and proposed several approaches to overcome the p-type and bipolar doping bottlenecks in these materials.

8263-04, Session 1

Hydrothermal growth and properties of group III (indium, gallium, and aluminum) doped bulk ZnO crystals

B. Wang, Solid State Scientific Corp. (United States); M. Snure, M. Mann, Air Force Research Lab. (United States); D. Look, Wright State Univ. (United States)

We have grown ZnO bulk crystals in the presence of group-III ions by the hydrothermal technique, to obtain In, Ga and Al-doped ZnO crystals, which are promising candidates to produce electrically conducting substrates that are needed for light-emitting devices. Hall-effect data measured on the crystals in the range 15-320 K has been fit to yield donor (ND) and acceptor (NA) concentrations; these can be correlated to impurity concentrations as determined by SIMS. We have found In, Al and Ga are the major donors while Fe and Li are the major acceptors in the ZnO crystals (within error, ND≈[In]+[Al]+[Ga] and NA≈[Fe]+[Li]). Photoluminescence spectra of indium, gallium and aluminum-doped ZnO, as well as Ga/N co-doped ZnO crystals have been measured from room temperature to 4K and display donor-bound exciton lines corresponding to the dopants. In the talk we will discuss the growth and properties of group III-doped bulk hydrothermal ZnO crystals in more detail.

8263-05, Session 1

Novel fabrication method for ZnO films via nitrogen-mediated crystallization

N. Itagaki, K. Kuwahara, K. Matsushima, K. Oshikawa, Kyushu Univ. (Japan)

We have demonstrated a novel fabrication method of ZnO films utilizing nitrogen mediated crystallization (NMC), where the crystal nucleation can be controlled because the nitrogen atoms interfere with the crystallization of ZnO films. Here, we utilize the NMC-ZnO films as homo-buffer layers for ZnO films in order to investigate their effects on the properties of ZnO based transparent conducting oxide (TCO) and epitaxial ZnO films, which are deposited by RF magnetron sputtering on glass and Al2O3 substrates, respectively.

Low resistive ZnO:Al (AZO) films with uniform spatial distribution have been obtained by utilizing NMC buffer layers. For 100 nm-thick AZO films fabricated by a conventional sputtering, the resistivity at the area facing the target erosion is 2.27 mΩ·cm, which is about 5 times higher than that at 60 mm away from the erosion. On the other hand, AZO films on NMC buffer layers exhibit uniform distribution of the resistivity of 0.25 - 0.35 mΩ·cm. These results reveal that controlling the crystallinity at the initial stage of deposition is of great significance, especially at the area facing the target erosion where the energetic species impinging on the growing films can induce a high density of nucleation with broad orientation distributions. The NMC buffer layers also improve the crystallinity of epitaxial ZnO films. FWHM of rocking curves of (002) diffraction is drastically reduced from 0.49o to 0.065o. From there results, we conclude that our method described here is full of promise for fabrication of high-quality ZnO-based materials.

8263-06, Session 2

Unraveling the mystery of conductivity at polar/nonpolar perovskite interfaces

S. A. Chambers, Pacific Northwest National Lab. (United States)

Complex oxides exhibit a rich array of properties as a result of the degrees of freedom that can be achieved by the choice of metal cations. This richness has been built upon by preparing interfaces of dissimilar perovskites. One of the most interesting and widely investigated systems of this kind is the LaAlO3/SrTiO3(001) (LAO/STO) heterojunction. Despite the fact that both materials are band insulators, their interface can exhibit electronic conductivity, at least when prepared under certain conditions. These results have been widely interpreted as being due to an electronic reconstruction (or charge transfer) resulting from the polarity mismatch between LAO and STO, giving rise to a two-dimensional electron gas on the STO side of the interface. This charge transfer is thought to eliminate the interface dipole, which if not removed by some means, would cause the electrostatic potential within the LAO to diverge. Most researchers tend to think of this interface in the most simplified way, as if it were atomically abrupt and defect free. Interestingly, XPS measurements show that the potential drop predicted to exist across the film because of the polarity mismatch simply is not present. Therefore, other explanations for the observed conductivity must be sought. We have developed one such explanation, based on cation mixing at the interface and unintentional La doping of the STO. In this talk, I will show evidence for this model, and present results for a similar system, LaCrO3/SrTiO3(001), which does not exhibit conductivity despite having a polarity mismatch.

8263-07, Session 2

Properties of TCO anodes deposited by APCVD and their applications to OLED lighting

R. Y. Korotkov, P. Ricou, L. Fang, Arkema Research Ctr. (United States); H. Schwab, M. Ruske, Philips Technologie GmbH (Germany); D. Gaspar, A. B. Padmaperuma, Pacific Northwest National Lab. (United States)

One of the materials that is currently considered in industry as a possible replacement for ITO thin film coatings is doped ZnO. The properties of the doped ZnO anodes are analyzed in 3D using high-throughput mapping tools. The 2D resistivities of the coatings measured by 4-point probe compare well with the resistivity values calculated from the 2D electron concentration and mobility maps derived from the spectroscopic ellipsometer measurements. To study the variation of the film properties along z-axis, the films are polished using mechanical planarization technique. The electrical depth profiles for these films are studied by differential Hall-effect and spectroscopic ellipsometer, wherever as structural depth profiles are studied using x-ray diffraction and TEM. The electron mobility increases continuously from the glass-film interface (10 cm2/Vs) to the ZnO film surface (25 cm2/Vs). The electron concentration depth profiles have bell-like dependencies with a maximum at 1.55 x 1021 cm-3 and the lower values observed at the corresponding glass and air-interfaces. The electrical properties in each removed slice of the ZnO are calculated using a multi-level conduction model. In addition to the increasing grain size from the substrate, the texture coefficients for the (002) reflection decrease and (103) reflection increase towards the air-film interface. Examples of the applications of the doped ZnO anodes in the OLED structures will be presented.

8263-08, Session 2

Electronic and optical properties of transparent conductive oxides from ab-initio calculations

A. Schleife, Lawrence Livermore National Lab. (United States); C. Roedl, F. Fuchs, K. Hannewald, J. Furthmueller, B. Hoeffling, Friedrich-Schiller-Univ. Jena (Germany); P. Rinke, Fritz-Haber-Institut der Max-Planck-Gesellschaft (Germany); J. B. Varley, A. Janotti, C. G. Van de Walle, Univ. of California, Santa Barbara (United States); F. Bechstedt, Friedrich-Schiller-Univ. Jena (Germany)

Parameter-free calculations are a modern, sophisticated complement to cutting-edge experimental techniques used for the exploration of material properties. Due to continuous progress of the theoretical framework and the numerical algorithms, this field largely benefits from the rapidly increasing power of computers. Therefore, ab-initio calculations are now capable of providing a deep understanding of the interesting physics underlying the electronic structure and optical absorption of the transparent conductive oxides.

First, an introduction of the recent theoretical-spectroscopy techniques this work is based on is given. By calculating the electronic quasiparticle states, we account for the excitation aspect of photoemission experiments. A combination of the non-local hybrid HSE functional and Hedin's GW approximation is shown to provide reliable results for the oxides. In addition, the optical absorption is investigated using the solution of the Bethe-Salpeter equation for the optical polarization function, which allows us to include excitonic and local-field effects in the calculations.

We compute the electronic band structure (including spin-orbit coupling) to clarify the valence-band ordering in ZnO and the influence of polytypism on the density of valence- and conduction-band states in In2O3. The quasiparticle energies and the optical-absorption spectrum calculated for SnO2 allow us to reconcile seemingly contradicting

experimental findings. Determining the branch-point energies by means of a Tersoff approach leads to a reasonable description of the natural band discontinuities of the oxides. Finally, the intricate interplay of transparency in the visible spectral range and a large n-conductivity of these materials is disentangled for ZnO by accounting for the influence of a degenerate electron gas on the excitonic effects. Throughout the talk, our findings are discussed with respect to experimental studies.

8263-09, Session 3

Thermal process induced change of conductivity in As-doped ZnO

C. Ling, S. C. Fan, The Univ. of Hong Kong (China)

As-doped ZnO films were fabricated by rf magnetron sputtering method with different substrate temperature TS. Growing with the low substrate temperature of TS=200oC yielded n-type semi-insulating sample. Increasing the substrate temperature would yield p-type ZnO film and reproducible p-type film could be produced at TS~450oC. Post-growth annealing of the n-type As-doped ZnO sample grown at the low substrate temperature (TS=200oC) in air at 500oC also converted the film to p-type conductivity. Further increasing the post-growth annealing temperature would convert the p-type sample back to n-type. With the results obtained from the studies of positron annihilation spectroscopy, photoluminescence, cathodoluminescence, X-ray photoelectron spectroscopy, secondary ion mass spectroscopy and nuclear reaction analysis, we have proposed mechanisms to explain for the thermal process induced conduction type conversion as observed in the As-doped ZnO films.

8263-10, Session 3

Doped gallium oxide nanowires for photonics

E. Nogales, I. López, B. Méndez, J. Piqueras, Univ. Complutense de Madrid (Spain); K. Lorenz, E. Alves, Instituto Tecnológico e Nuclear (Portugal); J. Á. García, Univ. del País Vasco (Spain)

Invited talk: Monoclinic gallium oxide, β-Ga2O3, is a transparent conducting oxide (TCO) that presents a very wide band gap, about 4.9 eV, displaying a semiconducting behavior and an optical transparency window that goes well into the ultraviolet (UV) region. Besides, it has strong chemical and thermal stability and a fairly high refractive index. Due to these facts, research on this material is mainly oriented to applications such as gas sensors, catalysis, laser lithography, solar cells, as well as UV optoelectronic and photonic devices. In particular, the morphology of nanowires made of this oxide presents specific advantages for light emitting nanodevices, nanowaveguides and gas sensors. Control of doping of the nanostructures is of the utmost importance in order to tailor the behavior of these devices.

In this work, doped gallium oxide nanostructures have been obtained. The growth of the nanowires is based on the vapor-solid (VS) mechanism obtained by thermal annealing treatment while the doping process was done in three different ways. In one of the cases, doping was obtained during the growth of the wires. A second method was based on thermal diffusion of the dopants after the growth of undoped nanowires, while the third method used ion implantation to introduce optically active ions into previously grown nanowires. The study of the influence of the different dopants on the luminescence properties of gallium oxide nanowires is presented. In particular, transition metals and rare earths such as Cr, Gd, Er or Eu were used as optically active dopants that allowed selection of the luminescence wavelength, spanning from the UV to the infrared ranges. The benefits and drawbacks of the three different doping methods are analyzed by SEM, TEM, X-ray microanalysis, confocal Raman and photoluminescence spectromicroscopy, cathodoluminescence in the SEM and photoelectron spectromicroscopy. The waveguiding behavior of the doped nanowires has been studied by confocal micro-photoluminescence and angle resolved cathodoluminescence.

8263-11, Session 3

Structural defects and shallow impurities in ZnO

A. Hoffmann, M. R. Wagner, Technische Univ. Berlin (Germany)

The optical transitions and dynamics of excitons, phonons, and defects in ZnO are reviewed. A comparative study of different ZnO single crystals as well as doped and undoped ZnO films reveals pronounced differences in the free and bound exciton luminescence which 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 influence of resonant and non-resonant excitation on the decay dynamics of phonons and excitons in ZnO. A strong resonance enhancement of the second order LO Raman modes is observed for excitation energies in resonance with the dominating bound exciton states. This enhancement is caused by the wave vector dependent Fröhlich interaction which leads to a pronounced coupling of excitons with LO phonons. Time resolved energy dispersive luminescence and Raman measurements enable the differentiation between the resonantly enhanced coherent Raman process and the non-coherent luminescence process.

8263-12, Session 3

Proliferating metal-insulator transition by x-ray in an electron doped vanadium dioxide thin film

K. Shibuya, RIKEN (Japan); M. Kawasaki, Y. Tokura, The Univ. of Tokyo (Japan)

Strongly correlated electron system often shows collective changes in electronic states by tiny external stimuli, being a candidate material for switching devices. A typical example is the metal-insulator transition in vanadium dioxide, which exhibits a huge jump in resistivity from high temperature metallic to low temperature insulating phases at around room temperature as well as a transmittance change in the infrared region. Dimerization of V ions to form spin singlet state opens the gap. Therefore, numbers of studies have been performed to realize electrical and optical switching devices operating at room temperature.

We have examined the stability of this metal-insulator transition against electron doping and x-ray irradiation. The metal-insulator transition temperature in VO2 thin films can be systematically reduced by electron doping with W6+ (V1-xWxO2), and eventually a metallic ground state is realized at around x = 0.08. The V-V dimerization was found to be locally disordered by x-ray irradiation at low temperature (< 50 K) for a sample with x = 0.065 in close vicinity to the metallic region. Thus generated phase separation was persistent at low temperature and accompanied with a percolative metallic conduction. Quantitative analysis revealed that one x-ray photon generates a metallic patch consisting of 105 V ions.

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8263-13, Session 4

Growth and characterization of large-diameter lithium-free ZnO single crystals

S. Wang, Fairfield Crystal Technology, LLC (United States)

Large diameter, lithium-free ZnO single-crystal substrates of high crystalline quality will enable development and commercialization of high-performance ZnO-based semiconductor devices, such as UV and visible-light emitting diodes (LEDs), UV laser diodes and solar-blind UV detectors for variety of applications. Fairfield has recently developed a novel crystal growth technology for producing lithium-free ZnO single crystal boules over 25mm in diameter. Fairfield also fabricated ZnO single crystal wafers in sizes up to 25mm in diameter. Chemical purity, crystalline defects, electrical and optical properties of ZnO single crystals were analyzed using variety of techniques. Results from crystal growth and material characterization will be discussed in this presentation. The research results prove that the novel crystal growth technique is a viable production technique for producing ZnO single crystals and substrates for semiconductor device applications.

8263-14, Session 4

New application fields of periodically polarity-inverted ZnO structures

J. Park, Hanyang Univ. (Korea, Republic of); S. Hong, Chungnam National Univ. (Korea, Republic of); J. Chang, Korea Maritime Univ. (Korea, Republic of); T. Yao, Tohoku Univ. (Japan)

ZnO is expected to have nonzero second-order susceptibility due to the lack of inversion symmetry in wurtzite crystal structures. From this characteristic, ZnO has attracted interest as a nonlinear optical material with high nonlinear optical response. Therefore, in terms of phase matching in nonlinear optical devices, the periodical array of polarity controlled ZnO films can be used a nonlinear optical material for potential applications in integrated optics.

We have established the selective growth technique of Zn-polar and O-polar ZnO layers on sapphire substrate using Cr-compound buffer layers. The Zn- and O-polar ZnO layers are successfully selected by varying the surface structure of CrN and Cr2O3, respectively. Based on the suggested in-situ polarity control method, we have fabricated 1D and 2D periodically polarity-inverted (PPI) ZnO structures with sub-micron scale periodicity. The fabricated PPI ZnO structures show the enhancement of second harmonic generation (SHG) intensity and enable quasi-phase matching in nonlinear optical effects to achieve effective frequency conversion of the incident laser light analyzed by simple photonic bandgap model. Finally, we will report that the results of vertically aligned ZnO nano structures including nano rods and nano walls on PPI ZnO templates with various synthesis methods. The selective growth of ZnO nano structures on Zn-polar regions in PPI ZnO templates was achieved without the consideration of synthesis method.

8263-15, Session 4

Innovative and cost-effective eco-synthesis of oxide-based materials by Electrostatic Spray Assisted Vapour Deposition

K. Choy, The Univ. of Nottingham (United Kingdom)

This paper gives an overview on the use of emerging novel and non vacuum Electrostatic Spray Assisted Vapour Deposition (ESAVD) based processes as alternative cost-effective and sustainable methods for the synthesis of a wide range of oxide nanostructured materials in the form of nanocrystalline thin and thick films as well as nanosized powder. The ESAVD process involves spraying atomised precursor charged droplets towards a heated substrate. The dense nanostructured film can be deposited by tailoring the charged precursor droplets to be decomposed and/or undergo heterogeneous chemical reaction on or near the heated substrate surface, whereas the porous films via the homogeneous and heterogeneous reaction, and nanosized powders can be synthesized via homogeneous gas phase reactions [1]. The fundamental aspects of ESAVD including process principle and deposition mechanism will be presented. A wide range of high purity nanostructured oxide materials with well controlled structure, stoichiometry and crystallinity can be deposited. These include: simple oxides (e.g. ZnO, TiO2, ZnO, Al2O3); doped oxides (e.g.In2O3-SnO2, F:SnO2,Sb:SnO2, Y2O3-ZrO2, Eu-Y2O3); multicomponent oxides (e.g.PbTiO3, BaZrO3, La(Sr)MnO3). The growth, structure and properties of selected thin film oxides for applications in photovoltaics, transparent electronics, piezoelectrics, and dielectrics will be highlighted.

[1] K. L. Choy, "Chemical vapour deposition of ceramic coatings", Progress in Materials Science, 48, 2, 2003, 57-170.

8263-16, Session 5

ZnO microwire quantum well heterostructures

C. P. Dietrich, M. Lange, M. Stölzel, H. Franke, M. Grundmann, Univ. Leipzig (Germany)

We report the fabrication of ZnO microwires with radial quantum well heterostructures that can be utilized as photonic emitter due to their distinct cavity characteristics. For this purpose we benefit from the unique properties of carbothermally grown ZnO microwires with respect to their excellent crystal quality and optical features such as formation of standing waves by total internal reflection - so-called whispering gallery modes (WGM) - representing high-quality naturally built microcavities.

Quantum well (QW) heterostructures were fabricated by pulsed-laser deposition (PLD) in radial direction on non-polar side facets of bare ZnO microwires using an off-angle PLD plasma plume. QWs that spectrally emit above or below bulk ZnO were achieved by embedding a thin ZnO or CdZnO layer between MgZnO barriers, respectively. In both cases, recombination has been analysed by means of time-integrated and time-resolved photoluminescence experiments and reveals clear QW properties. Further, all fabricated microwire heterostructures exhibit photonic eigenmodes covering the entire wire emission. These modes were unambiguously assigned to WGM passing the microwire.

We discuss the absorption mechanisms in ZnO wires caused by either the green or UV emission. On the one hand, QW luminescence energetically below ZnO (which is the case for CdZnO QWs between ZnO barriers) is subject to strong light absorption by the green defect band of ZnO. This can be suppressed by alloying the barrier with Mg atoms and therein reducing the intensity of the green band by saturating the intrinsic defects. On the other hand, optical eigenmodes in MgZnO/ZnO/MgZnO hetero-structures are absorbed by the ZnO core. This can only be overcome by increasing the overall shell thickness to the point that WGM can completely travel inside the wire surrounding. During the growth process, we observe a continuously transition from m-plane orientation to a-plane orientation of the wire side facets.

Nowadays, the prerequisites for highly efficient lasing are integration of low-dimensional active regions (such as QWs in heterostructures) and optimal light confinement (such as WGM in microwires or disks). With this work, we demonstrate the successful combination of QWs with optical eigenmodes and a first step to strong light-matter interaction and high-power lasing.

8263-17, Session 5

Modification and applications of ZnO nanocrystals by laser irradiation

T. Okada, K. Okazaki, K. Kubo, T. Shimogaki, M. Higashihata, D. Nakamura, Kyushu Univ. (Japan)

We report an influence and applications of phenomena induced by the laser irradiation on the ZnO nanocrystals. When the laser irradiation fluence is in the range 20 mJ/cm2 to 100 mJ/cm2, where the largest fluence is limited by the onset of laser ablation, the ZnO nanowires melt and re-crystallized. This phenomenon has been used for the laser annealing of the P ion-injected ZnO nanowires and the laser nano-soldering between the interface of the ZnO nanowires and a p-GaN thin film for the formation of a hetero pn-junction. Below 10 mJ/cm2, the lasing in a single ZnO nanocrystal was observed. We also report the comparative study on the lasing in a single ZnO nanowire and nanosheet, with the result that the nanosheet is usable as higher gain building-block for laser application.

8263-18, Session 5

White-light lasing in ZnO microspheres fabricated by laser ablation

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Zinc oxide, with wide band gap, has been investigated as a light emitter in ultraviolet region ; besides, oxygen vacancy in ZnO is known to cause broad green luminescence. Consequently, ZnO with defects is a potential white-light source. Here we successfully fabricated ZnO microspheres with the defects and found white-light lasing with extremely low threshold for the first time.

Recently, microscale materials have attracted much attention as optical microcavities. Among them, whispering gallery modes (WGM) of microspheres have the highest Q values. However, it has been very difficult to fabricate a semiconductor microsphere, a promising optical material. ZnO has a wurtzite structure and tends to grow in a hexagonal microwire shape. Thus lasing in a ZnO microwire has been reported. On the other hand, we succeeded in fabrication of ZnO microspheres whose diameter is 1~3 μm by laser ablation in superfluid helium.

We performed micro-photoluminescence measurements of single ZnO microsphere at room temperature. We observed efficient lasing with WGM structure in the whole visible and near-ultraviolet region from 1.7 eV to 3.3 eV in the ZnO microsphere with a CW laser. The lasing threshold was found to be around 100 W/cm2. This value is much smaller than that (170 kW/cm2) which has been recently reported in a ZnO microwire at 10K. This means that the fabricated sphere has very high Q value and is potential for many optical applications, e.g. nonlinear optical devices.

8263-19, Session 5

White light upconversion emission in Yb3+/ Er3+/ Tm3+ codoped oxy-fluoride lithium tungsten tellurite glass ceramics

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A transparent Tm3+- Yb3+- Er3+ tri-doped ions in TeO2-Li2O-WO3(TWLOF) glass have been sensitized by melt quenched method. According to the DSC result the precursor glass heated at glass transition temperature at 3450C for 10hrs transparent TWLOF glass- ceramics with precipitated crystalline phase LiYbF4 in this glass were successfully obtained. The visible white light upconversion (UC) emission have been achieved at room temperature under 980nm laser diode excitation. Bright blue at 483nm from Tm3+(1G4→3H6)but weak blue 437nm from Er3+(4F3/2→4I15/2) , bright green at 523nm(2H11/2→4I15/2 and at 545nm (4S3/2→4I15/2)from Er3+ ,and red at 662nm (4F9/2→4I15/2) from both Tm3+ and Er3+ ions , emission signals were identified. The most appropriate combination of RE in the TWLOF glass host (2mol% YbF3 1mol% ErF3 and 1mol%TmF3)has been determined with the purpose to tune the primary colour (RGB) respective emission and generate white light emission by varying the pump power. Energy transfer (ET) from Er3+ to Yb3+ then to Tm3+ is very important in this upconversion process. In our UC emission model, The 1G4 state is populated by ET of 2F5/2(Yb3+)+3H4(Tm3+)→2F7/2(Yb3+)+1G4(Tm3+). From the analysis of pump energy dependence investigation suggest that , for blue emission Tm 1G4 and Er 4F3/2 states excited by a stepwise phonon-assisted excited-state absorption process mainly consists in a three -photon while green and red upconversion emission due to two-photon. An additional cross-relaxation process between Tm(3H4→3H6) and Er(4I13/2 →4S3/2) also responsible for the population of the 4S3/2 and 2H11/2 state of Er3+. The investigation is helpful for multi colour emission under single infrared excitation in photonics devices.

8263-20, Session 5

Optimization of photoluminescence and electroluminescence of silicon nanocrystals in a superlattice host

M. Roman, D. W. Prather, Univ. of Delaware (United States)

Silicon is a versatile material in the photonics industry with a major drawback being inefficient light emission when compared to III-V materials. Several methods including porous silicon and silicon nanocrystals have been found to achieve light emission from silicon. Silicon nanocrystals can be made in various ways including silicon rich oxide films and superlattice films. The superlattice approach gives a unique flexibility in that the silicon and silicon dioxide layers can be individually adjusted to modify the properties of the nanocrystals. By controlling the silicon layer thicknesses, a specific size of nanocrystals can be targeted, thus tuning the emission wavelength. This property has been extensively reported on in the literature; however, the effects due to the silicon dioxide layer thickness are not well studied. In this work, superlattice films of silicon/silicon dioxide layers with silicon layer thicknesses varying from 0.4 to 0.8 nm and oxide layers varying from 2.7 to 5.1 nm were deposited via plasma enhanced chemical vapor deposition and followed by a high temperature anneal to precipitate nanocrystals. Both photoluminescence (PL) and electroluminescence (EL) measurements were taken on the samples and the output intensity was measured via spectrometer. It was found that for both PL and EL measurements, that there was a steady increase in the output intensity with increased oxide layer thickness until reaching saturation.

8263-67, Session 5

Recent advances and novel approaches of p-type doping of zinc oxide

O. Maksimov, The Pennsylvania State Univ. (United States)

Due to its high radiative stability and superior optoelectronic properties, such as wide direct band gap of ~3.4 eV and high exciton binding energy of ~60 meV, ZnO is considered for the fabrication of ultraviolet and visible light emitting and laser diodes, solar-blind photodetectors. Although proof-of-concept devices were already demonstrated, further progress in this area is slowed down by the difficulties of doping ZnO p-type. Here, we discuss problems associated with doping of ZnO, cover recent progress in this area, and discuss an alternative approach to increase p-type dopability via anion substitution, replacing oxygen with other group VI elements (S, Se, Te). We also propose that these anion-substituted alloys will be extremely promising for fabrication of photovoltaic devices, such as highly efficient thin film solar cells.

8263-21, Session 6

Metal oxide nanostructures and white light emission

M. Willander, Linköping Univ. (Sweden)

No abstract available

8263-22, Session 6

ZnO nanowire for tunable near-UV blue LED

B. Viana, Ecole Nationale Supérieure de Chimie de Paris (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. The presentation will focus on the electrochemical deposition and hydrothermal techniques two cost-effective, low-temperature electrochemical or aqueous solution methods for growing zinc oxide (ZnO) nanorods on p-electrode of GaN-LEDs. ZnO is a promising wide band gap alternative material due to its many advantageous properties such as direct bandgap at 3.37 eV, large exciton binding energy of 60 meV at room temperature, instead of 25 meV for GaN base materials, and easy nanostructuration. Wires of high structural and optical quality have been epitaxially grown on p-GaN single crystalline substrates in order to produce low cost new LEDs.

After integration of the heterostructure in a LED device, a rectifying behaviour has been found with a forward current onset at 3V. The diodes emitted a unique UV-light peak centered at about 397 nm for either as-prepared or annealed samples. The emission turn-on voltage was 3.9 V for the hydrothermal and 4.2 V for the electrodeposition. Then the UV-emission was very bright at very low applied forward bias leading to a new generation of UV LEDs.

We have shown that the emission wavelength could be tuned and shift toward the violet-blue region by up to 40 nm by doping with Cu or Cd [3]. Our results clearly state the remarkable quality of the pure and doped-ZnO electrochemical materials and high quality of the ZnO-NWs/p-GaN interface. Near-UV and violet-blue sources can be combined with efficient phosphors for solid-state lighting in order to replace fluorescent light sources with long lifetimes and high energy saving.

8263-23, Session 6

Photoresponse comparison of indium oxide (In2O3) nanomaterials

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Low-dimensional, metal-oxide semiconductor nanomaterials have stimulated great interest and extensive research due to their novel electronic and optical properties. Indium-oxide (In2O3) is a wide-band semiconductor material with documented bandgap values, recently revised from the old value 3.7 eV to 2.9 eV. As an intrinsic n-type semiconductor, indium oxide can be used as a resistive element in integrated circuits. Its nanostructures are used for a variety of applications including: field-effect transistors, nanoscale chemical sensors, optoelectronics, and transparent electrodes. However, one prominent issue for In2O3 nanomaterials is the parasitic blue -green emission, which is attributed to oxygen vacancies. This work investigates surface states and how they affect photoresponse performance in two different nanomatierals. In2O3 nanorods were grown on silica substrates by using self catalytic vapor-liquid-solid (VLS) growth process. The photoresponse was compared to thin film, tin-doped indium oxide (ITO). The nanorods demonstrated a wavelength dependent photoresponse while the conductive ITO thin film did not. Analysis shows that surface states in the nanorods cause a change in the Schottky barrier height resulting in a difference in their photoresponse performance.

In addition, an investigation of surface modification methods is demonstrated using commercial In2O3 nanoparticles with sizes ranging from 20-70 nm. Polyvinyl-alcohol (PVA) coated nanoparticles were compared to uncoated nanoparticles. The PVA coated In2O3 nanoparticles shows significant suppression of the parasitic green emission and enhanced UV-blue emission, proving that PVA can modify the defect states for In2O3 nanoparticles.

8263-24, Session 7

Oxide crystal-fibers grown by micro-pulling-down technique and applications for lasers and scintillators

J. Didierjean, FiberCryst (France); F. Balembois, Lab. Charles Fabry (France); N. Aubry, D. Perrodin, J. Fourmigué, A. Aubourg, I. Martial, FiberCryst (France); X. Delen, P. Georges, Lab. Charles Fabry (France)

The micro-pulling-down technique was used since the 80's to grow single-crystals with small diameters and long length. However, the quality of the grown crystals was too low for optical applications. Since 2003, Fibercryst improved this technique to reach high optical quality YAG and LuAG fibers, with diameters from 300 µm to 2 mm and length up to 1 meter. Applications are centered on lasers and scintillation.

For laser applications, we demonstrated growth of Nd:YAG, Yb:YAG, Yb:CALGO and Er:YAG materials, with diameters from 400 µm to 1 mm. A continuous wave power of 65 W was achieved in continuous wave operation in a simple linear Yb:YAG oscillator under 200 W pump power. A peak power above 7 MW was achieved in a double-pass amplification of 500 ps pulses from a micro-laser, using a Nd:YAG crystal fiber pumped with a 60 W laser diode. Energies of 4 mJ and 2 mJ per pulse were obtained respectively in Nd:YAG and Er:YAG in Q-switch linear oscillators with cavity length below 25 cm. Those results place single crystal fibers as a competitive laser technology for various applications in industry, medical science or military equipment.

For scintillating application, Ce:YAG, Ce:LYSO and Ce:LuAG fibers have been produced and tested.

They are good candidate to replace plastic scintillating fibers and to propose new detector concepts. They will provide significantly higher light yield, high-Z elements, a wider range of emission wavelength to adapt to the appropriate photo sensors and remain more resistant to radiation damage for long term operation.

8263-25, Session 7

Novel approach for chemical lift-off and wafer bonding of (In)GaN based devices using sacrificial ZnO template layers

A. Ougazzaden, Georgia Tech-Lorraine (France); D. J. Rogers, F. H. Teherani, Nanovation (France); S. Gautier, T. Moudakir, Supélec (France); M. Razeghi, Northwestern Univ. (United States)

Since the development of p-type doping of GaN in the early 1990s, there has been rapid industrial development and an exponential market expansion for (In)GaN-based p-n junction devices. These devices usually employ non-native substrates such as sapphire or silicon, however, because native GaN substrates with appropriate cost/quality/size are still not currently available in industrial quantities. Such non-native single crystal substrates bring constraints, however, such as significant crystal lattice mismatch, differences in thermal expansion coefficients, reduced crystal quality, poor thermal/electrical conductivity, device rigidity, opacity to the visible spectrum, limited size and relatively high cost levels.

Recently [1-6], the authors showed that ZnO thin films can be used as sacrificial templates for the chemical lift-off of (B,In)GaN thin films from insulating/costly/opaque substrates so as to wafer bonding them onto substrates with the desired cost/functionality profile. In this talk, we will give an overview of our efforts to develop this know-how to wafer-scale growth/transfer of active (In)GaN based p-n devices.

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[2] D. J. Rogers et al. Appl. Phys. Lett. 91 7 (2007) 071120

[3] A. Ougazzaden et al., Journal of Crystal Growth 310 (2008) 944-947

[4] D. J. Rogers et al. J. Vac. Sci. Technol. B 27, 3 (2009) 1655

[5] A. Ougazzaden et al., Proc. of SPIE Vol. 7603 (2010) 76031D-1

[6] S. Gautier et al., Proc. of SPIE Vol. 7940 (2011) 79400X-1

8263-26, Session 8

Highly correlated quantum Hall system realized at MgZnO/ZnO interfaces

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Recent advances in the growth technique of ZnO have led to an extremely high electron mobility of the two-dimensional electrons confined at the MgZnO/ZnO heterointerface. This achievement has paved the way towards a new regime of quantum Hall physics, where strong electron correlation effects are present because of the large effective mass of the electrons in ZnO. In our study, continuing efforts have further improved the electron mobility above 700,000 cm2/Vs. This mobility enhancement was enabled by the use of pure ozone as an oxygen source instead of a conventional oxygen radical source, which inevitably contaminates the films with a small amount of impurities. The Mg content was optimized to maximize the screening of impurity scattering by electrons, while minimizing the interface roughness scattering. For one of the high mobility MgZnO/ZnO heterostructures, we measured high-field magnetotransport properties which showed a clear signature of the fractional quantum Hall effect at nu = 1/3 at T = 0.04 K. Upon further increasing the magnetic field, strong localization was observed in Rxx while maintaining ordinary Rxy, suggesting a quantum Hall insulator or Wigner solid. In addition, rotation experiments revealed that the spin susceptibility was significantly enhanced to a value four times larger than the bulk. These features are considered as consequences of the enhanced electron correlation effects in the dilute limit, which is supported by the large effective mass of the electrons in ZnO. Thus MgZnO/ZnO heterostructures are very attractive systems for investigating correlation effects in quantum Hall physics.

8263-27, Session 8

Time-resolved photuminescence spectroscopy investigations of nonpolar homoepitaxial ZnO/(Zn,Mg)O quantum wells

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ZnO/(Zn, Mg)O heterostructures have been the subject of intense investigations, in connection with the potential application of these materials for optoelectronic applications in the blue-UV spectral region. However, such structures grown along the c-axis exhibit a Quantum Confined Stark Effect (QCSE) due to the huge built-in electric field along this direction. In order to eliminate the effect of the internal electrical field on the optical properties, one can grow them along non-polar orientations.

We report reflectance and time-resolved photoluminescence studies performed on a series of ZnO/(Zn,Mg)O single quantum wells, with 20 % magnesium content, grown on nonpolar M-plane oriented ZnO substrates. The optical spectra reveal strong in-plane optical anisotropies and clear reflectance structures, as an evidence of good interface morphologies. Signatures of confined excitons analogous to C-exciton in bulk ZnO, are detected using light polarized along the c-axis. Experiments performed in orthogonal polarization show confined states analogous to A and B bulk excitons. Envelope function calculations including excitonic interaction nicely match the experimental results. The integrated time-resolved photoluminescence spectra exhibit strong excitonic peaks from low (10K) to high (325K) temperatures. We find that the total integrated intensity remains quasi constant and that the exciton lifetime increases linearly with the temperature. This behavior is theoretically well described by a model heeding the exciton phase space filling. This indicates that radiative recombination of free excitons is dominating the quantum well photoluminescence even at room temperature.

8263-28, Session 8

Ion beams as a tool for advanced structural characterization in ZnO-based materials

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ZnO and its ternary alloys with MgO and CdO have emerged as one of the most promising alternatives for visible to UV optoelectronics [1]. However, the role that native defects play in the electronic structure of these materials is under intense debate [2], especially concerning the difficulties achieving reproducible p-type doping. Furthermore, the growth of high-quality ternary layers is challenging due to the appearance of phase separation for high amounts of Mg and Cd [3]. Therefore, the accessible range for bandgap engineering using ZnO-based ternaries is restricted in practice.

Ion beam techniques are powerful tools to investigate compositional and structural properties of thin films, allowing the depth-profiling of composition, defects and strain, as well as the identification of impurities. In this work we show the individual evaluation of defects in the IIb-metal and O sublattices in different compounds, taking advantage of ion channelling phenomena in combination with some specific nuclear resonances (such as 16O(α,α)16O at 3.035 MeV). For ZnO epilayers, different growth techniques are compared in terms of crystal quality and composition. Interestingly, the preferential annealing of Zn-related defects at low growth temperatures is demonstrated, pointing to the higher relevance of O interstitials for the electronic properties. Additionally, lattice-site location methods are used to determine the limits for single-phase growth in ternary compounds. Fingerprints of the IIb-metal and O sites confirm that a substitutional behaviour inside the wurtzite structure can be achieved for relatively high MgO or CdO molar fractions (>40%) by molecular beam epitaxy methods.

[1] K. Nakahara et al., Appl. Phys. Lett. 97, 013501 (2010).

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[3] I. Takeuchi et al., J. Appl. Phys. 94, 7336 (2003).

8263-29, Session 9

Optical properties of excitons in CuMO2 delafossite-type oxide thin films

T. Makino, RIKEN (Japan)

We report on optical properties of excitons in thin films of delafossite-type CuMO2 (M = Sc, Cr, Mn, Fe, and Co). Systematic studies of optical absorption and first-principles calculation revealed that all the compounds investigated have a bandgap energies as large as about 4 eV and excitonic binding energies of 0.3 to 0.5 eV. The bandgap energy showed an unexpected dependence on the atomic number of M. An abrupt change of this energy occurs for M = Cr, explained as a result of interaction between Cu3dz2+4s and M 3d bands. Ultrafast dynamics of exciton were also clarified and the lifetime of exciton was determined to be approximately 0.8 ns.

8263-30, Session 9

Microscopic origins of the surface exciton photoluminescence in ZnO nanostructures

E. McGlynn, Dublin City Univ. (Ireland)

Photoluminescence (PL) studies of the surface exciton peak in ZnO nanostructures at ~3.367 eV are reported to elucidate the nature and origin of the emission and its relationship to nanostructure morphology. Localised voltage application in high vacuum and different gas atmospheres show a consistent PL variation (and recovery), allowing an association of the PL to a bound excitonic transition at the ZnO surface modified by an adsorbate. Studies of samples treated by plasma and of samples exposed to UV light under high vacuum conditions show no consistent effects on the surface exciton peak indicating no involvement of oxygen species. X-ray photoelectron spectroscopy data indicate involvement of adsorbed OH species. The relationship of the surface exciton peak to the nanostructure morphology is discussed in light of x-ray diffraction, scanning and transmission electron microscopy data

8263-31, Session 9

Excitonic transport in ZnO

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We will present optical investigations of the lateral excitonic transport in ZnO using highly spatially and ps-time resolved cathodoluminescence spectroscopy (CL).

In spatial and time-resolved CL experiments the initial exciton lifetime, as well as its diffusion length are determined independently as a function of temperature. The characteristic temperature dependence of the free exciton mobility as calculated from mobility and diffusion length gives information about the underlying scattering processes. As excitons are electrical neutral particles, scattering by ionized impurities - the dominant scattering mechanism for all charge carriers at low temperatures - is not effective.

Our measurement setup allows two different types of experiments to investigate the exciton transport. The first one uses Ti-masks of rectangular shape and appropriate thickness to allow CL excitation with electrons through this mask while completely absorbing the emerging luminescence. The second one consists of a lightproof mask having circular openings with the diameters in the range of the exciton diffusion length. Here the decay time for the luminescence generated in the center of such a hole is strongly affected by the exciton lifetime plus the diffusion under the gold mask. The difference of the decay time of transients from the hole and an undisturbed area leads directly to the diffusion constant DFX. Using the rectangular Ti-masks the free exciton diffusion length is obtained by fitting the solution of the 1d diffusion equation to the shape of the FX-CL-Intensity of a CL-Linescan recorded perpendicular to the mask's edge.

Experimental results for bulk ZnO and ZnO epitaxial layers as well as polar MgZnO/ZnO quantum well structures are presented.

8263-32, Session 9

Electro-optical properties of barium titanate films epitaxially grown on silicon

S. Abel, D. Caimi, M. Sousa, T. Stöferle, C. P. Rossel, C. Marchiori, IBM Zürich Research Lab. (Switzerland); A. Chelnokov, CEA-LETI (France); J. Fompeyrine, IBM Zürich Research Lab. (Switzerland)

BaTiO3 (BTO) single crystals exhibit one of the largest Pockels coefficients (r42=1300pm/V) among oxides. This makes BTO an excellent active material for electro-optical (EO) devices such as switches, modulators or tuning elements. However, in order to harness these properties in silicon photonics circuits, the challenge is to integrate BTO as high quality thin films onto silicon substrates. Due to their tight relationship with the crystallographic symmetry and microstructure, the effective Pockels coefficients can indeed be enhanced in epitaxial films compared to polycrystalline layers.

For the first time we report on the EO properties of epitaxial BTO thin films on Si. The growth of BTO layers on Si(001) is performed by two deposition techniques. First, a thin single-crystalline strontium titanate (SrTiO3) seed layer is grown on Si by Molecular Beam Epitaxy, followed by a 100nm thick BTO layer deposited via rf-sputtering and an annealing step in oxygen. Throughout this process, the BTO keeps an epitaxial relationship to the Si-substrate.

Electrodes with different orientations relative to the crystalline lattice are patterned on the films using photolithography. The EO-properties of the films are then explored by analyzing the polarization changes of a transmitted laser beam (1550nm) induced by an electrical field. By varying the direction of the electrical field, a detailed study of the effective EO-coefficients rEff is performed. The experiments are compared with LiNbO3 as a widely used EO-material. Based on the results, potential layouts for integrated photonic devices are discussed in order to take advantage of the largest elements of the EO-tensor.

8263-33, Session 9

Optical probe of heterointerfaces composed of correlated electron oxides

M. Nakamura, RIKEN (Japan) and The Univ. of Tokyo (Japan); M. Kawasaki, Y. Tokura, The Univ. of Tokyo (Japan)

We have investigated interface electronic states of various p-n and n-n heterojunctions comprised of Mott insulators and an electron-doped band insulator by photocurrent spectroscopy.

Photocurrent action spectra revealed the existence of band discontinuity at the interface and band bending in the Mott insulators.

From this result as well as transport data, we have constructed a detail band lineup of Mott insulators. We have also clarified the modulation of the band structure when the carriers are electrically doped to the Mott insulators with use of the electromodulation spectroscopy.

8263-34, Session 9

Tuning optical properties of complex oxides: examples of nanoporous materials and perovskite heterostructures

P. V. Sushko, Univ. College London (United Kingdom)

Tuning optical properties of complex oxides: examples of nanoporous materials and perovskite heterostructures

8263-35, Session 10

Inorganic/organic ZnO-based hybrid structures for opto-electronics

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

This talk summarizes recent efforts to fabricate hetero- and nanostructures based on ZnO and various conjugated organic materials as well as to tailor their electronic and optical properties. Growth by molecular beam epitaxy/deposition in an all-UHV regime of both material components ensures well-defined interfaces and highest structural quality. The relevant growth mechanisms up to the level of organic/inorganic superstructures and the interfacial energy structure including “band-gap” engineering through molecular morphology are discussed. Direct electronic coupling of the fundamental excitations (Frenkel and Wannier-Mott excitons) across the interface is achieved with coupling constants on the meV-energy scale. Efficient nonradiative energy transfer reducing, e.g., markedly the organic lasing threshold, charge separation at the interface, and inorganic/organic pn-junctions are demonstrated.

8263-36, Session 10

Functionalization of ZnO surfaces with organic molecules

A. L. da Rosa, N. Moreira, A. Dominguez, T. Frauenheim, Univ. Bremen (Germany)

The understanding of the interaction of organic species with inorganic surfaces and nanostructures constitutes a step forward in the development of semiconductor hybrid devices such as solar cells and biosensors. Density functional theory has been employed to investigate ZnO surfaces modified with substituted methane molecules. We have found three relevant stabilization mechanisms acting on the surface stabilization: the passivation of surface oxygen lone-pairs happens via dissociative chemisorption processes, the electrostatic adsorbate-interations involving Zn surface sites and hydrogen interactions involving oxygen surface sites. Covalent ligand-substrate interactions have been found to play only a marginal role on the surface stabilization. Contradicting the usual chemical intuition, we have found no significant evidence for the formation of classical Lewis acid-base adducts on Zn surface sites.

8263-38, Session 11

Reactive dual magnetron sputtering of Ta2O5, Y2O3, TiO2, Al2O3, Zr2O3, and Nb2O3: optical and structural properties and thin film applications

S. J. Pearce, H. Esfandiarijahromi, M. D. B. Charlton, Univ. of Southampton (United Kingdom)

In this paper we perform a systematic investigation and optimisation of lambda controlled, reactive ion beam sputter deposition process conditions for a range of optical materials. The deposited films are compared for suitability for applications such as planar waveguides for optical interconnect, Laser device manufacture, multi-layer interference filters, and precision optical mirrors. Thin films of Tantalum Pentoxide, Yttrium Oxide, Titanium Oxide, Aluminium Oxide and Zirconium Oxide were deposited using a reactive dual-magnetron sputtering system (Leybold Helios Pro). Deposited film quality was optimised as a function of plasma power and gas flow, and an optimum oxygen working point was determined for each material. Power and lambda control methods were compared for the purpose of optimising optical quality of the layer. Deposited layers were characterised by x-ray photoelectron spectroscopy (XPS), Energy-dispersive X-ray spectroscopy (EDX), variable angle spectroscopic ellipsometry (VASE), X-ray diffraction (XRD) and SEM imaging. Waveguide losses were measured for each sample using a prism coupling arrangement. Tantalum Pentoxide guides with loss as low as 100nm reflection bandwidth over a half angle of 450 centred at 675nm. Reflectivity and transmission of the deposited mirrors was compared to the theoretical design. Good agreement between the theory and the practical filter/mirror designs was achieved confirming the material film quality.

8263-39, Session 11

P-type oxide thin film transistors produced at low temperatures

R. Ferrão de Paiva Martins, CEMOP/Uninova (Portugal)

P-type thin-film transistors (TFTs) using room temperature sputtered tin and copper oxide as a transparent oxide semiconductor have been produced. The SnOx films shows p-type conduction presenting a polycrystalline structure composed with a mixture of tetragonal β-Sn and α-SnO_x phases, after annealing at 200 °C. These films exhibit a hole carrier concentration in the range of ≈ 1016-1018 cm-3, electrical resistivity between 101-102 Ωcm, Hall mobility of 4.8 cm2/Vs, optical band gap of 2.8 eV and average transmittance ≈ 85 % (400 to 2000 nm). Concerning copper oxide CuxO thin films they exhibit a polycrystalline structure with a strongest orientation along (111) plane. The CuxO films produced between an oxygen partial pressure of 9 to 75% showed p-type behavior, as it was measured by Hall effect and Seebeck measurements. The bottom gate p-type SnOx TFTs present field-effect mobility above 1.24 cm2/Vs and an on/off modulation ratio of 103 while the CuxO TFTs exhibit a field-effect mobility of 1.3×10-3 cm2/Vs and an on/off ratio of 2×102.

8263-40, Session 11

Multicomponent dielectrics for oxide TFT

L. M. Pereira, P. Barquinha, G. Gonçalves, E. Fortunato, R. Martins, Univ. Nova de Lisboa (Portugal) and CEMOP/UNINOVA (Portugal)

In this work we present sputtered multicomponent dielectrics (MCD) based on mixtures of high k oxides such as HfO2 and Ta2O5 with high band gap ones (SiO2 and Al2O3). This way it is possible to get stable amorphous structure up to 800ºC, that does not happen for pure HfO2, for instance, that present a polycrystalline structure when deposited without any intentional substrate heating. Besides, also the band gap of the resulting films is increased when compared with pure HfO2 and Ta2O5 that theoretically is an advantage in getting a suitable band offset with the semiconductor layer on oxide TFTs.

Concerning the electrical characterization, the leakage current on c-Si MIS structures is low as 10-9 Acm-2 at 10 V for this MCDs, lower than on HfO2 and Ta2O5 The amorphous structure of the films also lead to a better dielectric/semiconductor interface as suggested by C-V characteristics on GIZO MIS structures that do not present significant variation with frequency. On other hand, the dielectric constant decreases due to the incorporation of SiO2 and Al2O3. Further improvement on insulating and interface characteristics is achieved with a stack of SiO2/MCD/SiO2.

These dielectrics were successfully integrated on GIZO TFTs produced at low temperature and results on electrically stressed devices will be presented.

8263-41, Session 12

Growth and characterization of Ga2O3 on sapphire substrates for UV sensor applications

S. Ou, D. Wuu, Y. Fu, T. Wang, R. Horng, National Chung Hsing Univ. (Taiwan)

Recently, monoclinic structure gallium oxide (β-Ga2O3) has attracted significant attention due to its wide band gap (~4.9 eV). Besides, it is also a thermally and chemically stable transparent conductive oxide over a large range from visible to ultraviolet. In this study, the Ga2O3 films were deposited on (001) sapphire at various substrate temperatures from 400 to 1000 °C by pulsed laser deposition using a KrF excimer laser. The results of x-ray diffraction exhibited that the film was amorphous as the growth temperature was 400 °C. When the growth temperature increased from 550 to 1000 °C, the films exhibited the diffraction peaks that are indexed to the planes of β-Ga2O3 phase. This implies that enough thermal energy is supplied to the ad-atoms on the substrate and increases the surface mobility, which leads to the appearance of β-Ga2O3 phase. From the optical transmittance measurements, the films grown at 550-1000 °C exhibit a clear absorption edge at deep ultraviolet region around 250-275 nm wavelength. The optical band gap of β-Ga2O3 films are 4.5, 4.67, 4.72, 4.85 and 4.9 eV as the films grown at 400, 550, 700, 850 and 1000 °C, respectively. It shows that the absorption edges are shifted towards short wavelength region (blue shift), i.e. increase in the band gap energy with increasing the substrate temperature. It indicates that the β-Ga2O3 films have high potential in UV sensor applications.

8263-42, Session 12

Controlling trap depth to enhance optical properties of oxides materials for medical imaging

B. Viana, Ecole Nationale Supérieure de Chimie de Paris (France)

In medical imaging, careful control of the doping and point defects should be realized to optimize the optical properties. Doping ions and defects could for instance offer a non radiative route which gives rise to a decrease of the luminescence intensity or lead to traps. When these traps are thermally released, they populate the excited state of an emitting centre, leading to uncontroled effects such as for instance afterglow or long lasting luminescence. If in some oxide based scintillators such as LPS ($Lu_2Si_2O_7$) there is no such deleterious afterglow, in the case of the LSO (Lu_2SiO_5) or LYSO afterglow could be very important and should be suppressed. These materials are readily used for X-Rays scans and positron emission tomography (PET) [1].

Sometimes, there is a great interest for materials with a long afterglow luminescence, also called persistent luminescence for various applications (emergency signing, luminous painting, and lighting sources). This concept was recently used for the development of new medical imaging called optical imaging [2]. In such system, oxides-nanoparticules of persistent luminescent materials (for instance Mn,Eu,Pr codoped silicates $CaMgSi_2O_6$) could present emission lasting for hours and this allows to follow in vivo and in real-time the biodistribution of these fluorescent nanoprobes. In that case, effort is done to improve the optical response and increase the afterglow. report their application for highly sensitive real-time in vivo bioimaging.

Effets on structural properties of the mixed oxides could be done and addition of various dopants could either enhance or eliminate the luminescence properties.

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8263-43, Session 12

Development of functional magnetic nanoparticles for biomedical application

Y. Ichiyanagi, Yokohama National Univ. (Japan)

Magnetic nanoparticles (MNPs), including those of nanoparticles of transition metals, such as iron oxide nanoparticles, cobalt oxide nanoparticles, and ferrite nanoparticles [1-3] with diameters between 3 nm and 34 nm have been developed by a wet chemical method. Ferromagnetic and superparamagnetic nanoparticles were obtained, and they have been further functionalized in order to realize biomedical applications [4]. Magnetic oxides are ceramic insulators; therefore, it is difficult for these materials to attach to any other molecules. Recently, we modified the functional groups, such as the amino, carboxyl, and thiol groups, of MNPs and these functional nanoparticles are further introduced into cells and localized by an external field. MNPs were then developed to cancer cell selective magnetic nanoparticles. On the basis of the abovementioned technique, SiO_2-shelled ferrite nanoparticles have been discussed for the use in hyperthermia treatments on the basis of measurements of their AC magnetic susceptibilities. The increase in the temperature of the samples in an AC magnetic field at a specific AC frequency was also measured, and the specific absorption rate (SAR) was evaluated for each sample.

Possibility of biomedical applications of magnetic nanoparticles was suggested.

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8263-44, Session 12

Vertically aligned ZnO-$ZnGa_2O_4$ core-shell nanowires for photoelectrochemical water splitting

M. Zhong, Y. Li, J. Delaunay, The Univ. of Tokyo (Japan)

Well-aligned one-dimensional semiconductor-photocatalyst core-shell nanowires are emerging as an attractive class of nanostructured photoanode for photoelectrochemical water splitting. In comparison to single material nanowires, the core-shell nanowire heterostructures are expected to offer more functionalities, such as broad-range light absorption, efficient charge separation, improved electrical conductivity, and enhanced chemical stability. In this report, large-scale synthesis and photoelectric properties of dense and vertically aligned ZnO-$ZnGa_2O_4$ core-shell nanowires for photoelectrochemical hydrogen generation are presented.

Vertically aligned ZnO-$ZnGa_2O_4$ core-shell nanowires were synthesized by a simple two-step chemical vapor deposition method on sapphire substrates. The nanowires are electrically connected at their bases through a layer of the same material ZnO-$ZnGa_2O_4$. The ZnO cores and $ZnGa_2O_4$ shells of the nanowires are of single crystal quality and have aligned crystallographic orientations as evidenced from XRD and TEM analyses. UV-VIS diffusion reflectance spectra of the ZnO-$ZnGa_2O_4$ nanowires show two clear absorptions from the ZnO cores and the $ZnGa_2O_4$ shells. Mott-Schottky measurement gives a flat-band potential of -4.5 V (pH = 7) and a carrier density of 3.5 10^{20} cm^{-3} for the ZnO-$ZnGa_2O_4$ core-shell nanowires. In comparison, the flat-band potential and the carrier density for vertically aligned ZnO nanowires were 0.2 V (pH = 7) and 6.7 10^{19} cm^{-3}, respectively. The enhanced cathodic flatband potential of the core-shell nanowires is attributed to the passivation of oxygen vacancies of the ZnO surface by the $ZnGa_2O_4$ shell. The increase in carrier density is understood as the formation of $ZnGa_2O_4$ shell layer and also Ga doping of the ZnO core. Finally, a stable photocurrent of 2 mA/cm^2 was obtained with the ZnO-$ZnGa_2O_4$ core-shell nanowires used as a photoanode at an applied bias of +0.5 V (versus Ag/AgCl) under Xeon lamp illumination. Detailed optimization of the synthesis process is in progress to increase the photocurrent by tuning the Ga concentration in the shell layer, enlarging the diameter of the core-shell nanowires and also incorporating dopants to improve visible light absorption.

8263-45, Session 13

Transient and persistent photoconductivity in complex oxide heterostructures and superlattices

H. Habermeier, Max-Planck-Institut für Festkörperforschung (Germany)

The physics of complex oxide interfaces is rich in intriguing phenomena ranging from the appearance of electrical conductivity at the interface of oxide band insulators to emerging magnetic order and even superconductivity. The underlying physics is regarded to be controlled by intrinsic parameters such as band bending effects, charge transfer and orbital reconstruction of the electronic system. In this talk, the concept of optical doping is introduced as external control parameter and photo-induced effects on the transport properties of manganite and cuprate thin films will briefly reviewed. This knowledge is used to study transient as well as persistent photoconductivity effects in YBCO-LCMO heterostructures and superlattices in order to address the problem of oxygen vacancies at the interface in those systems, based on the doping effect in oxygen deficient YBCO leading to persistent photoconductivity. Here, photo-generated electrons reside at the oxygen vacancy sites and the remaining holes contribute to the doping of the CuO_2 planes. Furthermore, it will be explored whether optical doping arising from vacancies either on the cation side (electron doping) or anion site (hole doping) can be regarded as a general principle.

8263-46, Session 13

Atomic-layer engineering of oxide superconductors

I. Bozovic, Brookhaven National Lab. (United States)

Using a unique molecular beam epitaxy system we synthesize atomically smooth thin films, multilayers and superlattices of cuprates and other complex oxides. [1] Such heterostructures show high-temperature superconductivity (HTS) and enable novel experiments. [2] I will review our most recent experiments on such films, including XRD, AFM, angle-resolved TOF-ISARS, transport measurements, high-resolution TEM, resonant X-ray scattering, low-energy muon spin resonance, ultrafast photo-induced RHEED, COBRA surface crystallography, and ultra-high magnetic field spectroscopy. The results include an unambiguous demonstration of strong coupling of in-plane charge excitations to out-of-plane lattice vibrations [3], a discovery of interface HTS [4] that occurs in a single CuO_2 plane [5], and evidence for local pairs and superconducting transition driven by phase fluctuations [6].

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8263-47, Session 13

Metallic quantum well states in artificial structures based on strongly correlated oxide

H. Kumigashira, The Univ. of Tokyo (Japan)

The quantum confinement of strongly correlated electrons in artificial structures provides an ideal platform for studying the behavior of correlated Fermi-liquid states in reduced dimensions, as well as for controlling the extraordinary physical properties of layered complex oxides, such as high-temperature superconductivity in cuprates, triplet superconductivity in ruthenates, and colossal magnetoresistance in manganites. In this talk, we report the creation and control of two-dimensional electron-liquid states in ultrathin films of $SrVO_3$ epitaxially grown on Nb:$SrTiO_3$ substrates, which are artificial oxide structures that can be varied in thickness by single monolayers. Angle-resolved photoemission from the $SrVO_3$/Nb:$SrTiO_3$ samples shows metallic quantum well states that are adequately described by the well-known phase-shift quantization rule, confirming the quantum confinement of strongly correlated electrons in the oxide artificial structures

8263-48, Session 13

Tuning elecronic phases by electric double layer transistor

Y. Iwasa, The Univ. of Tokyo (Japan) and RIKEN (Japan)

With the EDLT configurations, we have demonstrated electric field induced insulator metal transition in ZnO [1], and superconductivity in $SrTiO_3$ [2] and ZrNCl [3]. By utilizing ionic liquids in the ELDTs, the accumulated sheet carrier density has now reached 1 x 1015 cm-2, which is large enough to induce superconductivity in many doped superconductors, and provides a variety of opportunities to manipulate the electronic states of interfaces by gate voltages. The next thing to be tried is to induce superconductivity in materilas, which are not known to superconduct in bulk form. We chose $KTaO_3$ since it is well known as a quantum paraelectric like $SrTiO_3$, but no superconductivity has been reposted by means of chimeical carrier doping. We demonstate that, using the EDLT configuration, carriers of one order larger than that of the bulk can be doped causing electric field induced superconductivity [4]. The presnet result indicates that EDLT has a potential to realize a new electronic state which is not accessible by conventional chemistry.

In addition to superconductivity, we discusson the EDLT of magnetic semicpnductors, demonstrating that spin states and ferromagnetism can be controoled. These results strongly indicate that the EDL interface is a versatile and powerful platform to create and control the interface quantum phases.

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8263-49, Session 13

X-ray absorption spectroscopy (XAS) study of superconducting thin film single crystals

H. Oyanagi, National Institute of Advanced Industrial Science and Technology (Japan); A. Tsukada, NTT Basic Research Labs. (Japan) and Tokyo Univ. of Agriculture and Technology (Japan); M. Naito, Tokyo Univ. of Agriculture and Technology (Japan)

The electronic state of T'-type cuprates which exhibit superconductivity without doping was investigated by ab-plane polarized x-ray absorption spectroscopy (XAS) using thin film single-crystals prepared by molecular beam epitaxy (MBE). We find characteristic polarized pre-edge features in the K-edge absorption threshold ascribed to the 1s to the 3d empty states and to the 4p states evaluate the density of 3d holes and the d10 states, respectively. In this paper, the results of the application to the model systems, T'-La2CuO4 and T'-(La,Y)2CuO4, and references, T-La1.85Sr0.15CuO4 and T'-(La,Ce)CuO4 are described. The effect of oxygenation and deoxygenation on the Cu K- near-edge structures evidenced a reversible detachment of apical oxygen defects that strongly correlates with superconductivity. The results also indicate that the deoxygenation, well known as a common prerequisite for superconductivity for doped and undoped T'-type cuprates, removes apical oxygen defects but simultaneously introduces oxygen defects leading to the formation of d10 copper ions and carriers depending on deoxygenation condition.

8263-51, Session 14

Structure and properties of nano-oxides: a theoretical overview

S. T. Bromley, Univ. de Barcelona (Spain)

I overview recent developments and insights gained from the modelling oxide materials at the nanoscale. Two nanoscale regimes are clearly discerned: (i) a scale where every atom counts, and (ii) a size where structural, electronic, chemical and optical properties are essentially bulk-like (the scalable regime). The size at which this transition occurs strongly depends on the type of property one is examining and the structural and chemical parameters of the oxide material under consideration. The oxide/property dependency of this nanoscale transition has fundamental implications with respect to their application potential. Although I focus on oxides for which are optically interesting (e.g. ZnO, TiO2) I also briefly review other materials for obtaining a broader perspective on the general feature of nanoscale oxides.

8263-52, Session 14

Morphological effects on optical and electrical properties of ZnO nanostructures

S. H. Lee, J. Xu, X. Zhang, C. M. Parish, H. N. Lee, B. Smith, Oak Ridge National Lab. (United States); T. Yao, T. Goto, H. Miyazaki, Tohoku Univ. (Japan)

Invited talk

8263-53, Session 14

Real-space distribution of cavity modes in single ZnO nanowires

F. Güell, Univ. de Barcelona (Spain); A. R. Goñi, Consejo Superior de Investigaciones Científicas (Spain); J. O. Ossó, MATGAS (Spain); L. A. Perez, E. A. Coronado, La Univ. Nacional de Córdoba (Argentina); J. R. Morante, Institut de Recerca en Energia de Catalunya (Spain)

Scanning near-field optical microscopy (SNOM) has become nowadays a very powerful technique for investigating the optical properties of nanostructures with a sub-wavelength spatial resolution below 100 nm, such as waveguiding effects in ZnO nanowires (NWs). A spatially resolved study of the electromagnetic field distributions of different cavity modes in ZnO NWs is still lacking. In this work, we have used a near-field optical microscope to map out the evanescent fields of optically excited single-crystal ZnO NWs grown on quartz substrates by the vapour transport method using Au as catalyst. The SNOM measurements were performed at room temperature in transmission-collection mode using four different laser wavelengths (378, 514, 633 and 785 nm). They reveal a different spatial distribution of the electromagnetic fields associated to each cavity mode, which are unique properties of the NWs depending primarily on their size and the wavelength of the mode. Whereas for UV illumination the pattern exhibits two well defined bright lines running along the edges of the upper hexagonal facet of the wire, for red laser excitation the SNOM pattern displays a strong but wider maximum at the center of the facet. In order to interpret the experimental findings, we have performed electrodynamics simulations using the discrete dipole approximation (DDA), which is an accurate numerical method in which the object of interest is represented as a cubic lattice of N polarizable points. We notice the striking qualitative agreement between calculated and measured field distributions.

8263-54, Session 14

Influence of hydrothermal treatment on morphology and properties of ZnO nanostructures

X. Y. Chen, A. M. C. Ng, A. B. Djuri?ic, W. K. Chan, The Univ. of Hong Kong (Hong Kong, China)

Hydrothermal (HT) treatment at low temperature (~150oC) was performed on different ZnO nanostructures grown on different substrates such as Si, quartz, ITO/glass and sapphire. The water vapor environment and the high pressure of water vapor at that temperature were expected to improve the optical properties of ZnO nanorods. Meanwhile, no obvious changes in the morphology under such conditions were assumed.

However, significant changes were observed in both morphology and optical properties. Depending on the substrate used, treatment time and volume of the water in the autoclave, changes in the optical properties, and in some cases changes in the morphology could be observed. In terms of the optical properties, observed changes strongly depended on the starting properties of ZnO, so that both worsening and improvement in the UV-to-visible emission ratios can be obtained for different ZnO nanostructures.

In addition, for nanostructures on Si, leaching out of Si from the substrate has been observed, as clearly shown by energy-dispersive X-ray, transmission electron microscopy, and X-ray diffraction, as well as PL measurement. Presence of the blue emission at ~430 nm was attributed to the presence of SiOx in the samples. To examine this phenomenon in more detail, different metal nitrate precursors were drop cast on a bare Si wafer and subjected to HT treatment, and broad peak at ~430 nm was obtained in those cases as well. The effect of HT treatment on ZnO as well as the substrate used has been discussed in detail.

8263-55, Session 14

Solution-based strategies for synthesizing ZnO nanostructures with controlled morphology and composition

X. Wang, Univ. of Wisconsin-Madison (United States)

Solution-based strategies for synthesizing ZnO nanostructures with controlled morphology and composition

8263-56, Session 14

Engineered ZnO nanowire arrays using different nanopatterning techniques

J. Volk, Research Institute for Technical Physics and Materials Science (Hungary); Z. Szabó, Research Institute for Technical Physics and Materials Science (Hungary) and Univ. of Pannonia, Faculty of Information Technology (Hungary); R. Erdélyi, K. Q. Nguyen, Research Institute for Technical Physics and Materials Science (Hungary)

ZnO nanowires are currently attracting a great deal of interest due to a variety of potential applications, especially in photonics. However, their integration in the standard Si or compound semiconductor technology needs a precise control over the NW form, alignment, and crystallographic orientation.

In the presented work, the impact of various ZnO templates and masking layers on the wet chemically grown vertical and horizontal ZnO NW arrays was investigated. The NWs were seeded at nucleation windows which were patterned in a mask layer using various techniques such as electron beam and focussed ion beam lithography (EBL, FIBL), laser interference and nanosphere (photo) lithography (LIL, NSP), as well as AFM and nanoimprint lithography (NIL). The compared ZnO templates included oxygen-/zinc-polar ZnO single crystals, pulsed laser and atomic layer deposited (PLD , ALD) epitaxial layers, as well as sputtered polycrystalline ZnO films.

Scanning electron microscopy (SEM), convergent beam electron diffraction (CBED) and quantitative X-ray diffraction (XRD) revealed that the alignment, crystal orientation, and the polarity of the nanowires were dictated by the underlying seed layer, while their geometry can be tuned by the parameters of the nanopatterning and wet chemical processes. The comparison of the alternative nanolithography techniques showed that using direct writing nanolithography methods (AFM, FIBL, EBL) the diameter of the ordered ZnO NWs can be as low as 30-80 nm at a NW density of 100-1000 NW/um2, while NSP and LIL favour for larger nanostructures, with typical NW diameter of 150-250 nm, and enable large area patterning (1-100 cm2).

8263-71, Session 14

Development of wide-area catalyst-free growth of self-forming ZnO nanostructure array

D. J. Rogers, F. H. Teherani, P. Bove, V. E. Sandana, Nanovation (France); M. Razeghi, Northwestern Univ. (United States)

ZnO exhibits one of the largest families of nanostructures of all materials systems with a huge range of potential applications. Indeed, ZnO nanowires were recently identified, by Thomson-Reuters, as one of the most researched nanomaterials and they are forecast to play important roles in a whole range of emergent ZnO electronics applications. There are many reasons for this, including the remarkable and distinctive property set of ZnO combined with an ease of fabrication by various techniques and the uniquely large family of nanostructures that can be obtained.

In previous studies [1,2] it was demonstrated that Pulsed Laser Deposition (PLD) can give catalyst-free, self-forming and vertically-aligned nanostructure arrays with superior crystallinity and optical quality. The fact that these structures were self-forming and did not require a metal catalyst greatly simplifies the manufacturing (no need for metal catalyst deposition (typically gold for ZnO) or top-down processing) and also simplifies subsequent device fabrication (i.e. no metal on the surface to perturb processing/contacting). It was found that arrays with different morphologies could be obtained by PLD including vertical, tapering and broadening nanostructures. Amongst these, the tapering “moth-eye type” arrays are of particular interest for many optoelectronic applications due to their graded effective refractive index and excellent anti-reflection properties which predispose them for use in applications such as solar cells, sensors and LEDs. Although PLD gives nanostructures with excellent optical quality, attempts at wide area growth encountered an issue with the anisotropic plasma plume which creates an inhomogeneous growth. This paper reports on the development of an approach to homogenise the ZnO nanostructure array growth by PLD over 2 inch diameter wafers.

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8263-57, Poster Session

Fabrication and characterization of titanium dioxide and zinc oxide based ultraviolet photodetectors

J. C. Moore, R. Stansell, L. R. Covington, Coastal Carolina Univ. (United States)

We have fabricated and characterized metal-semiconductor-metal (MSM) Al:ZnO:Al and heterojunction ITO:TiO2:Al ultraviolet (UV) photodetectors on glass and c-plane sapphire substrates. Titanium dioxide nanoparticle thin films were fabricated via dip coating in a non-aqueous TiO2 nanoparticle suspension, resulting in polycrystalline nanoparticle films. Zinc oxide thin films where fabricated via thermal oxidation of dc-sputtered zinc-metal films with thermal annealing in air at 300°, 600° and 900°C. Films where characterized via x-ray diffraction (XRD) and photoluminescence (PL). XRD sprectra indicate anatase TiO2 and ZnO films possessing a polycrystalline hexagonal wurtzite structure without a preferred orientation. Films were grown between 100 nm and 500 nm in thickness. Room temperature photoluminescence (PL) spectra indicate that annealing temperature and film thickness can significantly affect UV emission and deep-level emission. Specifically, ZnO films annealed at 300°C exhibited the strongest UV emission intensity and lowest deep-level emission. Increasing deep-level green emission was observed with increasing annealing temperature, and a red shift in the excitonic UV band was observed. Increasing blue-level emission was observed for thinner films at higher annealing temperatures. Titanium oxide UV photodetectors were fabricated by coating ITO glass with TiO2 films and dc sputtered Al contacts on the back-side. ZnO UV photodetectors were fabricated via sputter deposition of ohmic Al contacts on ZnO thin films with subsequent thermal annealing. We have investigated the responsivity, spectral response, and photoresponse. Low temperature annealing of the underlying films results in visible-blind UV photodetectors for both oxide systems. Both fabrication techniques are considered low-cost and are scalable.

8263-58, Poster Session

Effect of V dopants on the electrical and optical properties of AZO thin films prepared by magnetron sputtering

Y. S. Wei, C. Liu, National Central Univ. (Taiwan)

In this study, the electrical properties of the V-doped AZO TCLs (transparent conductive layer) were investigated. Using the co-sputtering system, V-doped AZO thin films with different V doping contents were prepared. The doping concentration of V in the AZO thin films ranges from 1 wt.% to 10 wt.%. The resistivity of the as-deposited V: AZO (10 wt.%) thin films can reach a fairly good resistivity of 3.37 × 10-2 Ω-cm, which is much lower than the resistivity (3.15 Ω-cm) of the as-deposited AZO thin film. The resistivity of the V: AZO thin film can be further reduced by annealing. The lowest resistivity (1.56 × 10-3 Ω-cm) of V: AZO thin film occurred at 10 wt.% doping after 400 °C annealing for 30 minutes. Using Hall measurement, the carrier mobility and carrier concentration were measured. We found that the carrier concentration does not increase monotonically with the V doping concentration. The maximum carrier concentration occurred at the V doping concentration at 5 wt.%. As for the carrier mobility, we notice that it can be improved with V-doping concentration. Also, the microstructure d-value and grain size of V: AZO thin films characterized by X-ray diffractometer (XRD) would be reported. Finally, the conduction mechanism of the V-doped AZO will be discussed.

8263-59, Poster Session

Analysis of ZnO microfilms luminescence features caused by shallow levels

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The spectra of ZnO microfilms luminescence are quite diverse depending on purity and the degree of structure perfection. We investigated columnar films grown on silicon substrates by pulsed laser deposition and films prepared by sol-gel method on quartz substrates. In the luminescence spectra of these films two bands in near UV region were obtained. These bands are caused by recombination of excitons (~380 nm) and by recombination of electrons from the shallow levels (~393 nm). The nature of shallow levels (~140 meV below valence band) is not clear. Probably they are caused by interstitial Zn.

Luminescence of the samples investigated was excited by third harmonics of Nd:YAG laser (355 nm, 6 ns, 15 Hz) and registered with PET-79. Dependence of luminescence spectra on the density of pumping energy was investigated.

It was demonstrated experimentally that when the pumping intensity rises, in columnar films intensity of the excitonic band increases significantly slower than intensity of the band caused by shallow levels. In sol-gel samples intensity of excitonic band even decreases while the pumping intensity rises.These results permit to suggest that the effective pumping to conduction band becomes weaker but the pumping to the shallow levels intensifies when the pumping level rises.

Such situation can appear if the upper part of valence band depopulates and effective band gap width rises in the course of the pumping pulse. As a result excitation passes from conduction-band to the shallow levels. Simplified model of corresponding process based on the system of rate equations is considered.

8263-60, Poster Session

Carrier-concentration separation model for transparent conducting Sn:In2O3

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For the extrinsic transparent conductive oxide (TCO), the carrier concentration is contributed from the oxygen-vacancy and the substitution-reaction. In this study, a separation model is derived to estimate the individual contributions from the oxygen-vacancy and the substitution-reaction concentration to the total carrier concentration in an extrinsic TCO (Sn:In2O3). In this talk, we will report the detail derivation on the separation model. To verify the individual contributions of the substitution-reaction and the oxygen-vacancy concentration to the total carrier concentration calculated by the separation modal, the positron annihilation lifetime spectroscopy (PAL) is used to directly measure the oxygen-vacancy concentration in Sn:In2O3 thin films. The results show that the measured oxygen vacancy concentration matches that estimated by the separation model. So, we believe that the current-developed separation model can accurately estimate the individual contribution from the oxygen-vacancy concentration and substitution-reaction concentration for the total carrier concentration of extrinsic TCOs.

8263-61, Poster Session

Mach-Zehnder optical sensor based on pedestal anti-resonant reflecting optical waveguides

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In the past, different types of sensors have been proposed using Anti-resonant reflecting optical waveguides (ARROW) fabricated on silicon substrates [1, 2] due to these waveguide's many advantages over TIR waveguides, such as: polarization sensitivity, virtual single mode operation for large core areas which leads to low insertion losses when coupling light from a single mode optical fiber[3]. On the other hand, waveguides fabricated using Reactive Ion Etching (RIE) can present high sidewall roughness if metallic mask is used [4], which lead to undesirable losses. In previous works we have presented an alternative method for achieving the lateral confinement in ARROW waveguides fabricated with silicon technology which significantly reduced the propagation losses of the waveguides [5]. This method consists in doing the RIE step before the core definition so as to have the lower cladding layer and part of the silicon substrate etched away. This results in a waveguide sustained by a silicon pedestal as shown in the SEM micrographs in Fig. 1. Pedestal hollow core ARROWs have been proposed [6] and used to fabricate optical sensors but in the case of solid core ARROWs this has not been done yet.

In the present work, we present the results obtained by using pedestal ARROWs in the fabrication process of Mach-Zehnder interferometer based evanescent field sensors. Simulations results regarding propagation losses, mode profile and sensitivity to refractive index variation of liquid surrounding the core are also presented.

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8263-62, Poster Session

Time-resolved photoluminescence study of homoepitaxial ZnO/ZnMgO quantum wells grown by metal organic vapor phase epitaxy

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As an important II-VI semiconductor, ZnO has gained much interest in the last few years for its potential applications. ZnO is considered as an excellent candidate for short wavelength optoelectronic devices due to its wide band gap and to the large value of the exciton bounding energy. We investigate a series of samples embedding ZnO/(Zn,Mg)O quantum wells of different sizes by using temperature dependent time-resolved photoluminescence. The samples are grown by metal organic chemical vapor deposition on c-oriented and a-oriented ZnO substrates. The presence of built-in electric fields in the quantum wells grown along the c direction manifests itself not only through the energies of the optical recombination, but also through the size dependence of the recombination times. Generally, for laser excitation above the barrier band gap energy, characteristic large decay times are observed, with a strongly non-exponential decay shape. These results are analysed by taking account of the screening of internal fields by photo-injected electron-hole pairs, when appropriate. The effect of the internal electrical field on the optical properties is eliminated when the quantum well are grown along the a-direction. In this communication we compare the optical properties and their temperature dependence of quantum wells grown along polar and non polar direction.

8263-63, Poster Session

Erbium-doped silicon MOS devices for optoelectronic applications

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One of the most interesting topics nowadays for the silicon photonics community is the development of a CMOS compatible integrated light source working in the third telecom window. For this purpose, Er is usually introduced in dielectric media (SRSO or SRSN) and thus efficient injection, transport and excitation schemes have to be devised.1-3 We will review in this communication our latest attempts to realise such integrated devices and the prospect for a silicon injection laser.

MOS structures working as light emitting devices (MOSLEDs) have been fabricated. The oxide in the MOS gate stack has been replaced by an active layer based on Er-doped SRSO or a multilayer sequence of several SRSO/SiO2 pairs grown either by LPCVD or PECVD.

We have studied the injection and transport mechanisms as a function of the deposition technique, Si excess and annealing temperature. In the regime of light emission and for high temperature annealing treatments transport is dominated by tunnel Fowler-Nordheim injection with a reduced barrier. For highly defective layers submitted to low temperature or short annealing, conduction proceeds via Poole-Frenkel and light emission is very inefficient. Dominant excitation mechanism is impact excitation of hot electrons onto Er3+ ions, although under certain polarization conditions (short pulses and low electric field) a significant indirect excitation through Si-ncs is accomplished. External quantum efficiencies in excess of 0.5% are routinely achieved.

Integrated waveguide devices with resonant structures like Fabry-Perot and ring resonators coupled to waveguides are being fabricated with optimised materials. We will report on quality factors and losses/gain in these structures.

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8263-64, Poster Session

Green-emissive BaSi2O5:Eu2+ thin film phosphor and its transparent plasma display application

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Green-emissive BaSi2O5:Eu2+ thin film phosphor was prepared using a spin coating of Ba-Eu solution on SiO2 substrate. The BaSi2O5:Eu2+ thin film phosphor showed a high transparency of 75 %, and a bright 510 nm-green emission due to the f-d transition of the Eu2+ ion [1]. The relative change in film thickness and shape was determined improvement of external efficiency. The best external efficiency was achieved in a circular shape with a sharp film edge 100 nm thick. It is also confirmed by the optical simulation using LightTools.

8263-65, Poster Session

Electroluminescence in thick ZnGa2O4: Mn2+ phosphor film

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We demonstrated a new electroluminescence (EL) device in a 150 µm-thick ZnGa2O4: Mn2+ ceramic phosphor film. The phosphor film was achieved through a high-temperature heat treatment of pelletized ZnGa2O4: Mn2+ powder. The film was translucent, and the transparent Indium Tin Oxide paste was coated on the top and bottom sides. The fabricated EL device showed the large-area green emission from Mn2+ ions peaking at 505 nm (5 mm × 5 mm). The EL device was 1000 hours-aged under high humidity (85 %) and high temperature (85 °C), and its EL property was more stable, compared with a conventional ZnS powder-based EL device.

8263-66, Poster Session

Investigation for stressed Kane type semiconductors

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The Einstein relation for the diffusivity-mobility ratio of the carriers in semiconductors (DMR) is known to be very useful since the diffusion constant can be obtained from the ratio by knowing the experimental values of the mobility. The classical value of the DMR is equal to , (, , and are Boltzmann constant, temperature and the magnitude of the carrier charge respectively) which represents the well-known Einstein relation. The relation is valid both for electrons and holes. In this conventional form it appears that, the DMR increases linearly with and is independent of electron concentration. This relation holds only under the condition of carrier non-degeneracy although its validity has been suggested erroneously for degenerate materials. Landsberg first pointed out that the Einstein relation for semiconducting materials having degenerate electron concentration is essentially determined by the energy band structures. The nature of the variations of the DMR under different physical conditions has been studied in the literature and some of the significant features, which have emerged from these studies, are:

(a) the ratio increases monotonically with electron concentration in bulk semiconductors;

(b) the nature of these variations are significantly influenced by the band non-parabolicity;

(c) the ratio increases with the magnitude of the quantizing electric field in inversion layers;

(d) the ratio oscillates with the inverse quantizing magnetic field under magnetic quantization due to the SdH effect;

(e) the ratio exhibits composite oscillations with the various controlled parameters of semiconductor superlattices.

8263-69, Poster Session

Energy harvesting from millimetric ZnO single wire generators

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Groundbreaking research by Wang et al. [1] has shown that it may be possible to harvest energy from the piezoelectric response of ZnO nanowires to movement. More recently, the same group demonstrated that increased signal could be obtained using micrometer scale “single wire generators” [2].

This work reports on investigations into the possibility of further extending this advantage by using millimetric ZnO rods for energy harvesting.

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8263-70, Poster Session

ZnO nanorod cathodes for hydrogen evolution and storage

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Due to the attractive combination of a relatively high specific heat of combustion with a large specific energy capacity, molecular hydrogen (H2) is being investigated for use as an alternative to fossil fuels. Indeed, it is projected that H2 fuel cells would offer particular advantages for transportation because of reduced weight, a superior energy conversion efficiency and improved ecological friendliness [1]. Energy-efficient H2 production and safe storage remain key technical obstacles to implementation of an H2 based economy, however.

Although industrial H2 production is dominated by steam reforming of hydrocarbons, the energy costs of this process are relatively high and the purity is insufficient for fuel cell applications. H2 is also produced on an industrial scale by electrolysis. H2 produced by electrolysis is better adapted for fuel cell use because it is free of carbon monoxide contamination, which acts as a poison in proton exchange membrane fuel cells [2]. Industry currently employs iron (Fe) and nickel (Ni) as cathodes for the reduction of H ions into H2 molecules [3-10] - the hydrogen evolution reaction (HER) [11]. Fe and Ni have relatively high H2 evolution overpotentials, however (380 and 480 mV, respectively), which lead to significant consumption of electrical energy. In recent years, numerous studies have focused, therefore, on the quest for new electrode materials presenting higher electrocatalytic efficiency for HER [12-14].

Many semiconductor oxides, such as TiO2, WO3, ZnO, SrTiO3, Fe2O3, Cu2O, SiO2, etc., have been tested (in both bulk and nano form) [15-20]. In particular, several studies were carried out on the oxidation reaction at the ZnO surface and on the ability of ZnO nanorods (NR) to store hydrogen [21-29]. ZnO has also been investigated for use as a photocatalytic anode in solar-powered photo-electro-chemical (PEC) electrolysis, in which H2 is generated by direct water splitting in a cell with a metal cathode and a semiconducting anode [30, 31].

In this investigation, the HER electrocatalytic efficiency and the hydrogen storage capability of high quality ZnO NR grown on Si (100) substrates by pulsed laser deposition [32, 33] were investigated for use as cathodes in the HER for both acid and alkaline electrolytes. The electrochemical potential and Fermi energy of the ZnO NR were estimated from the electrochemical current density in the acid and alkaline solution via phenomenological thermodynamic analysis. As well as acting as an effective electrocalytic cathode, the ZnO NR appear to operate as a hydrogen reservoir. These results indicate that the ZnO NR have excellent potential for the storage of evolved H2.

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8264-01, Session 1

Hybrid organic integrated optical isolators

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The last decade has seen tremendous progress in the development of integrated photonics, with lasers, amplifiers, detectors, filters, modulators, variable optical attenuators, splitters, and couplers all being successfully integrated onto various material platforms including silicon-on-insulator, silica-on-silicon, indium phosphide, ion-exchange glass and polymers. A key functionality that has resisted integration is optical isolation, which is critical for preventing backreflection into increasingly sophisticated integrated lasers and amplifiers. We have previously shown that the integration of polymers with sol-gels and ion-exchange glass can be very effective for the fabrication of electro-optic modulators with low insertion loss and low drive voltage. We have now pursued a similar strategy for developing hybrid integrated optical isolators based on organic materials, including conjugated polymers, polymer magnetite nanoparticle composites, and magnetic ionic liquids. We have developed a sensitive magneto-optic polarimeter for measuring the Verdet constants of these new materials, where we have demonstrated Verdet constants at 1550nm wavelength as high as 10^5 °/T-m for regioregular polythiophene and 10^6 °/T-m for nanoparticle composites. Device geometries explored have included evanescent field polymer and sol-gel Mach-Zehnder interferometers, ion-exchange based low-birefringence waveguides, and magnetic ionic liquid filled capillaries. We will further report on the magneto-optic properties of these materials and progress towards realizing hybrid integrated optical isolators with sol-gels, passive polymers, and glass.

8264-02, Session 1

Magneto-optical mode conversion in a hybrid glass waveguide made by sol-gel and ion-exchange techniques

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Integration of magneto-optical devices, such as nonreciprocal optical isolators, is still a great challenge, due to the difficulties to embbed magneto-optical materials with integrated classical technologies. To overcome this problem, our group has developed a new approach based on a composite magneto-optical matrix that is fully compatible with ion-exchange glass waveguide technology. Using a sol gel process, a silica/zirconia matrix was doped by magnetic nanoparticles ($CoFe_2O_4$). Such a magneto-optical composite matrix has shown promising potentialities illustrated by a specific Faraday rotation of 310°/cm (@1550 nm). Using the dip-coating technique, a composite layer was 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.

Optical characterization demonstrated the efficiency of these hybrid structure in terms of lateral confinement. Furthermore TE to TM mode conversion has been observed when a longitudinal magnetic field is applied to the device. The amount of this conversion is in good agreement with the distribution of light between the layer and the guide obtained by numerical calculations, and the modal birefringence of the structure.

These results confirm that such an approach is a promising way to realize magneto-optical devices.

8264-03, Session 1

Slow light electro-optic modulator based on EO polymer-infiltrated slotted silicon photonic crystal waveguides

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Electro-optic (EO) modulators are one of the most critical building blocks in optoelectronic integration. A variety of EO polymer studies have been undertaken, because a EO polymer can provide very high modulation speeds in excess 100 GHz, and EO coefficients that are much higher than that of lithium niobate (~30 pm/V). We have recently demonstrated a novel EO polymer with donor-modified phenyl vinylene thiophene vinylnene bridge chromophores, exhibiting high EO coefficients (r_{33} > 150 pm/V). However, EO modulations using these polymers have been demonstrated mainly in large structures with centimeter scale, and is therefore inappropriate for effective chip-to-chip and intra-chip interconnections. To reduce the device length and the drive voltage in these EO modulators, interest has grown rapidly in a polymer infiltrated silicon slotted photonic crystal (PhC) waveguide structure. Silicon and EO polymer hybrid system combines the strong optical confinement and slow light mechanisms of silicon slotted PhC waveguides with the superior EO properties of polymers. Furthermore, extremely narrow gap of the polymer filled slot should lead to higher poling efficiency and lower driving voltage. In this paper, we design and fabricate the slotted silicon PhC waveguides combined with our novel EO polymer exhibiting large electro-optic properties. A slow light Mach-Zehnder EO modulator with a drive voltage amplitude of 0.75V, a bandwidth of 121GHz, and a length of only 50um is numerically demonstrated. We reveal a direct relationship between the observed EO responses and the tailored slow light dispersion properties in the fabricated slotted PhC waveguides.

8264-04, Session 1

TiO2 nanophotonic waveguides for on-chip nonlinear optical devices

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Titanium dioxide (TiO_2) is a promising material for nonlinear photonic applications. Its large bandgap (> 3 eV) means it is highly transparent and has minimal two photon absorption over a wide wavelength range. TiO_2's high linear and nonlinear refractive indices (> 2 and 25 × that of silica at 800 nm, respectively) allow for high optical confinement in nanophotonic structures, such as waveguides, photonic crystals and resonators, and efficient nonlinear interactions. Thus, TiO_2 is a potential platform for on-chip nonlinear optical devices operating across the three traditional telecommunications windows (800 nm, 1300 nm and 1550 nm).

In this contribution we report on the linear and nonlinear optical properties of TiO_2 nanophotonic waveguides. We deposit both amorphous and polycrystalline TiO_2 thin films with high refractive indices (2.4 at 826 nm) and low linear optical propagation losses (< 1 dB/cm at 826 nm) on oxidized silicon substrates. We define TiO_2 ridge waveguides with sub-micron widths using e-beam lithography and reactive ion etching. We optimize short pulse propagation and nonlinear interactions by engineering the group velocity dispersion and waveguide effective nonlinearity. Finally, we experimentally investigate both the linear and nonlinear optical properties of our TiO_2 waveguides using continuous-wave and femtosecond-pulsed laser sources, respectively, with the aim of determining their feasibility for on-chip nonlinear optical devices.

8264-05, Session 1

Fabrication of barrier-type slab waveguides in Er3+-doped tellurite glass by single- and double-energy MeV N+ ion implantation

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Ion implantation proved to be a universal technique for producing waveguides in most optical materials [1]. Tellurite glasses are good hosts of rare-earth elements for the development of fibre and integrated optical amplifiers and lasers covering all the main telecommunication bands. Er^{3+}- doped tellurite glasses are good candidates for the fabrication of broadband amplifiers in wavelength division multiplexing around 1.55 µm, as they exhibit large stimulated cross sections and broad emission bandwidth. Fabrication of channel waveguides in such a material was reported recently [2]. Parameters of waveguide fabrication in an Er-doped tungsten-tellurite glass via implantation of N^+ ions were optimized. First single-energy implantation at 3.5 MeV with fluences between $1\cdot10^{16}$ and $8\cdot10^{16}$ ions/cm2 was applied. Waveguide operation up to 1.5 µm was observed. Then double-energy implantations at a fixed upper energy of 3.5 MeV and lower energies between 2.5 and 3.25 MeV were performed to suppress leaky modes by increasing barrier width. Significant improvement of waveguide characteristics were found by m-line spectroscopy and spectroscopic ellipsometry.

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8264-06, Session 1

On-chip electro-optic waveguides in isotropic liquid crystal blends for switching applications

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We report on electro-optic waveguides induced in blends of isotropic thermotropic liquid crystals 4-cyano-4'-n-alkylbiphenyle (nCB) and ester oils. In particular, we show that the blends, besides preserving certain isotropic liquid crystal characteristics such as fairly large Kerr constants, good transparency over a broad spectral range and short response times, could be optimized with respect to their composition to obtain phase stabilization over a wider temperature range than in pure liquid crystals. The transition temperatures from nematic to isotropic phase as well as from crystalline to nematic phase were found to shift to lower temperatures with increasing concentration of oil, as indicated by thermal analysis with differential scanning calorimetry and morphological texture inspection.

We further demonstrate the performance of an integrated device containing electro-optical waveguides with core layers made from these isotropic blends for active manipulation of light beams, particularly for optical 1x2 switching, attenuation and routing. For this purpose, a special chip was designed to include a combination of straight waveguides with bends and couplers. The chip fabrication using wafer technology processing included blend integration with cladding layers and planar electrode structures. Device characterization results show that electro-optic waveguides with low insertion loss and sub-millisecond response time could be obtained. The device optical performance, i.e. coupling efficiency and optical loss, was found to be in good agreement with finite element method simulation results of voltage dependent guided mode profiles in the designed device geometry. Advantages of the proposed device for fast remote sensing applications will be discussed.

8264-07, Session 2

Rare-earth activated potassium double tungstate waveguide lasers and amplifiers

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Several fields, including optical communications, bio-sensing, health, and safety, will greatly benefit from on-chip high-gain amplifiers and high-power, compact, efficient, tunable or short-pulse lasers in channel waveguide geometry.

The rare-earth (RE) doped potassium double tungstates $KY(WO_4)_2$, $KGd(WO_4)_2$, and $KLu(WO_4)_2$ are very promising candidates for such applications. RE ions exhibit a long excited-state lifetime, typically ranging from hundreds of microseconds to milliseconds, thus permitting large excitation densities and distortion-free amplification of high-bit-rate signals in the small-signal-gain regime. The large interionic separation of ~0.5 nm of RE ions in double tungstates allows to exploit increased RE dopant concentrations without significant fluorescence quenching, which, together with the large absorption and emission cross-sections of RE ions in these host materials and the good overlap between pump and signal light provided by the optimization of the channel waveguide structure, leads to very high modal gain.

In this paper, our recent achievements in integrated waveguide amplifiers and lasers will be presented. When activated with Yb^{3+}, lasers with low threshold of a few mW, high slope efficiency of 76%, high output power of ~650 mW, tunability between 980-1045 nm, and low quantum defect of 0.7% were demonstrated. A high-gain waveguide amplifiers presenting a modal gain of ~935 dB/cm was achieved. In Tm^{3+}-doped waveguides, 31% slope efficiency and 149 mW output power at 1.9 µm were obtained. Finally, potential applications of this material in nanophotonic devices will be highlighted.

8264-08, Session 2

1.55-um hybrid waveguide laser made by ion-exchange and wafer bonding

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Optical amplifiers and lasers working at a wavelength around 1550 nm are essential for optical communications, eye-safe sensors and lab-on-chip. Glass integrated optics technology allows realizing such devices by using rare-earth doped substrates. However, the realization of passive functions may not be compatible with such substrates. Indeed for 1.55µm applications the presence of Erbium entails high signal absorption when not pumped. For this reason the combination of active and passive functions requires hybrid integration.

A new technological process and device architecture are proposed to integrate active functions on a passive glass substrate using the ion-exchange technology. The Ag+/Na+ ion-exchange in the silicate glass wafer is used to realize the passive functions and the lateral confinement of the amplifying section. Through an ion exchange of the same kind, a slab waveguide is made on the Erbium-Ytterbium doped glass wafer. The active glass is then molecularly bonded on the suitable area of the passive substrate. The potential of this structure has been demonstrated through the realization of FP lasers. Current work is dedicated to the realization of fully interfaced DFB hybrid lasers with a fully encapsulated Bragg grating and passive interfacing functions.

8264-09, Session 2

Supercontinuum generation using integrated Q-switched laser made by ion-exchange

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Supercontinuum generation using microstructured fibre has been studied a lot during the past decade. This kind of device is interesting for spatially coherent ultra-wide band spectrum generation, which is useful for one-shot optical coherent tomography measurement. Moreover, embedded systems for OCT need to be compact and robust. Nevertheless, only a few studies using microchips Q-switched lasers investigate compact devices since the bulk optics needed to couple the output beam into the microstructured fibre introduce vibration sensibilities and coupling losses. Using integrated optics Q-switched lasers realized on glass avoid these problems and gives the possibility to optimize the coupling efficiency between the optical fibre and the waveguide design.

In this paper, we present a supercontinuum source pumped with a glass integrated Q-switched laser made by ion-exchange. The key characteristics of this device are its mechanical stability and its compactness. Indeed, the device is composed of an ion-exchanged single mode waveguide realized in a Neodymium doped phosphate glass. The laser feedback is produced by a Fabry-Perot cavity with one multilayer dielectric mirror stuck on the input facet and with the Fresnel reflection on the output facet. We implemented a bis(4-dimethylaminodithiiobenzil)nickel (BDN) doped cellulose acetate thick film for the losses modulation around 1.06 µm. This device emitted 2.4 kW peak power pulses, which has been injected into a microstrucured fibre stuck on the output facet leaving an air-gap between the fibre and the waveguide to provide the Fresnel reflection. A spectrum going from 400 nm to 1600 nm has been obtained.

8264-10, Session 2

Analytical modeling of mid-infrared silicon raman lasers

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Silicon photonics has significantly matured in the near-infrared (telecommunication) wavelength range with several commercial products already in the market. More recently, the technology has been extended into the mid-infrared (mid-IR) regime with potential applications in biochemical sensing, tissue photoablation, environmental monitoring and free-space communications. The key advantage of silicon in the mid-IR, as compared with near-IR, is the absence of two-photon absorption (TPA) and free-carrier absorption (FCA). The absence of these nonlinear losses would potentially lead to high-performance nonlinear devices based on Raman and Kerr effects. Also, with the absence of TPA and FAC, the coupled-wave equations that are usually numerically solved to model these nonlinear devices lend themselves to analytical solutions in the mid-IR. In this paper, an analytical model for mid-IR silicon Raman lasers is developed. The validity of the model is confirmed by comparing it with numerical solutions of the coupled-wave equations. The developed model can be used as a versatile and efficient tool for analysis, design and optimization of mid-IR silicon Raman lasers, or to find good initial guesses for numerical methods. The effects of cavity parameters, such as cavity length and facet reflectivities, on the lasing threshold and input-output characteristics of the Raman laser are studied. For instance, for a propagation loss of 0.5 dB/cm, conversion efficiencies as high as 56% is predicted. The predicted optimum cavity (waveguide) length at 2.0 dB/cm propagation loss is ~ 0.34 cm. The results of this study predict strong prospects for mid-IR silicon Raman lasers for the mentioned applications.

8264-11, Session 3

Hybrid silicon/III-V laser sources based on adiabatic mode transformers

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Silicon photonics has generated an outstanding interest for optical telecommunications and signal processing, as well as for inter- and intra-chip interconnects in microelectronic systems. Recent research has focused on the realization of silicon optoelectronic integrated devices using large scale, low-cost, and highly accurate CMOS technology. While silicon is now considered as the material of choice for passive optical components due to its low-loss beyond 1.1 µm and high-index-contrast with its native oxide, it is however a very poor light-emitting material.

Currently, the preferred method of integrating laser sources is to attach prefabricated III-V lasers to silicon chips one at a time. This method also has the disadvantage of requiring submicron precision alignment to enable efficient coupling, which is time consuming and not adapted for high-volume fabrication.

A particularly promising approach is based on molecular bonding of III-V epi-grown material on top of a patterned silicon-on-insulator (SOI) substrate. This can be performed either at the die or wafer level depending on the application needs. Hybrid Si/III-V lasers are then realized by employing a collective fabrication procedure, enabling the integration of complex photonic systems onto the silicon platform. Using this technology, Fabry-Pérot, racetrack, and distributed feedback lasers were demonstrated [1, 2].

Generally, the bonded structure is designed to support a common optical mode distributed between the III-V structure and the underlying Si waveguide. In this way, the major part of the field is located in the silicon waveguide and only a few percent, i.e. the tail of the optical mode, overlaps with the multiple quantum wells of the III-V active region. The laser mode is then mainly concentrated in the passive silicon waveguide to the detriment of the modal gain. Another difficulty of this approach is the tight control of the low-index bonding layer, whose thickness must be kept as thin as possible, typically lower than 10 nm. This technological

constraint constitutes a limiting factor for both the design and fabrication process. It also makes difficult the integration with other passive and Si/Ge-based active components since Si-circuits are not encapsulated prior to bonding and III-V processing. These innovative evanescently-coupled laser structures have obviously several attractive features; however, they use III-V materials inefficiently given that there is a trade-off to find between modal gain and output coupling efficiency.

In this communication, we report on experimental demonstrations of electrically driven hybrid Si/III-V lasers which are based on the supermode control of a two coupled waveguides system [3-5]. The proposed architecture definitely overcomes the aforementioned trade-off inherent to the Si evanescent lasers previously reported. The novelty is that the optical supermode is fashioned along the cavity length to obtain a strong overlap with the gain region (rather than the evanescent tail) while maintaining a high coupling efficiency with the bottom silicon waveguide. This results in a larger gain available for amplification.

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8264-12, Session 3

Edge-emitting III-V/Si hybrid laser: fabrication and efficient coupling to silicon waveguide

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Active optical components, monolithically integrated with passive silicon photonics on the same chip, are currently in high demand for such applications as optical computing, optical interconnects and lab-on-a-chip photonics. One of the solutions to large-scale monolithic III-V/Si integration is thought wafer bonding.

In our study we use plasma assisted wafer bonding approach for realization of a novel III-V/Si Fabry-Perot laser with sidewall modulated Bragg mirrors and output light coupled to a silicon waveguide via low loss 3D adiabatic taper coupler. For numerical simulations of the laser structure and mode conversion in the coupler, we utilize finite element method (COMSOL). Fabrication is carried out through two-step self-aligned RIE etching of the lithographically defined structure, followed by oxygen RIE treatment to shape 3D profile of the coupler. Finally, we experimentally investigate the optically pumped laser characteristics and coupler losses to determine the feasibility of their further integration with silicon photonics and CMOS platforms.

The main advantages of the proposed laser/coupler system design are: 1) adiabatic nature of the coupler, both vertically and horizontally, which minimizes the losses compared to the commonly used evanescent coupling approach; 2) The mode/gain overlap in the laser resonator can be relatively large and tuned by the design; 3) simple and robust fabrication. Therefore, our approach has a potential to greatly improve the energy efficiency and production cost of large scale III-V/Si integrated circuits.

8264-13, Session 3

Recombination and loss mechanisms in Ga(NAsP)/(BGa)P QW lasers grown lattice-matched to exact (001) silicon

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Electrical injection laser operation in monolithically integrated Ga(NAsP)/(BGa)P QW lasers on an (001) silicon substrate shows great promise for future integration of photonics with electronics. Lasing has been obtained up to 165 K with a threshold current density (Jth) of 1.6 kAcm-2 at a wavelength of 861 nm. Achieving room temperature operation with low Jth requires an understanding of the physical origins of the high threshold current in these devices. In this work we present a comprehensive study of the threshold current and its temperature dependence in Ga(NAsP)/(BGa)P/Si QW lasers. The important recombination mechanisms of the lasers are investigated by measuring both facet and spontaneous emission spectra in the temperature range of 40-165 K. The characteristic temperature, T0 (T1) is measured on these devices to be 196 K (98 K) at 110 K, decreasing to 73 K (35 K) at 165 K. From the measured Jth and its radiative component we find that non-radiative processes become dominant at higher temperature in these lasers and contribute to ~56% of the Jth at 165 K. The application of hydrostatic pressure shows that Jth increases with pressure much faster than the radiative current, suggesting the presence of carrier leakage into localised states. The pressure co-efficient for the band gap of the device is measured to be ~6.3 meV/kbar and Jth for the devices increased by ~47% up to 7 kbar at 165 K. The prognosis for room temperature lasing on silicon with this approach will be discussed in more depth at the conference.

8264-14, Session 3

Highly efficient coupling between a photonic crystal cavity and a bus waveguide

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We experimentally demonstrate a new technique for coupling light between a low refractive index contrast bus waveguide and a photonic crystal cavity. In general, coupling between waveguides of different refractive indices is very inefficient as there is a significant phase mismatch between the supported modes. Based on the approach of [1], we develop a novel approach to achieving this match.

We have fabricated oxide clad PhC cavities [2] with polymer waveguides positioned directly above, such that there is an overlap between the evanescent tails of the two modes. By suitably engineering both the cavity and the waveguide effective index, phase matching is achieved giving very strong coupling between the two modes. We have experimentally realised efficiencies of 75% for cavities with Q~50,000. With further optimisation, theory suggests that 95%+ coupling is possible [3].

Vertical coupling offers some important advantages. In plane coupling to PhC waveguides perturbs the cavity introducing new k-vector components that are above the light cone, thus reducing the Q-factor [4]. Furthermore, low index contrast waveguides are very well matched to lensed optical fibres, giving excellent coupling of light on-chip. This makes this an exceptionally promising technique allowing PhC cavities to be used in applications requiring low insertion losses, such as WDM systems and low power non-linear optics.

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[3] Physical Review E 62, 7389-7404 (2000)

[4] Optics Express 13, 2596-2604 (2005)

8264-15, Session 3

Polymer waveguides based on silicon optical benches

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In this paper, the polymer waveguide with a 45°reflector is developed on the silicon optical bench (SiOB). This technique can be applied for the optical interconnects of inter- or intra-chip applications. The proposed polymer waveguide fabricated on SiOB including a Si-based 45° reflector with 20-um depth and a straight rectangular waveguide with core size of 40 μm × 20 μm, which size are very suitable to apply for connection of fiber with high coupling and no coupling lens needed. The inaccuracy of fabrication with polymer waveguide can be controlled less than 5 um, which may cause less than 1-dB coupling variation.

In the framework, the 1550-nm light source was coupled to polymer waveguide and directly bend into the detector by 45°reflector. The insertion loss of straight rectangular waveguide is -2.49 dB, and its propagation loss is -2.085 dB/cm, due to this material of polymer is applied for propagation of 850-nm light source. In the bending waveguide with a 45°reflector, the insertion loss is -5.62 dB, and the 1-dB degradation tolerance of input single-mode fiber is about 24 μm in the vertical direction, and 8 μm in the horizontal direction, which can be applied for miss-alignment of VCSEL/PD assembly.

8264-16, Session 4

A perturbation approach for the design of coupled resonator optical waveguides (CROWs)

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We propose a simple and accurate technique for the design optimization of coupled resonator optical waveguides CROWs. The technique is based on tapering the coupling coefficients at the CROWs stages to achieve arbitrary realizable filter response. A perturbation theory is developed for the linearization of the design problem. The coupling coefficients are expanded around a known mean coupling value. By dumping the higher order perturbation terms, we ignore the effect of multiple reflections among the rings introduced by the small adjustment of the coupling coefficients. This is a first order accurate approach as it takes into account only multiple reflections introduced by the zero order terms.

The design problem is then formulated as an optimization problem. The optimal filter design is achieved by solving a constrained linear least square problem. This optimization problem can be solved efficiently to get the global optimal design. Our technique is accurate and efficient compared to other nonlinear approaches. Our technique has been verified using different proposed targeted filter responses.

We utilize our perturbation approach for optimal filter design. We conducted several examples that include third, fifth, and tenth order coupled ring resonators. Highly selective tenth order filter with flat response is proposed. We compared our results to the existing techniques to prove its accuracy. A lossy structure is utilized to verify the versatility of our technique to take losses into consideration for design purposes [1].

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8264-17, Session 4

Theoretical model for the effective nonlinearity of surface plasmons based on a Green function formalism

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A theoretical model is proposed for describing the effective nonlinearity of surface plasmons supported by a single interface between a metal and a linear dielectric (or a vacuum), where the nonlinearity results solely from the nonlinear response of the metal. The response to the polarization fields driving the nonlinearity are modeled using a Green function formalism for surface optics. An expression for the effective nonlinear coefficient of the single-interface surface plasmon is obtained. The theory presented here can be extended to more complicated multilayer geometries in a straightforward manner, allowing its use for describing the nonlinearity of other plasmon modes such as the long-range and short-range surface plasmons. The theory is employed to investigate the self-phase modulation of the single-interface surface plasmon in silver and gold structures. We discuss the possibility of using surface plasmon self-phase modulation to estimate the value of the third-order nonlinear susceptibility of metals through experimentation.

8264-18, Session 4

Modeling and analysis of multiple ring-resonator performance as optical filter

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Optical ring resonators are versatile passive devices essential in ever expanding communication systems. Delay line signal processing using z-transform method has been used in this article. The key feature of this method is to modulate the unit delay. Once the unit delay is formulated the total delay can be expressed as integer multiple of unit delay. The frequency response of ring resonator is generally periodic in nature and one such period is defined as free spectral range (FSR)[1].

The overall transmittance of double ring resonator(DRR) and triple ring resonator(TRR) with ring loss can be determined in z-domain using Mason’s rule[1].

An important parameter used in characterizing an optical filter in frequency domain is the group delay function. Group delay is defined as the negative derivative of the phase of transfer function with respect to the angular frequency. So group delay function can also be mathematically represented in z-domain[2].

The ring resonators as discussed in this article present structural dispersion around the resonant frequencies. Dispersion causes broadening of signal pulses around the resonant peaks. Among various types of dispersion, structural dispersion is relevant here [2]. It can be measured as the rate of change of group delay with respect to frequency

Frequency response plot,Group delay and Dispersion of the DRR and TRR is computed using MATLAB.

A silica based planer waveguide DRR and TRR have been studied in this article. FSRs obtained in both the cases are very wide compared to the corresponding class of ring resonators. A judicious choice has to be made while selecting the operating range.

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8264-19, Session 4

Design of multilayered strip SiON waveguide for polarizer application

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Polarizer is the key component for the devices which require a single polarization for their operation. In this paper we propose a four-layered strip waveguide based TE-mode polarizer. A four layered strip waveguide grown on silicon substrate and having a silicon oxynitride (SiON) guiding film (thickness d2) with silicon oxide (SiO2) as buffer (thickness d1) and cover is proposed and analyzed through transfer matrix formulation. The dependence of polarization characteristic on the waveguide parameter such as aspect ratio b/a (b is width & a is height of the strip waveguide) and hence effective index (neff) is discussed. It is shown that by changing the ratio b/a from 0.5 to 2.0 (or d2 = b = from 0.5a to 2.0a) an effective TE-mode polarizer having passband in the third communication window of 1550 nm is achieved which have an insertion loss of less than 1dB/cm. The choice of SiON is made for its highly desirable features such as low insertion loss, wide range of refractive index tailoring and realization of compact devices because of its low bending loss. The present configuration of optical polarizer will find applications in integrated optical circuits, signal processing from fiber optic sensors and fiber gyroscopes.

8264-20, Session 4

Asymmetrically coupled bus with tunable ring resonators for multiple functionalities: Fano resonance, asymmetric transmission, and wavelength shifting

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Transmission properties of bus waveguides coupled with carefully designed multiple ring resonators, of which the refractive indexes can be tuned by the nonlinearity of the signal or external pumps, are investigated using the finite difference in time domain (FDTD) method, and theoretical analysis method. The symmetrical and asymmetrical nested coupling structures of multiple rings are designed, and different functionalities are numerically realized in these structures. Fano resonant transmissions, together with sharply asymmetrical field localizations in the rings are obtained when the signals are incident from different ports. These properties are used to realize highly efficient optical switching, and optical diode with high contrast transmission ratios. When the refractive of the cavities are modulated periodically (with a frequency of ωm, and modulation intensity of Im) by an external pump, we find that the frequencies of the resonant signals localized in the rings may be shifted by an amount of Nωm (with N positive or negative integers), and then output from different ports. Factors that affect the frequency shifting efficiency are investigated, which include the modulation frequency ωm, modulation intensity Im, quality factor Q of the ring resonators, and the asymmetry of the coupling system. These structures and properties presented here may find potential applications in nano-photonic systems.

8264-21, Session 5

Enhancing gradient optical force in silicon photonic devices

M. Li, Univ. of Minnesota, Twin Cities (United States)

(Invited Talk) Generation of strong optical forces in integrated photonic devices enables the convergence of nanomechanics and nanophotonics. In this talk, we will describe several schemes, including coupled optical cavities and plasmonic structures, to enhance optical forces in planar silicon photonic systems. Their potential applications for tunable photonics and sensing will be discussed.

8264-22, Session 5

The development of a novel monolithic spectrometer chip concept

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A new type of monolithic, chip-based spectrometer based on the novel concept of a series of electrically addressable high-Q resonators coupled to a ridge waveguide is presented.

A series of resonators has been designed on an III-V semiconductor platform to select and detect wavelengths over a desired spectral region forming a highly integrated monolithic spectrometer. The general concept is based on resonant detection utilising optically active semiconductor disk micro-resonators which provide high wavelength selectivity with photo-detection. This integrated spectrometer chip has a number of advantages over traditional spectrometers. As well as being solid state and having no moving parts, the co-location of wavelength dispersion and detection has the potential for excellent spectral responsivity. By varying the dimensions and composition of the resonator design, this approach may be used to develop spectrometers that operate in the UV, visible and infrared ranges.

In this paper we describe the design of a spectrometer chip designed to target a specific region of the near-infrared region with applications in gas detection. Design aspects include optimisation of the size and composition of the resonators and maximised coupling to a ridge waveguide. A prototype InP-based spectrometer chip has been fabricated targeting a 10nm band width in the near-infrared. Initial results on a prototype spectrometer chip will be presented highlighting the spectral and electrical performance of this miniature spectrometer concept.

8264-23, Session 5

On-chip interrogation of a silicon-on-insulator microring resonator based ethanol vapor sensor with an arrayed waveguide grating(AWG) spectrometer

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Silicon -on -insulator (SOI) optical microring resonators fabricated with the standard CMOS fabrication technology have recently gained considerable attention for energy efficient , compact and low cost biomedical and environmental sensing applications. High sensitivity to the surrounding refractive index variations, high compactness, direct wavelength multiplexing capabilities, simplicity, and the promise for mass fabrication are among the interesting features supported by SOI microring resonators. On the other hand, despite the strong case for microring resonators for sensing , there exist some issues which need to be addressed in order to ensure the feasibility of such sensors. One major limitation currently is the cost of optical sources and /or spectrum analyzers required to drive and interrogate these sensors. Either expensive light sources or spectrum analyzers are usually used with sensors built around microring resonators. An attractive approach to address this problem is the use of on-chip spectrometers along with cheap broadband light sources. We experimentally demonstrate on-chip interrogation of an SOI microring resonator based gas sensor with a compact Arrayed Waveguide Grating(AWG) spectrometer. We have designed and fabricated a 200GHz AWG with strongly overlapping output channels, and used it to interrogate the wavelength shift from a ring resonator based ethanol vapor sensor on the same chip. Ethanol vapor concentration ranging from 100-1000ppm is readily detected by monitoring the intensity ratio between two adjacent AWG channels to which the microring resonance overlaps. Such an integrated sensor-interrogator approach is presented as an alternative to the current costly and off-chip read-out systems used for ring resonator based sensors.

8264-24, Session 5

Array of subwavelength rectangular holes in palladium for optical hydrogen detection

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The extraordinary optical transmission of sub-wavelength rectangular hole arrays of Pd on a Si substrate in the infrared region is applied to detect hydrogen. The main transmitted peak of the Pd hole array shifts toward longer wavelengths when exposed to hydrogen. We found that the shift value of the main transmittance peak is controlled by the hole shape. Large aspect ratios of the rectangular holes result in large shifts of the transmittance peak for the same hydrogen concentration. The effect of the aspect ratio of the holes is explained by numerical simulation using the RCWA method. The large shift value obtained with high aspect ratio hole is explained by a change in the electric field profiles of supported modes enabling strong interaction with the Pd matrix. Experimental observation of the peak shifts as a function of the hole aspect ratio is reported and found in good agreement with the predicted shift values. It is concluded that the reported all-optical scheme of hydrogen detection produces peak shifts that enable the detection of hydrogen.

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8264-25, Session 6

Amorphous photonic membranes for broadband chemical sensing applications

R. D. Whaley, Jr., S. D. Abbey, P. Rajan, Ohio Univ. (United States)

While there has been extensive development on integrated sensors in the near-IR region due to the maturation of Si, SOI, and III-V materials, these technologies are not easily translated into the visible and near-UV regions which are critical for the detection of many chemicals of environmental and security interest. This work focuses on the use of wide bandgap, amorphous materials, specifically, amorphous zinc oxide (a-ZnO), amorphous hafnium oxide (a-HfO2) and amorphous beryllium zinc oxide (a-BeZnO), in the development of broadband chemical sensors operating at critical absorption lines spanning the near-UV (200 nm) to the near-IR (1.55 μm).

The architecture employed for this research is a nanoscale membrane (typically 40 - 100 nm thick) that supports a guided low optical overlap mode (LOOM) - an optical mode in which approximately 1% of the electric field is confined to the lossy core region. The resulting extended mode has a greatly enhanced analyte overlap, yielding a device sensitivity (~70%) that is over an order of magnitude higher than current high-performance, dielectric evanescent wave sensors (~2%) as modeled by analytical and finite element methods. Due to the extended nature of the LOOM, sensing across the entire spectral range can be achieved with a single waveguide design - critical for multi-point chemical sensing architectures. Additionally, due to the large field concentration at the membrane surface, we investigate the use of these nanoscale LOOM structures as SERS substrates. which may yield larger enhancement factors (>104) than what is currently seen in the visible and near UV.

8264-26, Session 6

Foil-based optical technology platform for optochemical sensors

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This paper describes the development of a low-cost technology platform for fluorescence based optochemical sensors incorporating arrays of multimode lightguides and coupling structures integrated into a flexible substrate. The proposed configuration provides inherent multi-analyte detection capabilities, and future integration of light sources, fluorescent sensing elements, and photodetectors. This will provide a foil-based generic platform for optoelectronic nose applications in medical, biochemical, and environmental diagnostics at a molecular level.

Flexible lightguides are fabricated using two technologies, photolithography in the case of siloxane-based polymers and soft-lithography based replication techniques followed by capillary filling in the case of poly(dimethylsiloxane) (PDMS) lightguides. In both cases, specific core and cladding materials are used. Excimer laser-ablation is used to fabricate micro-prism coupling structures for incoupling from OLED and LED to lightguide. Outcoupling to a photodiode is realised with the fabrication of a 45° micromirror, having a loss of 0.5dB.

As part of the characterisation in the visible spectrum, which is essential for fluorescent sensing applications, a systematic approach is adopted in finding out the spectral transmission characteristics of the proposed siloxane-based and PDMS-type optical polymers. Stand-alone films are used to avoid interactions at the interfase with glass or quartz substrates. Spectral data is compared with loss values obtained by cut-back measurements for several wavelengths from visible to mid-IR and a propagation loss smaller than 0.24dB/cm was found. Refractive index measurements were performed using an ellipsometric technique and coupling elements were designed based on these values.

8264-27, Session 6

Compact static Fourier transform spectrometer in glass integrated optics in the NIR and visible domain

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Spectrometers are now often used to analyse the proprieties of optical light emitted, reflected or scattered. For that, a lot of compact spectrometers have been developed to obtain low cost system easy to use. These last years, we proposed a Fourier transform spectrometer (LLIFTS) realized in glass integrated optics. This system is realized after single step lithography using no moveable parts or complex etching process to realize a dispersive grating. The principle of the LLIFTS lies on a two-beam interferometer in planar design using a leaky loop waveguide structure coupled to a plane waveguide. Thanks to the loop radius, the gap evolution between the plane waveguide and the loop, the leaky loop structure has the advantage of controlling the shape of the interference pattern measured at the end of the component. The square root gap evolution gave a spectral resolution of 11 nm in the near infrared domain. But the spatial fringe period remained too small to be well sampled directly by a linear camera. Now, new results are obtained with a better gap evolution and the interference patterns have been measured in the wavelength range from 600 nm to 1630 nm. Spectral resolution of 7 nm and 2 nm has been reached respectively with wavelengths of 1500 nm and 660 nm. Moreover, a direct measurement of the interference pattern with a linear camera of 2048 pixels set at the end of the component is shown to demonstrate the realization of an entire compact system.

8264-28, Session 6

Development of a slow-light spectrometer on a chip

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We discuss the design and development of a slow-light spectrometer on a chip. The basic idea behind a slow-light spectrometer is that the refractive index of a slow-light material is highly frequency dependent. Thus, any physical interaction that depends on the value of the refractive index will show an enhanced wavelength sensitivity if its optical components are replaced by slow-light elements. A key goal is to analyze and then develop various sorts of spectrometers to see which can be most significantly improved by the use of slow-light techniques. The objective is to use slow-light media in the form of photonic crystal structures as highly dispersive elements in order to achieve extremely high spectral resolution in a chip-sized spectrometer. We investigate various designs based on photonic crystal waveguides and grating structures. Samples are fabricated using electron-beam lithography and UV photolithography on a Silicon on Insulator (SOI) platform. Optimal parameters for the photonic crystal array elements are determined by varying the lattice constants and fill factors for a given design and by measuring the resulting properties such as light transmission and optical dispersion. Fourier-transform spectral interferometry (FTSI) is used to determine the group index as a function of wavelength for the different waveguide structures.

8264-29, Session 7

Volume structuring of transparent materials by ultrashort laser pulses: potential and applications

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Within the past decade, ultrashort laser pulses have shown a tremendous potential for precise microstructuring. Especially, the possibility to realize three-dimensionally localized modifications within the bulk of transparent materials has recently attracted increasing interest. When intense ultrashort pulses are tightly focused into the transparent material, the intensity in the focal volume can become high enough to initiate nonlinear absorption processes. This results in the creation of a hot electron-ion plasma, leading to permanent structural changes inside the sample without affecting the surface. Depending on the processing parameters, either isotropic refractive index changes, self-organized sub-wavelength structures leading to form birefringence or microvoids can be generated in the focus [1].

In this presentation the fundamentals of the femtosecond volume structuring will be discussed. Various applications will be highlighted, including the direct writing of embedded waveguides and waveguide arrays, fiber Bragg gratings (FBG) or volume Bragg gratings (VBG). When high repetition rates are used, cumulative effects can become important, and the ultrashort laser pulses might be used as a localized heat source within the volume. This can be harvested e.g. for the direct bonding of different glasses without adhesives and minimized thermal stress.

1. K. Itoh, W. Watanabe, S. Nolte, C.B. Schaffer, “Ultrafast processes for bulk modification of transparent materials”, MRS Bull. 31, 620 (2006).

8264-30, Session 7

Mode-conversion cavities-applications in integrated optics

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In this talk we describe new type of waveguide resonators in which mode converting gratings serve as mirrors. Initial experiments showing how these resonators can be used in add-drop filters will be discussed.

8264-31, Session 7

Broad-area laser diode with stable single-mode output

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High power single-mode pump laser diodes operating around are key components for Erbium-doped devices. Much effort is still currently devoted to improve both wavelength stability and achievable output power, while maintaining stable single-mode operation.

The emission wavelength is usually stabilized by an external Fibre Bragg Grating (FBG), whose thermal expansion coefficient are only one eighth the one of a semiconductor laser. This configuration requires free-space optics between the laser diode and the fibre or a lensed fibre to ensure a low-loss coupling efficiency, which increase fabrication costs, dimensions and mechanical instabilities.

In addition, the maximum achievable output power is limited because the high optical power density can damage the laser facet. The trade-off between catastrophic optical mirror damage and single-mode operation has thus been reached.

A solution consists on using Broad-Area Laser Diodes (BALD), which present hundreds of micrometers wide emitters. The objective is then to improve the beam quality by locking the BALD emission on its transverse fundamental mode.

We propose in this article a solution based on an adiabatic transition made by ion-exchange on glass. The input is a wide waveguide with vertical step-like refractive index profile whereas the output is a narrow waveguide whose vertical profile is diffusive. It thus offers an efficient coupling efficiency with both a BALD at the input and a single-mode FBG at the output.

The wavelength stabilization over the whole current range of the BALD, which emits at the Bragg wavelength, is also demonstrated.

8264-32, Session 7

Photonic nanojet-induced modes: fundamentals and applications

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Previously we introduced photonic nanojet-induced modes (NIMs) occurring in long straight chains of optically coupled microspheres due to periodical focusing of light. These modes appear under condition when the distance between adjacent focused beams matches the size of two touching spheres. In this work we show that in the limit of geometrical optics these modes exist in a narrow range of spheres' indices around 1.7 whereas in chains of more compact spheres with the wavelength scale dimensions they occur at smaller indices around 1.6. Experimental studies are performed using high quality sapphire and ruby spheres with diameters 300 μm assembled inside hollow core waveguides operating in IR regime. Fourier analysis of the transmission spectra measured at telecom wavelengths with the resolution about 1pm showed that NIMs are the only surviving modes in sufficiently long chains. Due to tight periodical focusing of light and distributed feedback properties these modes can be used in nonlinear and laser applications. These structures can be also used for developing devices capable of focusing beams of light delivered by multimodal fibers or waveguides. We optimized the device designs for laser surgery in contact mode with strongly absorbing tissue. It is demonstrated that chains formed by three or five spheres with a refractive index of 1.65-1.75 provide a two-fold improvement in spatial resolution over single spheres. The results are found to be in a good agreement with direct measurements of the focal spots in such structures.

8264-33, Session 7

Polarizer based on graphene

J. T. Kim, S. Choi, Electronics and Telecommunications Research Institute (Korea, Republic of)

Graphene, a flat monolayer of carbon atoms packed into a two-dimensional honeycomb lattice, have been attracted a great attention due to its remarkable properties. In photonics, graphene opens a way to develop novel optoelectronic devices, such as photo-detector, modulator, and polarizer. As an extended application of graphene in photonics, we fabricated a graphene-based polarizer and investigated its characteristics. A CVD-grown graphene is placed on a optical waveguide. The measured TE/TM extinction ratio of the fabricated graphene polarizer is about 10 dB.

8264-58, Session 7

Polymer waveguides with reduced in-plane bend loss for electro-optical PCBs

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One of the key challenges in designing polymer waveguide based electro-optical printed circuit boards (OPCBs) is providing an optical waveguide interconnect layout that can meet the stringent routing requirements inherent to navigating densely populated waveguide components while complying with the practical optical design rules for embedded waveguides.

In-plane bends are inextricable from high density waveguide layouts, however optical bend loss is the greatest inhibitor to the commercial viability of deploying optical waveguides in such systems. Practical values for optimum waveguide bend radii range from 10 mm to 15 mm, whereby the bend loss is minimized with respect to arc length and bend radius. From a design point of view, it would be very difficult to accommodate bend radii that large within a high density OPCB interconnect layout, especially where high numbers of optical waveguides are involved.

We present a concept and fabrication method for creating nested polymer optical waveguides with reduced bend losses to enable higher density routing on an OPCB. While conventional polymer waveguides are comprised of a higher refractive index core, which is fully surrounded by a lower index cladding, the fabrication of the nested waveguides involves a second patterning step whereby the cladding is structured around the core, such as to create a secondary high index contrast boundary near the primary core-cladding boundary. The purpose of this is to reduce the in-plane bend losses incurred on tightly routed optical channels.

We have designed and fabricated nested multimode polymer waveguides, evaluated varied cladding sizes and structures and present preliminary results of our measurements. We have also simulated these structures using the beam propagation method (BPM).

8264-35, Session 8

Silicon-plasmonic router for optical interconnects: PLATON approach

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Recently, the combination of surface plasmon photonics and Silicon-on-Insulator (SOI) was suggested as a promising candidate to satisfy the constraints of miniaturisation of optical devices which could be relevant for optical interconnects.

This contribution presents experimental results of a 2x2 silicon-plasmonic router for optical interconnect applications featuring 480Gb/s throughput capabilities at telecom wavelengths, thereby demonstrating for the first time the practical application of a plasmonic device for high throughput optical data processing. The router platform has been developed in the framework of the European project FP7 STREP Platon (Merging Plasmonic and Silicon Photonics Technology towards Tb/s routing in optical interconnects, 2010-2012). It relies on a novel dual-ring Dielectric-Loaded Surface Plasmon Polariton (DLSPP) 2x2 switch heterointegrated on a SOI motherboard that is responsible for traffic multiplexing and header processing functionalities as well as on the opportunity offered by plasmonic circuitry to carry optical signals and electric currents through the same thin metal circuitry. The heating of the dielectric loading by the electric current enables to design low foot-print thermo-optical switches driving the optical signal flow.

Perspectives towards extending integrated plasmonic functionalities on SOI motherboards such as compensation of losses by optical pumping, all optical switches or in-line thermo-electric power monitoring of the signal flow without destroying the signal itself will be detailed.

8264-36, Session 8

Engineered plasmonic nanostructures for microfluidic biosensing

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Recent advances in nanofabrication have enabled unprecedented capabilities to engineer metallic nanostructures and harness surface plasmons, which are electron density fluctuations at the metal interface. This hybrid surface electromagnetic wave can squeeze light into nanometer-scale volumes and increase light-matter interactions beyond conventional diffraction limits, which can benefit many applications in biosensing, nanoscale imaging, and spectroscopy, to name a few.

This work will focus on a series of nanofabrication methods, including focused ion beam (FIB) lithography, nanoimprint lithography, and template stripping, to make high-performance plasmonic devices, and demonstrate their utility in applications such as protein biosensing, microfluidics, and spectroscopy.

Metallic films perforated with sub-wavelength apertures are used for surface plasmon resonance (SPR) biosensing. Using this platform, it is possible to determine the on-off rates and equilibrium constants of various antibody-antigen interactions in a lipid membrane environment. In addition, the unique geometry of nanohole SPR sensors allows the formation of pore-spanning lipid bilayers to enable studies on transmembrane proteins, which are very difficult to study with conventional biosensing instruments. High-throughput and low-cost fabrication of these plasmonic nanostructures will enable a new class of optical biosensors that can benefit basic research and drug discovery.

8264-38, Session 8

Integration of nanostructures and waveguide core for surface enhanced Raman spectroscopy: a novel excitation method

S. J. Pearce, M. D. B. Charlton, M. E. Pollard, S. Oo, R. Y. Chen, Univ. of Southampton (United Kingdom)

Surface Enhanced Raman Spectroscopy (SERS) allows the intensity of Raman scattering to be enhanced by a factor of 106 by placing molecules within a few nm of a rough metal surface. SERS is used to identify and quantify molecules, viruses and bacteria in low quantities. In conventional SERS measurement, the excitation field is incident normal to the surface and couples to surface plasmon modes associated with flat or randomly roughed precious metal surface, which are inherently localised within a few 10s of nm to the surface of the device. In this paper we investigate a completely different configuration for the excitation mechanism, incorporating an optical waveguide beneath a nanostructured precious metal surface. The pyramidal geometry projects the Plasmon field into free space, thus increasing the cross section of interaction between the analyte molecules and optical fields, thereby increasing device sensitivity. In this arrangement the excitation field comes from underneath and enters the nanostructures at the base. This allows the emission to reach the discrete sensing areas effectively and provides ideal parameters for maximum Raman interactions. Using FDTD modelling methods the waveguide coupled SERS nanostructures were analysed and an optimum gold thickness was determined. The model investigates efficiency of coupling between the waveguide and surface plasmons, but also investigates spatial localisation around sharp features of the geometry. We also investigate temporal response of the system.

8264-39, Session 8

Compact optical microcavity structures for enhancement of absorption and transmission cross sections of subwavelength plasmonic devices

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Resonant subwavelength plasmonic apertures can efficiently concentrate light into deep subwavelength regions, and therefore significantly enhance the optical transmission through the apertures, or the absorption in the apertures. In addition, grating structures, consisting of periodic arrays of grooves patterned on the metal film on both sides of a metal aperture, are commonly used to enhance the coupling of incident light into the aperture through the excitation of surface plasmons. For efficient surface plasmon excitation, however, the period of the grating has to be equal to the surface plasmon wavelength, and several grating periods are required. Thus, such structures need to be several microns long. In this paper, we show that a compact submicron structure consisting of multiple optical microcavities on both the entrance and exit sides of a subwavelength plasmonic slit filled with an absorbing material can greatly enhance the absorption cross section of the slit. We show that such microcavity structures can increase both the coupling of incident light into the slit mode, as well as the resonant absorption enhancement in the slit by fine tuning the reflection coefficients at the two sides of the slit. An optimized submicron structure consisting of two microcavities on each of the entrance and exit sides of the slit leads to ~9.3 times absorption enhancement compared to an optimized slit without microcavities at the optical communication wavelength of 1.55 microns. Finally, we show that multiple microcavity structures can also be used to greatly enhance the coupling of free-space radiation into subwavelength plasmonic waveguides.

8264-41, Session 9

Optofluidic SERS on inkjet-fabricated paper-based substrates

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As a bio/chemical sensing technique, surface enhanced Raman spectroscopy (SERS) offers sensitivity comparable to that of fluorescence detection while providing highly specific information about the analyte. Although single molecule identification with SERS was demonstrated over a decade ago, today a need exists to develop practical solutions for point-of-sample and point-of-care SERS systems. In recent years, optofluidic SERS has emerged, in which microfluidic functions are integrated to improve the performance of SERS. Advancements in optofluidic SERS are leading towards portable analytical systems, but the devices are currently too expensive and too cumbersome for limited resource settings. Recently, we demonstrated the fabrication of SERS substrates by inkjet printing silver nanostructures onto paper. Using a low-cost commercial inkjet printer, we chemically patterned cellulose paper to form hydrophobic regions, which can control the aqueous sample on the paper microsystem. Additionally, we inkjet-printed silver nanoparticles with micro-scale precision to form SERS-active biosensors. Using these devices, we have been able to achieve detection limits comparable to conventional nanofabricated substrates. Furthermore, we leverage the fluidic properties to enhance the performance of the SERS devices while also enabling unprecedented ease of use. Paper dipsticks concentrate a relatively large sample volume into a small SERS-active detection region at the tip. Likewise, paper swabs collect samples from a large surface area and concentrate the collected molecules into a SERS sensor on the paper. We will summarize the progress in the fabrication and use of these paper-based optofluidic devices, and will describe their use in practical applications for point-of-sample detection.

8264-42, Session 9

Optofluidics: waveguides and devices

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Optofluidics merges optics with microfluidics in order to realize optical devices in which fluids act as an optical material. This approach enables an unprecedented level of integration, tunability and reconfigurability.

In this work we review recent results of our work on optofluidics. We show that single and multimode optofluidic waveguides with low loss can be realized using antiresonant reflecting optical confinement (ARROW). These waveguides can be fabricated using full standard silicon technology or hybrid silicon-polymer processes. ARROW waveguides have been used in order to realize complex optofluidic devices like Mach-Zehnder interferometers and ring resonators.

8264-43, Session 9

Vertically coupled polymer microresonators for optofluidic label-free biosensors

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Optofluidic label-free biochemical sensors integrating optical microresonators are highly attractive for real-time, high sensitivity detection of chemical or biochemical species. In this paper we report on the design and fabrication of polymeric microracetracks optical resonators for optofluidic label-free biosensing. In the domain of optical integrated devices, polymer materials offer the advantages of low cost, easy fabrication, low scattering loss on sidewalls of waveguides, and high coupling efficiency to optical fibres and waveguides. Moreover, for biochemical sensing, polymer surfaces can be easily modified to immobilize a wide choice of target molecules. Polymers are also well compatible with microfluidic circuits, facilitating the insertion of photonic circuits into optofluidic cells. The vertical coupling configuration, in which resonators are vertically coupled to the buried bus waveguide, presents several advantages in comparison with the lateral coupling configuration, particularly in the context of optofluidic biosensors. Polymeric microracetracks were fabricated using the SU-8 negative photoresist and the CYTOP fluorinated polymer, using a combination of a simple near UV lithography and reactive ion etching technology. Vertically coupled microracetracks immerged in deionized water display high Q-factors (> 35000) and finesse up to 25. Surface sensing experiments performed with these microresonators using TAMRA-cadaverine as a test molecule, which can be quantified through fluorescence and radioactivity analyses, demonstrated a very low detection limit of 0.22 attograms.

8264-44, Session 9

High Q silica microbubble resonators

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Microbubble resonators (MBRs) combine the unique properties of whispering gallery mode resonators with the intrinsic capability of integrated microfluidics. Here an improved fabrication method of microbubble resonators is presented, based on the heating of a slightly pressurized capillary by a rotating arc discharge. Rotation of the electrodes ensures an homogeneous distribution of the heat all over the capillary surface. The demonstrated microbubble resonators have Q factors up to 10^7 at 773 nm and around 10^8 at 1550 nm. For fabricating the MBR, we used a commercial silica capillary with an OD of about 280 µm and wall thickness of about 20 µm, the MBR has an OD of about 340 µm and a wall thickness of 4 µm ± 0.5 µm.

Microbubbles were filled with water and three different aqueous solutions of ethanol in order to test the refractive index (RI) sensing capabilities of such resonators, which also show a good temporal stability. We monitored the spectral resonance as the MBR was filled. When water fills the MBR, a red shift of about 2 GHz is observed. By fitting the resonance shift versus the change in RI, the RI sensitivity can be obtained. However, the limit of detection (LOD) of a sensor should also take into account the sensor resolution. The spectral shift can be located down to 1/100 of the fullwidth half maximum of the resonance mode with ease. Assuming that the resolution of our system is around 1/50, the LOD of our MBRs is about 10^-6 RIU.

8264-34, Poster Session

Waveguide grating couplers in low index materials

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Waveguide grating couplers permit efficient coupling to planar waveguides, complete with relaxed alignment tolerances and the possibility of wafer scale device testing without cleaving. To date, most solutions have been implemented as 1D gratings in high index contrast waveguides (typically SOI) with high coupling strengths and lateral mode converters. Here, we report the design and optimization of 1D grating couplers in waveguides with cores of relatively low index materials (n<1.8). Optimal basic parameters are derived from grating theory and confirmed with FDTD simulations scanning over etch depth and grating period. Several optimizations are tested, including top claddings, buried dielectric mirrors, and buried metal mirrors. More than 80% coupling efficiency to air is predicted for a uniform grating, 20 periods long, with a carefully placed buried metal reflector. Two-dimensional photonic crystal (PhC) and photonic quasicrystal (PhQC) designs are also investigated for the purposes of achieving both unidirectional (vertical) and polarization-insensitive coupling. The designs are intended for monolithic integration in polymeric planar lightwave circuits mass-produced by a roll-to-roll nanoimprint lithography process.

8264-45, Poster Session

Sensor for optical characteristics of liquid using gapped waveguides: theory

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A sensor for measurements of optical characteristics (a refractive index and absorption) of liquid has been theoretically investigated. We use a gapped single mode waveguide 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. Therefore, an optical loss of the gapped waveguide becomes greater as a gap width. In addition, the optical loss depends on the refractive index of the liquid in the gap as the light beam greatly expands in media with smaller refract index. In this work, we have derived an equation for evaluation of the optical losses by approximating the fundamental mode in the waveguide by a Gaussian function for the two-dimensional slab waveguide. And we clearly show the relationship between the optical loss and the refractive index of liquid filled into the gap for various gapped waveguides. We have also designed a saccharimeter for the liquid with Brix scale 0-20% by using the gapped waveguide. Optimum gap width for the a saccharimeter depends on the spot size of the fundamental mode in the waveguide. For example, the optimum gap widths are evaluated as 0.1 mm and 0.4 mm for the spot sizes of 0.01 mm and 0.005 mm, respectively.

8264-46, Poster Session

Design of multiple nano-ring based metallic nanophotonic superlens

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Subwavelength metallic nanoaperture based localization of surface plasmon (SP) has drawn enormous interests recently. In this study, we report the results of subwavelength nanoaperture-based SP localization applied to the development of metallic nanophotonic superlens for applications as high-resolution diffractive lenses and optical antennas. Subwavelength apertures consist of multiple nano-ring apertures: in particular, nanophotonic lenses investigated here were designed to have two nano-ring apertures for simplicity. The ring apertures were to have fixed 50 nm depth and 350 nm width on a BK7 glass plate (substrate) with adhesion layers. The internal diameter of an inner ring aperture was 1,600 nm. For TM-polarized light incidence at λ = 488 nm, electromagnetic near-fields were calculated as the distance between the two ring apertures (r) was varied. Focused light transmission was observed to occur for the range of r from 750 to 1,100 nm. The calculated maximum intensity, focal length, lateral full-width of half-maximum (FWHM), and axial FWHM of the obtained focal spots were, respectively, 5.74~5.98, 4,638~6.588 nm, 390~450 nm, and 2,485~2,825 nm. Focal length and lateral FWHM were found to increase proportionally with r. Afterward, at r = 950 nm, variations in the near-field properties were calculated in response to environmental changes such as refractive indices of metal, substrate, and ambience. The preliminary results suggest that the ring nanoapertures can act as nanophotonic lenses with optical characteristics optimized for specific applications.

8264-47, Poster Session

Integrated surface plasmon resonance array sensor using semiconductor optical amplifier

G. Oh, Chung-Ang Univ. (Korea, Republic of); D. Kim, Korea Photonics Technology Institute (Korea, Republic of); H. Kim, T. Lee, B. Lee, Y. Choi, Chung-Ang Univ. (Korea, Republic of)

The phenomenon of surface plasmon resonance (SPR) was first observed in an attenuated total reflection mirror devised by Kretschmann and Otto. These resonance characteristics have been employed as a real-time monitor of the surface interactions in a medium of interest. One of the most promising detection methods in biosensors, they are based on the detection of the SPR because this method allows one to monitor binding events in real-time without labeling. Different types of SPR sensors have been developed recently, which are comparable to or better than conventional SPR sensors in terms of sensitivity, compactness, and cost. Variable incident angles and broadband light sources for SPR sensors are required in order to increase the sensitivity. In this paper, we propose a novel SPR array sensor using wideband sources with a single fluidic channel. The SPR sensors are integrated with a semiconductor optical amplifier used to generate the broadband light source and are arrayed with different incident angles in order to increase the sensitivity. More detailed results will be presented.

8264-48, Poster Session

Experimental measurement of photonic/plasmonic crystal dispersion applied to the investigation of surface plasmon dispersion for SERS sensing applications

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In this paper we describe an experimental measurement procedure and automated system for analysis of angle dependent dispersion associated with dielectric photonic crystals or surface Plasmon polariton dispersion associated with nanostructured metallo-dielectric surfaces. This fully automated system utilizes a broadband spectroscopic reflectometry method to acquire polarization resolved data. Angular dispersion is mapped by illuminating a sample with a white light laser ranging from 450nm to 1800nm. A movable fiber probe then collects the reflected signal. Dips in reflectivity then correspond to partially coupled Bloch modes. The measurement system can also be used for analysis of waveguide grating couplers, mapping far field profiles of LEDs, mapping angular absorption properties of solar cells, and mapping far field diffraction patterns of diffractive structures.

The measurement system is then applied to the investigation of Plasmon dispersion of periodic arrays of metal coated inverted pyramids for applications as SERS sensors. Comparisons are then made to computational simulations derived by both 'Rigorous Coupled Wave Analysis' method, and 'Plane Wave Method'. Measured experimental dispersion patterns are found to closely match simulation in the exact frame of wavelength (400nm to 900nm).

8264-49, Poster Session

Nanowire coupled to a waveguide for the characterization of the guided light

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We show numerically and experimentally how a nanowire coupled with a waveguide can be used as a multipurpose tool for guided wave characterization. This tool has the advantage of being weakly perturbative and to give access to a local measurement of the field properties.

When put in the proximity of the waveguide, the nanowire scatters one part of the evanescent guided signal and this scattered light is a signature of the guided signal. The first way to retrieve the information from this scattered light is to analyze its angular variation (the shape of the radiation pattern). Practically it only requires to put one or several intensity detector in appropriate positions. The longitudinal variation gives access to information such as: propagation direction, polarization state or local depth of the waveguide. The transverse variation gives access to the transverse profile of the mode which allow to characterize the mode order (fundamental or higher order) and the local width of the waveguide. Another way to retrieve information from the scattered light is to collect it before sending it for further characterization: the wavelength or the polarization state can easily and precisely be characterized this way.

Compared to a situation where light has to first be decoupled from the waveguide, analyzed and then recoupled, we have the advantage of a very simple, practical and weakly perturbative characterization method. Moreover, in a situation where local properties of the guided signal varie, a serie of nanowire is able to characterize these local variations.

8264-50, Poster Session

Analysis of total internal reflection mirror based on horizontal slot waveguide

T. Lee, H. Kim, G. Oh, B. Lee, Chung-Ang Univ. (Korea, Republic of); D. Kim, Korea Photonics Technology Institute (Korea, Republic of); Y. Choi, Chung-Ang Univ. (Korea, Republic of)

Photonic devices based on slot waveguide structures are newly developed class that has received significant attention as a solution for guiding light in the low-index material within the nanometer range in recent years. They have been applied in a great variety of optical devices such as microring resonators, modulators, biosensors and optical devices for manipulation of nano-particles and DNA molecules. One of the important issues in the waveguide structure using microcavity is total internal reflection (TIR) mirror because it can influence the performance of photonic device in a significant way. Recently, the bending efficiency of vertical slot waveguide with different structure has been analyzed. However, the interface roughness of the waveguide which have high E-field intensity induces to high scattering loss. In addition, a vertical slot fabrication involves in a very narrow region etching which can cause large roughness in the vertical interfaces.

In order to reduce the propagation loss and facilitate the fabrication process, horizontal slot waveguides have been proposed and fabricated, recently. In this paper, we have designed and analyzed TIR mirror for using a resonator based on horizontal slot waveguide. Our proposed structure is consisted horizontal slot waveguide of rib type to enlarge contact region with TIR mirror. To analyze Goos-Hänchen shift, we have theoretically calculated length of evanescent field at TIR mirror using 3D-FDTD method. The presented TIR mirror loss analysis can be applied to enhance the efficiency of horizontal slot waveguide resonator which can potentially be used in many silicon based optoelectronic devices.

8264-51, Poster Session

Visible and near infrared wavelength photonic crystal fiber splitter for multi wavelength spectral domain optical coherence tomography

J. B. Eom, Korea Photonics Technology Institute (Korea, Republic of); E. J. Min, B. Lee, Gwangju Institute of Science and Technology (Korea, Republic of)

We report the fabrication and performance of the 2×2 photonic crystal fiber (PCF) splitter that was designed as a single mode splitter at the visible and near infrared and used as the beam splitter for a spectral domain optical coherence tomography (SD-OCT) system. The PCF splitter has been made by coupling PCFs to a planar lightwave circuit (PLC) splitter chip. The PLC splitter chip was fabricated to have a single mode property with 630 nm cutoff wavelength and the PCFs were securely connected to the PLC chip through PCF block arrays having lithographically fabricated V grooves. The core width of the splitter chip was about 3 μm×3 μm and the core-cladding index difference was about 0.25 %. With the implemented PCF PLC splitter, we have obtained a low excess loss of 1.2 dB and a low polarization-dependent loss of 0.19 dB at 680 nm with wide band coupling property. With the proposed 2×2 PCF splitter, SD-OCT images of human finger, nail, and tooth successfully obtained by using 680 nm, 840 nm, and 930 nm SLD source. This PCF PLC splitter is expected to have high resolution OCT and optical coherence microscopy (OCM) by using supercontinnum source and wide band spectrometer.

8264-52, Poster Session

Polarization-dependent phase modulators incorporating low loss birefringent polymers

J. Kim, S. Park, B. Cheon, K. Kim, W. Chu, M. Oh, Pusan National Univ. (Korea, Republic of)

Optical phase modulators to control the amount of phase delay depending on its polarization are an important device for polarization management of guide waves. Ordinary phase modulators based on thermo-optic (TO) effect has negligible polarization dependence. However, if the phase modulator could control the phase of the light depending on its polarization, the device would be useful for various polarization controlling devices. By incorporating a novel low-loss birefringent polymer, we demonstrate the phase modulator with significant polarization dependence for TE and TM polarizations. To find the TO coefficient for each polarization, Mach-Zehnder modulator device was prepared. The change of effective refractive index was calculated from the measured amount of phase shift in the MZ modulator. The TO coefficient for effective index became -1.257 × 10-4 and -1.395 × 10-4 for TE and TM mode, respectively. The difference of TO coefficient was 0.137 × 10-4 compared to that of ordinary TO phase modulator, 0.066 × 10-4. By incorporating polarizer-analyzer configuration, we measured the efficiency of polarization conversion from a straight waveguide. Input polarizer was adjusted to 45° for exciting both TE and TM polarizations. Depending on the difference of phase delay between the two polarizations, output polarization was modulated. For an electric power of 130 mW applied on the micro heater, 2π phase retardation between TE/TM modes was obtained. Insertion losses of the polarization-dependent phase modulator were 2.74 dB and 1.95 dB for TE/TM mode, respectively. By using a polarization analyzer, the output polarization state was traced on a Poincare sphere in order to verify the output polarization is continuously variable as a function of applied heating power.

8264-53, Poster Session

Near infrared external cavity tunable laser based on polymer waveguide Bragg grating

N. Son, K. Kim, J. Kim, M. Oh, Pusan National Univ. (Korea, Republic of)

External cavity lasers operating at near infrared (NIR) wavelength is demonstrated by incorporating polymer waveguide Bragg reflectors. 3rd-order Bragg grating and oversized rip waveguide structure were designed by using the effective index method and the transmission matrix method. To facilitate fabrication of grating, a 3rd-order grating structure is incorporated on the polymer waveguide with an oversized rib structure. The polymer waveguide is fabricated using low-loss fluorinated polymer materials with refractive indices of 1.462 and 1.435 for the core and the cladding layers, respectively. The external feedback laser with 875-nm Bragg grating exhibits single mode lasing located at 850-nm wavelength with an output power of 0 dBm, a 20-dB bandwidth of 0.2 nm, and a side mode suppression ratio of 40 dB. The superior thermo-optic effect of the polymer waveguide enabled direct tuning of the Bragg reflection wavelength by applying the electrical power on a micro-heater. The output wavelength was tuned from 852.26 nm to 834.26 nm with wavelength steps of 0.4 nm for an applied electrical power of 2 W.

8264-54, Poster Session

Evaluation of damping ratio in a glass-based guided-wave optical microphone with a diaphragm

M. Ohkawa, K. Murata, T. Sato, Niigata Univ. (Japan)

In clinical Magnetic Resonance Imaging (MRI) and functional MRI (fMRI), microphones are useful tools for communication between patient and physician. Microphones using lightwave sensing technology are available even in high magnetic fields like the MRI, because the microphones are not susceptible to electromagnetic interference. So, our group has demonstrated silicon-based and glass-based guided-wave optical microphones, consisting of a diaphragm and a waveguide across the diaphragm.

Incidentally, in microphones, frequency response is one of important specifications. Damping of the vibration plate is very significant to avoid strong resonance. In this study, we experimentally examined the damping ratio for a glass-based optical microphone with no damping structure, before considering realization of the proper damping of which the damping ratio is 0.707.

A guided-wave optical microphone with a diaphragm of 20 mm X 20 mm X 0.15 mm was fabricated using two glass substrates: a Corning #0211 glass as a diaphragm plate and a soda-lime glass with a 20 mm X 20 mm square hole as a support structure of the diaphragm. The damping ratio of the fabricated microphone was evaluated both from the frequency response and from the step response. In the frequency response, the damping ratio was determined to be 0.009 from the resonance characteristic around the first resonance frequency. Also, in the step response, the damping ratio was evaluated to be 0.009 from the transient output after the applied acoustic sound is turned off. The reasonable damping ratios were successfully obtained from both the frequency and time domain measurements.

8264-55, Poster Session

Waveguide polarization converters incorporating UV-curable reactive mesogen

W. Chu, S. Kim, J. Kim, K. Kim, M. Oh, Pusan National Univ. (Korea, Republic of)

Photonic devices used for precise management of light polarization have been gradually diversified to provide technical solutions for various applications such as coherent optical communications, polarization-sensitive coherent tomography, and optical sensors detecting polarization changes. As a crucial device for the polarization control, integrated optical polarization converters have been widely investigated. A free-standing optical wave-plate film consisting of Reactive mesogen (RM) and low-loss optical polymers was fabricated in this work, and the film was inserted across the polymer waveguide to form an integrated optical polarization converter. RM is an organic liquid crystal molecule that can be self-aligned to have an optic axis of birefringence when coated over a polyimide alignment film. For convenient evaluation of the polarization converters, waveguide polarizer and analyzer were fabricated in series with the converter. The polarization conversion efficiency was measured to be 25 dB for the wavelength range from 1520 to 1580 nm. The waveplate film had a thickness of 14 µm, and it induced an additional insertion loss of 0.3 dB when by the film insertion across the polymer waveguide. In the temperature dependence measurement, the device exhibited phase retardation change of 4.7° for a temperature change from 25 to 100 °C, which corresponded to a birefringence change of 2.6%.

8264-56, Poster Session

Polymer waveguide integrated-optic current transducers

M. Oh, W. Chu, K. Kim, J. Kim, Pusan National Univ. (Korea, Republic of)

Optical current sensors are indispensable devices for the accurate monitoring of large electrical currents in environments suffering from severe electromagnetic interference. In this work, various functional optical devices are integrated on a single chip in order to construct optical current sensors 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 individual device characteristics affecting final sensor performance are optimized through the analysis of the final output signal as a function of various input polarization states. The phase difference between the two circularly polarized waves imposed by the Faraday effect of the optical fiber is detected using the polymeric integrated optical chip. In the experiment of electrical current measurement, the optical signal exactly followed the 4 kA, 60 Hz sinusoidal waveform source current. The polarization dependent output response phase modulation current sensor module incorporating the integrated-optic device to measure the optical phase retardation exhibited good linearity with deviation less than 0.2%. The integrated-optic device provides inherent polarization maintaining characteristics and precise controllability of the optical path length in the interferometric sensor. Single chip integration reduces the complexity of the interferometry, and enables mass-production of low-cost high performance current sensors.

8264-57, Poster Session

Colorimetric resonant detection of biochemical agents in mesoporous silicon based photonic crystals

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A colorimetric resonant mesoporous silicon photonic crystal is used as a surface binding platform for biochemical detection. Periodic porous silicon (P-Si) structures were fabricated by electrochemical etching of p-type Si(100) wafers in 21% ethanol solution of fluoric acid by periodical modulation of the current density of 40 mA/cm2 (low porosity) and of 200 mA/cm2 (high porosity). The layers were formed parallel to the surface of the silicon plate with pores of about 30 and 50 nm in diameter in layers of low and high porosity, respectively. We studied P-Si based microcavities (MC), composed by two Bragg mirrors separated by $\lambda/2$ thick MC layer of high porosity, where λ is the central wavelength of the MC mode. Both Bragg mirrors are composed of 20 layers with alternating porosity and of the optical thickness of $\lambda/4$. After the fabrication, some samples were annealed in an oven at 400 °C for 20 min in order to partially oxidize the P-Si structure and thus increase their wetability.

We have tested annealed and non-annealed samples as refractometers by measuring the reflectivity spectra using a white light source at normal incidence. We have optically verified the presence of proteins and chemicals as a shift in the reflectivity spectrum of P-Si PC and MC. These effects were perfectly reversible and reproducible.

8264-59, Poster Session

Nano sensor technology based on semiconductor nanocrystals

T. Otto, J. Martin, Fraunhofer-Institut für Elektronische Nanosysteme (Germany); U. Staudinger, E. Demir, P. Pötschke, B. Voit, Leibniz-Institut für Polymerforschung Dresdene e.V. (Germany); T. Gessner, Fraunhofer-Institut für Elektronische Nanosysteme (Germany)

Advancing use of light weight structures, e.g. in automotive or aircraft engineering, makes structural health monitoring an important issue. However, common used networks of discrete sensor nodes are expensive, difficult to integrate and questionable concerning reliability. We present a new concept of material integrated sensor technology for detection, storage and

visualization of mechanical stress and load conditions. Key feature is a double layer consisting of a piezoelectric layer and a semiconductor nanocrystal polymer composite film. Electrical charges are generated within the piezo layer by application of a mechanical load to the structure. The charges are transferred to the composite film and injected into the nanocrystals, causing non-radiative exciton recombination. This results in photoluminescence quenching, which can be detected as local optical contrast. We have investigated the influence of various charge transport materials, among them N,N′-Bis(3-methylphenyl)-N,N′-diphenylbenzidine (TPD) and carbon nanotubes (CNT) composites, on charge injection and storage properties. Thin transparent layers of CNT composites consisting of a polycarbonate matrix and 2 wt.-% multi-walled nanotubes have been produced by solution casting. These films exhibited low surface resistivity values of about 1e5 Ohm/sq whereas non-transparent thin films of PMMA with 2 wt.-% multi-walled CNTs even demonstrated resistivity values of only about 1e3 Ohm/sq. The photoluminescence of CdSe/ZnS core/shell quantum dots has been switched off by application of external voltages smaller than 20 V. It was possible to store the charges in the QDs, and hence the offstate, for several hours. Optical contrast ratios up to 1:125 have been detected so far.

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8265-01, Session 1

Requirements for optical interconnect and networking devices for low-energy communications within digital systems

A. L. Lentine, Sandia National Labs. (United States)

Information and communications technology (ICT) consumes 10% of the nation's electricity, with data centers comprising a 25% of the total. Interconnections between switching and routing equipment, between integrated circuits on a printed circuit board (PCB), and within integrated circuits are becoming a growing fraction of the total power consumption. The use of optical modules for interconnection between electronic sub-assemblies is increasing, but the approach will not scale as bandwidth needs increase.

Intimate integration of optics and electronics will be required for power consumption to decrease significantly over today's optical interconnect solutions. These future solutions are likely to require single mode operation to reduce receiver complexity and power dissipation, and dense wavelength division multiplexing to enable increased bandwidth density and waveguide technology to facilitate packaging in a manner compatible with today's electronic circuit boards.

Silicon photonics is well known to be a candidate for satisfying the requirements for these future systems. We will review the applicable devices and their requirements to enable reduced energy consumption in these systems. In particular, we will discuss the advantages and disadvantages of connecting processing or switching and routing subsystems with optical networks versus optical interconnections of electronic networks.

8265-02, Session 1

Multicore fiber link demonstrating large bandwidth density for future multimode optical interconnects

B. G. Lee, C. Baks, F. E. Doany, D. M. Kuchta, P. K. Pepeljugoski, C. L. Schow, IBM Thomas J. Watson Research Ctr. (United States)

Optical interconnects are now prevalent in high-performance computing (HPC) systems. Their superior bandwidth-distance product compared to electrical interconnects has been leveraged to facilitate performance scaling within the most aggressive machines in recent years. However, optical fiber systems in future HPC generations must meet growing bandwidth requirements, while maintaining feasible power and cost targets in addition to maintaining manageable volumes of fiber cabling. As a result, increasing bandwidth per fiber while only marginally increasing link cost and power is a primary goal for future optical interconnects. This presentation will describe recent results in multicore multimode fiber technologies, which may provide the added bandwidth per link required in next generation HPC systems.

A transmitter and receiver have been developed to interface to a seven-core graded-index multimode fiber constructed by OFS. The transmitter consists of a flip-chip packaged assembly with 130-nm CMOS driver ICs and custom VCSEL arrays (fabricated by Emcore Corporation) arranged to interface the multicore fiber. A silicon carrier with optical vias allows optical access to the VCSEL devices. The receiver consists of two wire-bond integrated 4-channel transimpedance amplifier ICs and a six-channel photodiode array (again fabricated by Emcore Corporation) to interface the multicore fiber. Aggregate data transmission of 120 Gb/s per fiber was realized. Bit-error rate measurements characterizing the amplitude and timing margins are performed to analyze the crosstalk experienced by the multiple channels within the link.

8267-30, Session 1

Optics in computers, servers, and data centers

H. J. S. Dorren, Technische Univ. Eindhoven (Netherlands)

No abstract available

8267-31, Session 1

Chip-scale integrated optical interconnects: a key enabler for future high-performance computing

M. W. Haney, Univ. of Delaware (United States)

Integrated Optical Interconnect (OI) technology is poised to provide the ultra-high chip-level bandwidths needed within future high performance computing (HPC) systems. Integrated OI will enable HPC to scale to the 50 GFLOPS/W level - far beyond the projected performance of HPC systems based on conventional metal trace-based interconnect fabrics. Emerging Si-photonics-based and hybrid III-V OI platforms are projected to enable this unprecedented HPC throughput scaling by providing channel densities that are higher, and link power requirements that are lower, than those provided by electrical interconnects. However, before the full benefits of integrated OI may be realized, efficient and cost-effective packaging must be developed that provides the desired "seamless" integrated OI fabric at the inter- and intra-chip levels, yet is compatible with conventional chip/package/board integration technology. Si-photonics, with its integrated single-mode waveguides fabrics, is projected to provide superior interconnect bandwidth densities, while hybrid multi-mode waveguide-based OI platforms may provide easier interfacing and packaging. But what platform will best enable Si-CMOS performance to scale to its full potential as the Silicon technology node approaches its ultimate limit? In this paper, the performance scaling benefits of chip-scale OI are reviewed and packaging/interface issues are discussed to highlight key remaining challenges to the high-impact deployment of integrated OI in future HPC systems.

8265-03, Session 2

Silicon photonics in computing applications

M. Watts, Massachusetts Institute of Technology (United States)

The continued Moore's Law scaling of microelectronics is driving not only compute power and storage, but the communications links required to feed the growing information capacity. The growth in information content is straining wireless networks, the wavelength division multiplexed (WDM) communications on telecom links, communications within the data centers that power the Internet and increasingly the processor-to-memory communication subsystems within personal computers. The exponential growth of Moore's Law scaling is sufficiently intense that even short reach electrical communication links to peripheral devices will be outstripped in the near future. Ultimately, it is conceivable that even on-chip electrical communications will need to be replaced with optical links.

With the demonstration of high-speed and low-power silicon modulators and germanium detectors, along with flattop filters on CMOS lines around the world, silicon photonics has emerged as a potential solution to each of these communication bottlenecks. Yet, despite these developments significant challenges remain. To date, no consensus exists for integration with CMOS nor has a WDM source to power these chips been clearly identified. Moreover, only a handful of devices have been effectively integrated together and cost-effective packaging solutions are years away. For silicon photonics to be widely adopted these and other challenges will need to be addressed. Here, we review recent results in silicon photonics and compare options for the addressing some of the remaining challenges.

8265-04, Session 2

Multiprocessor silicon photonic interconnects: a systems perspective

P. Koka, Oracle Labs. (United States)

The high bandwidth density and low power consumption characteristics of silicon photonics devices can provide a high performance interconnect solution for multiprocessor systems. At the same time his

technology also poses a new set of constraints and challenges in architecting, designing, and integrating such systems.

The 'macrochip' multiprocessor architecture leverages a photonically interconnected array of processor and/or memory chips to provide a flexible platform to build heterogeneous systems. The design considerations for such a system are influenced largely by the system architecture, the programming model and devices needed for their implementation. This talk will first describe the macrochip platform, technology constraints and potential interconnect solutions with the various device building blocks. Then it will present some topology choices that range from a WDM point-to-point interconnect to more complex switched data channel networks. It will close with a detailed analysis of these design choices and show the impact of the device constraints on performance and power consumption along with some recent ultra-low power device implementation results.

8267-32, Session 2

Chip-scale photonic interconnection networks for energy efficient processor-memory communications

K. Bergman, Columbia Univ. (United States)

No abstract available

8267-33, Session 2

Low-power integration of on-chip nanophotonic interconnect for high-performance opto-electrical IC

D. Ding, D. Z. Pan, The Univ. of Texas at Austin (United States)

No abstract available

8265-05, Session 3

Advanced silicon device technologies for optical interconnects

L. Wosinski, Royal Institute of Technology (Sweden); Z. Wang, Univ. Gent (Belgium); F. Lou, Royal Institute of Technology (Sweden); D. Dai, Zhejiang Univ. (China); S. Lourdudoss, L. Thylen, Royal Institute of Technology (Sweden)

Silicon photonics is an emerging technology offering novel solutions in different areas requiring highly integrated communication systems for optical networking, sensing, bio-applications and computer interconnects. Silicon photonics-based communication has many advantages over electric wires for multiprocessor and multicore macro-chip architectures including high bandwidth data transmission, high speed and low power consumption. Following the INTEL's concept to "siliconize" photonics, silicon device technologies should be able to solve the fabrication problems for six main building blocks for realization of optical interconnects: light generation, guiding of light including wavelength selectivity, light modulation for signal encoding, detection, low cost assembly including optical connecting of the devices to the real world and finally the electronic control systems.
In this talk we will present our technology approaches and different solutions for these building blocks. Our passive devices are based on Si nanowire waveguides fabricated using our optimized amorphous silicon technology as well as commercially available SOI wafers. We have realized a number of wavelength selective devices such as ultra-compact arrayed waveguide gratings and etched diffraction gratings. For active components we develop a novel technology for monolithic integration of InP on Si through nano-epitaxial lateral overgrowth. For in/out-coupling of light we developed high-efficiency nonuniform gratings as well as grating couplers that include polarization splitting function. Finally for future applications we develop sub-wavelength light confining structures based on surface plasmon waveguiding. In these structures light is guided at the metal-dielectric interfaces, which causes high propagation losses. Our research is concerned with finding solutions with tractable losses and retained confinement.

8265-06, Session 3

Recent advances in manufactured silicon photonics integrated circuits

D. Feng, B. J. Luff, M. Asghari, Kotura, Inc. (United States)

The need for low-energy high bandwidth optical solutions is driving the acceptance of silicon photonics as the platform of choice to address connectivity bottlenecks. Kotura has focused on the development of a manufacturable silicon photonic platform to demonstrate the practical realization of this technology. In this talk, we will review the progress in the development of key photonics components such as splitters, filters, wavelength division multiplexers, variable optical attenuators, GeSi modulators, Ge photodetectors, and mode transformers for low-loss fiber interfacing. In addition, we will also review recent advances in monolithic and hybrid integration of the key building blocks to form high-performance manufacturable photonic integrated circuits such as variable (de)multiplexers, coherent receivers and transceivers for 100G and beyond.

8265-07, Session 4

Silicon-based nonlinear photonics

A. L. Gaeta, Cornell Univ. (United States)

We show that the silicon-based platform offers a number of key advantages to developing nonlinear optical devices that can operate with very low powers and over ultrabroad bandwidths. Such devices can be used to generate new frequencies from the visible to mid-infrared regimes.

8265-08, Session 4

Advanced integration, processing, and interconnection technologies for high-energy conversion efficiency crystalline silicon solar cells

L. A. Eldada, SunEdison (United States)

We describe advanced integration architectures, processing technologies and interconnection schemes for the production of high energy conversion efficiency crystalline silicon solar cells.

8265-21, Poster Session

Micro-integrated, high power, narrow linewidth diode lasers for precision quantum optics experiments in space

A. Wicht, Ferdinand-Braun-Institut (Germany) and Humboldt-Univ. zu Berlin (Germany); E. Luvsandamdin, A. Kohfeldt, Ferdinand-Braun-Institut (Germany); M. Schiemangk, Humboldt-Univ. zu Berlin (Germany); S. Spiessberger, A. Sahm, F. Bugge, J. Fricke, H. Wenzel, Ferdinand-Braun-Institut (Germany); A. Peters, Humboldt-Univ. zu Berlin (Germany) and Ferdinand-Braun-Institut, Leibniz Institut für Höchstfrequenztechnik (Germany); G. Erbert, G. Tränkle, Ferdinand-Braun-Institut (Germany)

Quantum optical sensors start to play a role in various fields like fundamental physics, inertial navigation, geophysics, and precision time keeping. Their ultimate sensitivity is reached in space. These applications hence require high power, narrow linewidth lasers that emit at specific wavelengths and that are compact and robust, lightweight, and energy efficient.

Here we present Master Oscillator Power Amplifier (MOPA) and Extended Cavity Diode Lasers (ECDLs) currently being developed for atom interferometry experiments on ultra-cold Rubidium atoms (780.24 nm) to be carried out onboard a sounding rocket in 2013.

The laser systems are based on a micro-integration technology that integrates laser chips, lenses, optical isolators, temperature sensors, and micro-Peltier elements on an AlN micro-optical bench with a footprint of only 10 x 50 mm2. The total weight is as low as 5 grams.

The MOPAs are based on a discrete combination of a DFB master oscillator and a ridge-waveguide tapered amplifier chip. The MOPA provides an output power in excess of 1 W with a FWHM linewidth of 1 MHz (10 µs) and an intrinsic linewidth of 100 kHz. It can be tuned by >1 nm. The system has successfully passed vibration tests that simulate the mechanical load of a sounding rocket launch.

The ECDL provides an output power in excess of 100 mW with a FWHM linewidth (10 µs) of less than 60 kHz and an intrinsic linewidth of less than 3.6 kHz. It can be tuned by more than 100 GHz.

8265-22, Poster Session

Integration of 3D plasmonic devices with silicon-on-insulator-based optical circuitry

R. Yang, Z. Lu, Rochester Institute of Technology (United States)

To exploit the attractive features of subwavelength plasmonics, efficient coupling methods to convert optical power to plasmon waves have been extensively explored. Other than the conventional momentum matching technique such as prism or grating coupling, the direct coupling scheme has proved to be both compact and broadband. MIM waveguides have the virtue of ultra-small, strictly-confined mode size and acceptable propagation loss, plus the metal layers provide a feasible interface for novel electrical pumping channels. More importantly, numerical simulations have predicted up to 70% coupling efficiency when 1550-nm light is coupled from a 300-nm wide dielectric waveguide into a 50-nm silver-air-silver plasmonic waveguide. Conventionally, the MIM slots are vertically orientated and therefore difficult to engineer their depths to achieve further plasmonic mode transformation. On the other hand, laterally patterned gap waveguides can eliminate the existence of multimode propagation and focus plasmonic beam to subwavelength regime.

In this paper, we report a compact plasmonic coupler based on direct coupling method onto a silicon-on-insulator substrate. Taper-assisted mode transformation via adiabatic approach will then be applied to achieve a single-mode plasmonic propagation confined in a deep-subwavelength dielectric core. It is the first demonstration on silicon-based optical circuitry to accomplish sub-100-nm MIM confinement in both transverse directions for 1550-nm light. The plasmonic junction converts photons to surface plasmons and then back to photons with 7.35 dB conversion loss, and has successfully focused multimode plasmonic propagation to deep subwavelength (80 nm by 50 nm) single mode propagation with 2.28 dB/µm propagation loss.

8265-23, Poster Session

Integrated Si/III-V racetrack lasers, photodetectors, and waveguide-to-fiber surface grating couplers

A. Descos, B. Ben Bakir, N. Olivier, J. Fedeli, B. André, CEA-LETI (France)

Recently, we demonstrated for the first time high-temperature, high-power, continuous-wave operation of hybrid Fabry-Pérot lasers based on adiabatic mode transformers. The hybrid structure is formed by two vertically superimposed waveguides separated by a 100nm-thick SiO2 layer. The top waveguide, fabricated in an InP/InGaAsP-based heterostructure, serves to provide optical gain, and the bottom Si-waveguides system, which supports all optical functions, is constituted by two tapered rib-waveguides (mode transformers), two distributed Bragg reflectors (DBR), and a surface-grating coupler. The supermodes of this hybrid structure are controlled by an appropriate design of the tapers located at the edges of the gain region. In the middle part of the devices, almost all the field resides in the III-V waveguide so that the optical mode experiences maximal gain, while in regions near the III-V facets, mode transformers ensure an efficient transfer of the power flow towards Si-waveguides.

To demonstrate how this approach can be declined in various designs, we realized, on the same chip, hybrid racetrack lasers and photodetectors. The III-V heterostructure and the coupling scheme are the same employed in the Fabry-Pérot laser cavity; the only difference being that the pair of DBRs defining the cavity is now replaced by a Si-racetrack. The laser structure consists of a hybrid racetrack ring resonator with a directional coupler formed at the opposite side of a 550 µm-long III-V waveguide. The racetrack ring radius is 80 µm. The directional coupler length and gap are 370 µm and 0.8 µm, respectively. A photodetector and a waveguide-to-fiber surface grating coupler are located at both ends of the directional coupler to collect light from the clockwise and counterclockwise propagating laser modes. The laser threshold is around 30 mA with a maximum fiber-coupled power of 2.8 mW.

8265-09, Session 5

Scaling CMOS photonics transceivers beyond 100 Gb/s

A. Mekis, S. Abdalla, P. M. De Dobbelaere, D. Foltz, S. Gloeckner, S. Hovey, S. Jackson, Y. Liang, M. Mack, G. Masini, R. Novais, M. Peterson, T. Pinguet, S. Sahni, J. Schramm, M. Sharp, D. Song, B. P. Welch, K. Yokoyama, S. Yu, Luxtera (United States)

We report on the performance of an integrated four-channel parallel optical transceiver built in a CMOS photonics process, operating at 14 Gb/s per channel. The optical engine of the transceiver comprises is a single silicon die and a hybrid integrated DFB laser. The silicon die contains the functionality of an optical transceiver: the transmitter and receiver optics, the electrical driver, receiver and control circuits. We also describe the CMOS photonics platform, which consists of an optically enabled CMOS process, a photonic device library, and a design infrastructure that is modeled after standard circuit design tools. We discuss how this platform can scale beyond 25 Gb/s per channel speeds and to much higher channel counts.

8265-10, Session 5

Photonic integrated system-in-package platform for Tb/s silicon-plasmonic router

T. Tekin, Technische Univ. Berlin (Germany); A. Suna, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); O. Gili de Villasante, P. Tcheg, Technische Univ. Berlin (Germany); B. Wang, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); S. Lutzmann, B. Bouhlal, Technische Univ. Berlin (Germany); N. Pleros, E. Kriezis, Aristotle Univ. of Thessaloniki (Greece); M. Baus, M. Karl, AMO GmbH (Germany)

In today's Peta-flop High-Performance Computing (HPC) machines the size and power consumption appear to be daunting issues, signifying that new technological and architectural considerations will be required in order to be able to move towards Exascale-computing powers. Whereas silicon photonics emerges as a powerful technology for low-loss and high bandwidth optical connectivity in integrated circuit environments, servers and network switches are already consolidating into high-density blade enclosures in order to reduce space and cooling requirements. These determine new tasks for switching infrastructures of miniature data networks: the next generation of routing circuitry has to provide high throughput capabilities while keeping in line with the requirements of small foot-print, low power consumption and low latency. Next generation computing architectures are needed with ultra low power consumption; ultra high performance with novel photonic interconnection technologies. The objective of the recently proposed high bandwidth Photonics Interconnection Layer for Converged Microsystems using System-in-Package Technology, namely PICSiP, is to develop a CMOS compatible underlying technology to enable next generation optical computing architectures.

In this work, we present a silicon photonics based integrated system-in-package platform (PICSiP) for Tb/s router application. As routing platform employ three different technologies: silicon photonics, plasmonics and electronics. Compatibility between various components has to be ensured to allow for their seamless interfacing and interoperability. The 4x4 router architecture exploits a SOI platform employing 340x400nm2 waveguide structures and hosting four 7:1 SOI multiplexing circuits, four photodiodes, an electronic IC control circuit and the 4x4 dielectric-loaded surface plasmon-polariton (DLSPP)-based switching matrix.

8265-11, Session 5

Chip-scale demonstration of 3D integrated intrachip free-space optical interconnect

H. Wu, B. Ciftcioglu, R. Berman, J. Hu, S. Wang, I. Savidis, M. Jain, D. Moore, M. Huang, E. Friedman, G. Wicks, Univ. of Rochester (United States)

This paper presents the first chip-scale demonstration of a novel intra-chip optical interconnect system based on free-space optics. This system provides point-to-point links between each laser-photodetector pair to construct an all-to-all intra-chip communication network, significantly improving the performance of future high performance many-core microprocessors. Unlike other electrical and waveguide-based optical packet-switching networks, this intra-chip free-space optical interconnect system exhibits low latency, low energy consumption, low loss and no bandwidth degradation regardless of the topological distance. A 1x1-cm2 chip prototype is fabricated on a germanium substrate with integrated photodetectors (PD), commercial 850-nm vertical-cavity-surfaceemitting-lasers (VCSEL), and fabricated micro-lenses. The germanium PDs are of the metal-semiconductor-metal structure with an amorphous-silicon barrier enhancement and surface passivation layer, which mitigates large dark current and improves bandwidth. The micro-lenses are built on a fused silica substrate via melting and reflowing photoresist on the substrate, and subsequently dry-etching into the substrate. The whole 3-D stack is integrated by placing the commercial VCSEL into a groove etched into the carrier substrate, bonding a glass spacer layer to facilitate the wirebonding from the VCSEL to the carrier chip, and aligning the micro-lenses on the fused silica chip onto the both PDs and VCSELs on the carrier chip at the same time. The prototype achieves 4-dB transmission loss and less than -20-dB crosstalk with a 3.3-GHz small signal bandwidth at 1-cm distance.

8265-12, Session 5

Low-loss photonic wires defined by LOCal Oxidation of Silicon (LOCOS)

Y. Xiong, W. N. Ye, Carleton Univ. (Canada)

Low loss silicon-on-insulator (SOI) photonic wires are key building blocks for on-chip silicon photonic circuits. We demonstrate low loss photonic wires, in both the straight and bent waveguide configurations, fabricated by the LOCal Oxidation of Silicon (LOCOS) process, in which a protective stack consisting of a thin thermal pad oxide layer overlaid by a thicker silicon nitride is used to mask the waveguides during the growth of the field oxide. A shallow etch step to the silicon layer facilitates the vertical sidewall formation of the photonic wire. The oxidation in the LOCOS produces ultra-smooth sidewalls with the expected width variation of ±0.3 nm. The starting SOI wafer has a 260 nm thick Si layer. The process flow simulations using SUPREM-4 first predict a trapezoidal-shaped cross-sectional profile of the waveguide, which in turn determines the final geometrical dimensions required for a single-mode operation at the 1550 nm wavelength. Our simulation results show that a waveguide that is patterned with a mask width of 600 nm supports only the fundamental quasi-TE (x-polarized) mode. In this case, the waveguide has a trapezoidal shape with a height of 136 nm and an FWHM of 654 nm. The minimum requirement for the bending radius is 7 um in order to achieve a negligible bending loss of 0.2 dB/cm. Our experiments demonstrate the formation of the straight and bent waveguides using the LOCOS process. We also present the measurement data to compare to our simulated results.

8265-13, Session 6

Nanophotonics for datacom and telecom applications

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Semiconductor optical amplifiers based on quantum dots show small-signal cross-gain modulation bandwidths exceeding 40 GHz. In large signal operation wavelength conversion at 80 Gb/s over 10 nm is presented. Two section mode-locked lasers at 40 GHz yield ultra-low jitter of 200 fs in hybrid operation. Optical feedback presents an alternative way to effectively reduce the jitter and opens up the possibility to extract a microwave signal, having the same properties as the optical pulse comb, from the absorber section.

8265-14, Session 6

Rolled-up InAs/InGaAsP quantum dot microtube lasers

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Rolled-up quantum dot micro- and nano-scale tubes have emerged as a highly promising candidate for nanoscale lasers and coherent light sources for applications in integrated nanophotonics. They are formed when coherently strained semiconductor bilayers with incorporated self-organized quantum dot heterostructures are selectively released from the host substrates, due to the relaxation of strain. In this context, we have performed a detailed investigation of the fabrication and characterization of InAs/InGaAsP quantum dot tubes and demonstrated, for the first time, rolled-up quantum dot tube lasers with emission wavelengths at ~ 1.5 µm. In this experiment, pseudomorphic InAs/InGaAsP quantum dot heterostructures are grown on InP substrates by chemical beam epitaxy, and the tubular optical cavity is formed by selectively etching the underlying InP layer. The resulting quantum dot tubes exhibit diameters of ~ 5 µm and wall thicknesses of 50 nm, or larger. Three-dimensional optical confinement is achieved by fabricating free-standing quantum dot tubes and by introducing parabolic corrugations on the tube surface in a single photolithograph step. Such devices exhibit strong coherent emission in the spectral range of ~ 1.55 µm. We have further demonstrated optically-pumped InAs/InGaAsP quantum dot tube lasers, which exhibit an ultralow threshold of ~ 1.5 µW at 80K. Work is currently in progress to demonstrate high performance 1.55 µm quantum dot tube lasers at room temperature and to develop electrically injected nanoscale quantum dot tube lasers by using a p-i-n lateral injection scheme.

8265-15, Session 6

Identification of localized group-velocity dispersion of nanostructured silicon waveguide devices using white-light interferometry

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Recently nanostructured silicon waveguide devices (NSWDs), such as nano-scale strip or channel waveguides, slot waveguides, and photonic crystal waveguides(PhCWs), have attracted a significant interest because of their potential applications to nonlinear-optic functional devices. Very strong light confinement within their sub-micrometer or nanometer-size waveguide structures is proven to be very effective for the third-order nonlinear applications such as four-wave-mixing, third-order harmonic generation, self-phase modulation, stimulated Raman scattering, and slow-light. Efficiency of some of such nonlinear effects depends strongly on the phase-matching condition between the pump beam and nonlinear generated signals which can be achieved by having proper dispersion engineering schemes on the devices. The NSWDs usually have a significant group velocity dispersion (GVD) depending on the waveguide dimensions or/and structural shapes. The NSWDs are used to have tapering sections and/or grating sections for efficient fiber coupling because of their small waveguide scales. All these sections contribute to the GVD of the entire NSWDs. Thus, the knowledge of the GVD of each part of the NSWDs is very important.

This paper presents our recent achievement with a simple white-light Mach-Zehnder interferometric method to identify localized GVD of the NSWDs. Conventional methods of measuring the GVD of optical fibers or waveguides are related to measurement of the total GVD of the entire NSWDs. Recently time-resolved heterodyne detection technique and the near-field scanning microscopy technique are demonstrated to measure localized group delay of the PhCW devices, but the techniques have a limited group delay resolution depending on laser pulse-width used for the measurement. It is demonstrated that our white-light interferometric method can measure very accurate group delay dispersion up to 0.5 fs/nm resolution. This method has been applied to determine not only the GVD profile of the entire NSWDs but also that of their localized structural section.

8265-16, Session 6

Plasmonic coherent perfect absorption by guided-mode resonance for active switching and integrated photonics application

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Plasmonics is considered a highly useful building block for nanoscale photonic integration. Guided-mode resonance (GMR), in particular, in quasi-reversible systems like a surface plasmonic nanostructure is a key phenomenon governing active functionality of nanoscale integrated circuits. By virtue of strong entanglement in phases and intensities between discrete and continuum modes, the interference nature of GMR can excellently explain the underlying physics of many strong plasmonic resonance phenomena, such as switching of plasmonic coherent perfect absorption and emission of light, abnormal phase shifting in reflection from corrugated metallic surfaces, and extraordinary transmission of light. Active control of plasmonic GMR is theoretically studied and experimentally demonstrated for potential applications to photonic integrated circuits in deep subwavelengh dimensions.

8265-17, Session 7

Light guidance through void: silicon slot waveguides and their rigorous characterizations

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When the dimensions of an optical waveguide are much smaller than the operating wavelength, unique materials and structural dependent properties can be observed [1] and these recently have been receiving much attention [2]. In this regard, silicon has been particularly attractive as the low-cost and mature CMOS fabrication technology widely used in the electronics industry can be exploited. The strong discontinuity of high index contrast of silicon allows light confinement in low-index region. The access of high field intensity in the low-index region allows design of highly efficient optical sensors and various nonlinear photonic devices. A rigorous H-field based full-vectorial modal analysis has been carried out, which can more accurately characterize the abrupt dielectric discontinuity of a high index contrast optical waveguide. As a result, the full-vectorial H and E-field and the Poynting vector profiles can be shown in detail. Design of vertical slots supporting TE modes and horizontal slots supporting TM modes, and novel photonic devices incorporating such slots will be presented.

1] D M H Leung, et al., Rigorous modal analysis of silicon strip nanoscale waveguides, Optics Express, vol. 18, pp.8528-8539, 2010.

2] D M H Leung, et al., Numerical analysis of asymmetric silicon nanowire waveguide as compact polarization rotators, IEEE Photonics Journal, vol.3, p.381-389, June 2011.

8265-18, Session 7

A speckle-based CMOS sensor for arbitrary surface movement detection with correlated double sampling and gain error correction

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This paper presents a CMOS sensor for accurate tracking of speckle movements on arbitrary surfaces. The sensor is made of a pair of comb filters with a pitch of 5.6 µm and decayed by 90° to produce quadrature signals. The readout circuit is a 60 dB amplification chain with offset and KTC noise compensation, providing a digital output signal. The direction and frequency of the quadrature signals are resolved externally by zero-crossing detection. Compared to a previous realization [1], the sensor includes a correlated double sampling stage to remove kTC noise. To minimize gain error, the following techniques were used: 1/ dummy finger pixels, 2/ common centroid sensor structure with interleaved finger layout, 3/ gain trimming through variable capacitor. Special care was taken to minimize signal coupling between fingers, which can result in inacceptable movement drift. Integrated into a 180 nm CMOS process, the sensor and readout circuit occupy an area 0.1 mm2 and consume 24 µW at full speed of 64 ksample/s. The maximal tracking speed of the surface is 0.25 m/s with an accuracy of about 5µm. The combined use of gain error minimization and kTC noise cancellation results in very good tracking performance: negligible residual drift and minimal observable displacement of 5 µm.

[1] Wang, C., Tanner, S., Farine, P., “A speckle-based CMOS sensor array for arbitrary surface movement detection,” Proceedings of SPIE Vol. 8069, 80690Z (2011).

8265-19, Session 7

Time-and-Frequency-Domain Modeling (TFDM) of hybrid photonic integrated circuits

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The competence of integrating a large number of optical elements on single wafer-dices involves the design of complex photonic chips that might contain hundreds of elements with diverse functionalities. Photonic Design automation (PDA) can contribute to the progress of this by providing compliant, time efficient and reliable environments for the simulation of photonic integrated circuits (PICs).

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. Such photonic circuits consist of linear PICs sub-elements, as is the case of most of the Silicon-based PICs, and are efficiently analyzed in the frequency domain. However, in a more general situation, photonic chips contain non-linear or active elements as well, requiring e a time-domain description.

In approaches up to date, even in the presence of a single non-passive element, this type of hybrid circuit is modeled in the time-domain. An FIR filter is calculated for each S-matrix describing a passive element in time-domain.

Although FIR design methods provide a very accurate solution, they intrinsically degrade near the edges of the signal band. This turns into a problem in large-scale integrated PICs, due to multiplicative effects in the inaccuracy that makes it a non-scalable solution for modeling hybrid PICs.

With this contribution, we elaborate on the time-and-frequency domain modeling (TFDM), a new method for efficient modeling of hybrid large-scale PICs that aids pure time-domain simulations. Further we review analytical models of basic PIC elements by means of several application examples.

8265-20, Session 7

Integrated silicon photonic nanocircuits and technologies for optical communications and optical sensing

S. He, D. Dai, Zhejiang Univ. (China)

Smaller size is desired for optical integration in order to have higher integration density and lower cost, which is very important for optical communication, optical sensing and optical interconnect. Silicon-on-insulator (SOI) nanowires give a very promising way to realize ultrasmall photonic integrated devices because of the ability for ultrasharp bending as well as the CMOS compatibility. As a typical integrated-type (de) multiplexer, ultrasmall arrayed-waveguide gratings (AWG) are very attractive for many applications. We have developed several types of ultrasmall SOI-nanowire AWG with novel layouts. Since SOI-nanowire devices are usually severely polarization-sensitive, a polarization diversity system consisting of polarization splitters and rotators is usually desired as a general solution to polarization issues. We have proposed several novel designs for ultracompact polarization devices.

SOI nanowires also give a good platform for optical sensing with high sensitivity because of an enhanced evanescent field. We have developed SOI-nanowire-based optical sensors by using MZI (Mech-Zehnder interferometer)-coupled microrings and cascaded rings.

We also note that the size of an SOI nanowire is still limited to the order of wavelength in each direction. In contrast, surface plasmon (SP) waveguides could provide a nano-scale waveguiding and confinement of light. However, the conventional nano-scale SP waveguides are usually quite lossy. We have proposed two types of novel hybrid plasmonic waveguides to achieve a nano-scale confinement and low loss propagation. The hybrid plasmonic waveguides offer a way to transfer both photonic and electronic signals along the same circuit, which is attractive for active components, e.g., tunable filters and optical modulators.

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8266-01, Session 1

Biophotonic sensors on a silicon chip for Raman spectroscopy and optical coherence tomography

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Highly sensitive optical methods have been developed for the detection and analysis of biotissue. Integration on a silicon microchip offers cost reduction and instrument miniaturization. We demonstrate that for thin samples, integrated waveguides have a higher light collection efficiency than fiber probes. Further improvement of the collection efficiency by more than an order of magnitude is achieved with a novel on-chip arrayed-waveguide-grating (AWG) sensor, based on the confocal arrangement of two AWGs, acting as focusing illuminator and signal collector, respectively. We launch laser light and measure Raman spectra from extracted human teeth through an integrated AWG spectrometer, paving the way toward the detection of early dental caries with a compact, hand-held, integrated spectrometer (collaboration with National Research Council Canada, Winnipeg, Canada and Erasmus Medical Center, Rotterdam, The Netherlands). We also present results of a spectral-domain optical coherence tomography (SD-OCT) system using AWG spectrometers with footprints of only a few cm2, central wavelengths of 800 nm and 1300 nm and free spectral ranges of 20 nm and 78 nm, respectively. Interferometric distance measurements are performed by launching broadband light into a free-space Michelson interferometer, with its output coupled into the AWG. A maximum imaging depth of 1 mm and axial resolutions of 25 µm and 20 µm in air are demonstrated for the 800-nm and 1300-nm ranges, respectively. Using the AWG spectrometer combined with a fiber-based SD-OCT system, we demonstrate cross-sectional OCT imaging of a multi-layered scattering phantom (collaboration with Academic Medical Center, University of Amsterdam, The Netherlands).

8266-02, Session 1

Temperature-independent vertically coupled double-ring sensor

Y. Xiong, W. N. Ye, Carleton Univ. (Canada)

Label-free biosensing techniques simplify the procedure of biomolecular detection without labelling the target molecules. Label-free biosensors based on high index contrast silicon-on-insulator (SOI) optical microring devices hold great promises for biomolecular analysis. We develop an SOI vertically coupled athermal microring resonator biosensor with a double-ring configuration. Our design introduces a reference ring and a sensing ring, both vertically coupled to a common bus waveguide, which effectively isolates the thermal effects, addressing one of the biggest challenges faced by SOI ring sensors. Both the reference and the bus waveguide are buried under a spacing material, while the sensing ring is situated on top and is exposed to the sensing medium. By determining the resonance wavelength shifts of the reference ring induced by temperature change, the thermal dependent effects from the total response of sensing measurements in the sensing ring can be removed to obtain a temperature-independent sensing performance. Simulation results show that the cladding-induced sensing resonance wavelength shift is 24.66 nm when the cladding index changes from 1 to 1.35. In addition, the vertically coupled configuration offers less stringent fabrication requirements for the coupling separation as the separation is precisely controlled by timing the deposition/growth rate of the spacer layer. We fabricate our ring sensor using the LOCal Oxidation of Silicon (LOCOS) process, which has recently been demonstrated as an effective means of defining optical waveguide in SOI with low loss due to the ultra-smooth sidewalls. Such double-ring biosensors are anticipated to be useful for biomedical and environmental application.

8266-03, Session 1

Investigation of parallel coupling mechanisms in silicon integrated chip sensors

O. Zero, A. Aksnes, Norwegian Univ. of Science and Technology (Norway)

The characteristics of silicon together with its fabrication flexibility make it an excellent opportunity for many integrated photonic applications. Based on the characteristic properties of optical components such as: waveguides, couplers, resonators, gratings and finally photonic crystals; one is able to construct a complex system capable of performing many complicated tasks. However, as soon as the system grows complex, the number of coexisting phenomena increases, which makes the system extremely difficult to investigate simply and merely by analysing its components separately. Furthermore, the ultimate performance of such complex systems relies heavily on accounting for every possible channel of coupling and how the components can interact with each other. Such channels could mean interference, intermodal coupling, spectral filtering or a combination, and diffraction or phenomena related to the photonic bandgap.

The aim for our study is to investigate the performance of optical systems combined with a few of the popular optical components integrated on a single silicon chip. By using numerical methods and simulation software (COMSOL, MATLAB), coupled systems are investigated in the context of sensing small changes in the refractive index of a specimen and measuring small mechanical vibrations. As an example, a membrane deflection sensor is presented, whose structure is composed of gratings and directional couplers. Various mechanisms of coupling of the optical elements are then analysed separately and later combined together and investigated globally in both 2- and 3-dimensional simulations.

8266-05, Session 1

Manipulation, trapping, and SERS detection of nanoparticle-coated microspheres in optofluidic waveguides

K. D. Leake, S. Mascharak, P. Measor, Univ. of California, Santa Cruz (United States); B. S. Phillips, A. R. Hawkins, Brigham Young Univ. (United States); P. Mascharak, H. Schmidt, Univ. of California, Santa Cruz (United States)

Surface enhanced Raman spectroscopy (SERS) active microparticles were produced by coating carboxylated-polystyrene microspheres with silver nanoparticles. These particles are found to be SERS active for rhodamine 6G detection when compared with a negative control. Synthesis conditions including temperature and time were varied in order to maximize SERS activity and silver coverage. Using on-chip microscale optofluidic antiresonating reflecting optical waveguides (ARROWs), the SERS particles were optically manipulated and trapped using 800nm light. Trapping was achieved using counter-propagating beams in a loss-based trap. The number of particles was controllable in the trap, thus allowing for a wide range of applications. The trapped particles were illuminated by a second beam, of lower power visible light, for excitation and detection of SERS. The visible light illuminates only the trapped particles allowing for prolonged, selective SERS analysis at a waveguide intersection. The combination of nanoparticle SERS enhancement with all-optical microparticle control and a planar optical geometry opens new perspectives for label-free biosensing on a chip.
This work was supported by the National Institute of Biomedical Imaging and Bioengineering (grant 1R21EB008802), the W.M. Keck Center for Nanoscale Optofluidics, and the Defense Advanced Research Projects Agency (DARPA) under Contract No. HR 0011-10-1-0075.

8266-06, Session 2

Optical resonators for ultra-sensitive biosensing

F. Vollmer, Max Planck Institute for the Science of Light (Germany)

We demonstrated the use of hybrid photonic-plasmonc modes in microsphere optical resontors coupled to plasmon nanoparticles for sensitivity enhancements in label-free biosensing applications. We quantitatively analyze the binding of a model protein to gold nanoparticles from high-Q WGM resonance frequency shifts and quantitate the sensitivity enhancement by simulating frquency shifts and linewidths changes using generalized Mie theory.

M.A. Santiago-Cordoba, S.V. Boriskina, F. Vollmer, and M.C. Demirel, “Nanoparticle-Based Protein Detection by Optical Shift of a Resonant Microcavity,” Appl. Phys. Lett., Aug. 2011 (COVER PAPER).

8266-07, Session 2

Photonic crystals: a versatile platform for optics-based biological detection

B. T. Cunningham, Univ. of Illinois at Urbana-Champaign (United States)

The narrowband optical resonances provided by photonic crystal surfaces can be engineered to provide high intensity evanescent electric fields, to direct photon emission efficiently in desired directions, and to act as highly efficient reflectance filters for wavelengths spanning ultraviolet through infrared. Photonic crystal surfaces can be inexpensively produced over large surface areas in many material systems, including flexible plastic, and have been used to produce high sensitivity label-free biosensors, substrates for fluorescence enhancement, and discrete frequency chemical imaging systems. This talk will summarize recent technical advancements and life science applications for photonic crystal surfaces and related detection instrumentation. The development of label-free imaging systems for quantification of biomolecule binding density in array formats and for monitoring the interaction of live cells with surfaces will be described, with applications for DNA microarray quality control and stem cell differentiation imaging. Recent efforts to improve upon the detection resolution of photonic crystal label-free biosensors through generation of narrowband laser emission will be discussed, with applications in pharmaceutical high throughput screening. Photonic Crystal Enhanced Fluorescence (PCEF) utilizes optical resonances at multiple wavelengths in the visible region of the spectrum to simultaneously magnify the electric field intensity exposed to surface-bound fluorophores and to increase the collection efficiency of fluorescence emission, resulting in substantially increased detection sensitivity for gene expression analysis and cancer biomarker detection in serum. Photonic crystals designed as high efficiency reflectance filters for specific wavelengths in the infrared are being applied to the development of rapid infrared absorption imaging systems for chemical imaging of cells within biopsy specimens.

8266-08, Session 3

Photo-induced trimming of chalcogenide-assisted silicon photonic circuits

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We present an innovative and efficient technique for post-fabrication trimming of photonic integrated circuits (PICs). The approach here proposed exploits the high photosensitivity of chalcogenide glasses (ChGs) to induce local and permanent modifications of the optical properties and spectral responses of ChG-assisted devices. This is achieved simply by selectively exposing the circuit to a low intensity near band-edge visible light source.

In this contribution we experimentally demonstrate the potential of this technique on ring-resonators-based devices realized on a silicon-on-insulator platform, for which post-fabrication treatments enable to counteract the strong sensitivity to technological tolerances. Photosensitive ChG-assisted silicon waveguides were realized by thermally evaporating a 420-nm-thick coating layer of As_2S_3 on top of conventional silicon channel waveguides (500-nm-width, 220-nm-height) fabricated with electron-beam lithography. An effective index change exceeding 1e-2 was observed, which corresponds to a resonant wavelength shift greater than 6 nm, largely exceeding the random resonance spread due to fabrication tolerances.

Neither the ChG layer deposition, nor the trimming process introduces appreciable additional losses with respect to the bare silicon core waveguide. Performances of the trimming technique, speed, time stability and saturation effects, as well as nonlinear behaviour and infrared writing issues have been thoroughly investigated and experimentally characterized.

We show that this simple, low-power consuming and low-cost technique enables to finely compensate technological inaccuracies and to target desired specifications with no need of tight fabrication tolerances. Furthermore, it is the key to realize programmable and reconfigurable PICs, where customized and specific functionalities can be written and erased on generic architectures.

8266-09, Session 3

Tensile strained germanium for photonics

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The combination of n-type doping and tensile strain in germanium allows to enhance direct conduction band occupancy under external pumping and to reach optical gain using the direct optical recombination.

We have developed a method to effectively transfer the residual stress in Si3N4 films to the core of defect-free germanium waveguides fabricated on GaAs substrates. We have investigated the emission in 50 µm long, 1 µm large and 500 nm thick germanium waveguides with the Si3N4 stressor deposited on its top. Finite element analysis of the fabricated structures shows that the tensile strain is inhomogeneous in depth. The germanium layer exhibit highly-strained region (0.6%) in the vicinity of the stressor. The emission spectrum of the germanium waveguide shows a broad emission peak with a maximum at 1560 nm associated with direct recombination in the relaxed region of the germanium layer and a sharp peak at 1680 nm associated with recombination in the tensile-strained region. We have evidenced optical gain for the 1680 nm emission through the observation of the broadening decrease typically of 25%, when the pumping power is increased by two orders of magnitude. The peak width narrowing is also observed when the pumping length is increased for a fixed pumping power. By using variable strip length method we have measured a net optical gain of 80 cm-1.

We have also investigated tensile strained Ge films grown on InGaAs buffers and we will present both structural and optical characterizations of these germanium films. We will discuss the perspective to realize laser emission in germanium by using this approach.

8266-10, Session 3

Glass-based silicon-clad optical device designs

R. C. Gauthier, K. Medir, Carleton Univ. (Canada)

The 3-layer slab configuration forms one of the simplest waveguide geometries from which integrated optic devices can be configured. The addition of a thin high dielectric overlay of silicon can greatly alter the slab waveguide properties and provide a means of accessing silicon photonics within the glass based platform. We begin with a review of the modal properties of waveguides without and with the thin silicon overlay followed by the design of integrated optic silicon clad devices. When the 3-layer slab waveguide has a segment along its center clad with silicon it forms a 3-4-3 layer structure. Depending on the thickness of the clad silicon layer, the overall device can be configured as an MMI when a few modes are supported directly in the silicon layer. It is shown that the modal properties of the silicon layer guided light are highly dependent on the superstrate index making this design a simple and sensitive index of refraction sensor. We also address issues related to efficient coupling from the 3-layer to 4-layer waveguide configurations. The design of adiabatic couplers showing over 90% coupling efficient to single mode silicon waveguides in the SOI device platform are presented. The presentation is theory based and makes use of modal methods, beam propagation and FDTD to simulate design performance. The discussion is restricted to slab waveguide configurations with results and concepts presented easily extended to channel waveguide designs.

8266-11, Session 3

Loss reduction of silicon slot waveguides with ALD-grown thin films

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The slot waveguide facilitates nanoscale light confinement into a low-index material on silicon [1], creating great potential to improve the performance and to add the functionality of silicon photonic devices. We have shown that thin film growth using the atomic layer deposition (ALD) technique is capable of controlled partial or complete filling of slot waveguides, and that ALD grown titania has loss of less than 1 dB/cm [2,3]. The recent emergence of ALD grown thin films into microelectronics industry directly demonstrates the CMOS compatibility of ALD, making the technique attractive for CMOS photonics.

In this work, we present our studies on ALD clad slot waveguides. We show reduction of propagation loss in silicon slot waveguides. With an ALD grown titania thin film cladding, propagation loss as low as 7 dB/cm for a deep-UV patterned slot waveguide is achieved. Nonlinear properties of ALD materials and material systems and their use for all-optical silicon photonic devices are also discussed.

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8266-12, Session 4

New concepts in silicon component design using subwavelength structures

I. Molina-Fernandez, Univ. de Málaga (Spain)

Subwavelength gratings (SWGs), based on the use of periodic structures with pitches much smaller than the wavelength, are the subject of intense research in the field of integrated optics, because they enable engineering of the effective refractive index of the material by means of standard lithographic and etching techniques. This introduces a new degree of freedom in the design of photonic devices opening the possibility of improving device performance and potentially reducing fabrication complexity and cost. SOI technology is receiving considerable attention as a key technology for optical interconnects and as a platform for hybrid integration of photoniccircuit due to its compatibility with standard CMOS technology, circuit miniaturization, and potentially low cost. This technology is also the ideal platform to develop the possibilities of the SWG structures as,driven by microelectronics interests, nanofabrication techniques are highly developed and allow for the fabrication of SWG structures, with small enough feature sizes to stay into the subwavelength regime. Indeed deep-UV lithographic techniques can enable large-scale manufacturing of these structures. In this work we demonstrate the use of SWGs, and refractive index engineering concepts, through the application to several devices of practical importance, including a fiber-to-chip grating coupler and Multimode Interference (MMI) couplers. We furthermore discuss the potential of controlling not only the material refractive index but also its dispersion characteristics.

8266-13, Session 4

Deterministic aperiodic nanostructures for silicon photonics

L. Dal Negro, Boston Univ. (United States)

Efficient schemes for electromagnetic field localization and intensity enhancement are essential requirements for the design and engineering of novel Si-based optoelectronic components that leverage on broadband enhancement of optical cross sections, such as optical biosensors, photodetectors, solar cells, light sources and nonlinear elements. Recent advancements in the design and fabrication of Deterministic Aperiodic Nanostructures (DANS) have provided novel opportunities for the generation of broadband field localization, enhancement, and light-matter coupling on the nanoscale.

DANS are optical media in which the refractive index fluctuates over length scales comparable or smaller than the wavelength of light. DANS are designed by deterministic algorithms that interpolate in a tunable fashion between periodicity and pseudo-randomness. As a result, DANS are readily fabricated using conventional nanolithographic techniques and display unique transport and localization properties akin to random media. In this talk, I will discuss the main engineering applications of DANS in the context of Si-based nanophotonics and optical device technologies. Specifically, I will focus on the broadband enhancement of optical fields for multi-frequency light sources, novel aperiodic laser structures, plasmon enhanced light emitters and optical biosensors. Moreover, the applications of DANS to the enhancement of nonlinear interactions on Si-based optical chips will also be discussed. Finally, our recent work on circularly symmetric light scattering, photonic-plasmonic enhanced absorption and phase singularities in deterministic aperiodic structures with circular Fourier space will be presented, and its impact for the design of Si-based thin-film solar cells will be discussed.

8266-14, Session 4

Selecting the polarization in silicon photonic wire components

D. Xu, A. Delage, R. Ma, S. Wang, J. Lapointe, J. Schmid, P. Cheben, M. Vachon, S. Janz, National Research Council Canada (Canada)

Silicon photonic wire waveguides are highly birefringent, and they are generally designed to operate for one particular polarization. For a commonly used waveguide cross-section of 220 nm x 450 nm, TE polarization is preferred while the TM mode suffers unacceptably high intrinsic bending loss. For waveguides with a silicon thickness larger than 250 nm, TM polarization is well supported and has been used in a variety of devices. For evanescent field sensing applications, TM polarization is preferred since it provides a higher response than that by TE polarization. In optical filters, both TE and TM have been employed. However, the choice of polarization has largely appeared to be arbitrary. In this presentation we review the pertinent polarization-dependent properties, including the propagation loss, bending loss, mode transition loss, back-reflection and fabrication tolerance. Through theoretical and experimental evidence, we showed that TM polarization has several important advantages. Resonators for TM polarization have a more relaxed fabrication tolerance, and suffer less back-reflection. We experimentally demonstrate high performance resonators operating in TM with a radius down to 2 um. We suggest guidelines for a considered choice of the operating polarization.

8266-15, Session 4

Broadband signal processing in photonic crystal waveguides

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Photonic crystal waveguides offer a host of opportunities for very compact optical signal processing functionalities. In the nonlinear domain, we have demonstrated optical performance monitoring at data rates up to 640 Gbit/s, efficient four wave mixing, an all-optical XOR gate as well as ultrafast tunable delay. In the linear domain, photonic crystal cavities enable modulators with extremely low power, down to fJ/bit, as well as ultracompact WDM systems.

8266-16, Session 5

Design and applications of silicon waveguide grating couplers

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We shall review the basic physics of waveguide gratings for coupling between optical fibers and silicon photonic wire waveguides. Our recent work on waveguide grating couplers will be reviewed, including an apodized grating coupler [1] with engineered coupling strength to achieve Gaussian-like output profile, which greatly improved the fiber-chip coupling efficiency. In particular we shall discuss a new class of grating couplers involving the use of sub-wavelength nanostructures [2] to engineer the optical properties of the grating. We shall describe the application of effective medium theory in the design of sub-wavelength structured grating couplers, which, when properly engineered, can offer broadband coupling (>80nm 1dB bandwidth) [3] and polarization independence [4]. Other applications of waveguide gratings, for example the 2D gratings for polarization-diversity scheme, bi-wavelength gratings for optical transceivers [5] and gratings as 3dB splitters [6] will also be briefly discussed.

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8266-17, Session 5

Compact and efficient couplers for silicon slot waveguides

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The slot waveguide facilitates nanoscale light confinement into a low-index material on silicon [1]. Using the slot waveguide structure, silicon-based waveguides can also be efficiently integrated with optimal materials for specific applications (e.g., electro-optic materials, or non-linear materials with small two-photon absorption). However, the nanoscale non-Gaussian mode profile suggests that coupling problems are non-trivial. Nevertheless, couplers based on conventional principles, such as adiabatic mode conversion, can be realized [2]. For high-index contrast waveguides, these couplers can even be made remarkably efficient and compact.

In this work, we study theoretically and experimentally slot waveguide couplers for different applications. We present strip-to-slot waveguide couplers with a length as small as 10 µm and with their feature sizes of more than 100 nm, which exhibit efficient coupling into the slot mode and negligible scattering. We demonstrate coupling loss of less than 1 dB for a ten micron long coupler from a strip waveguide to slot waveguide, fabricated using the 248 nm deep-UV lithography. We also discuss ring resonator couplers, multimode multislot structures for 2x2 couplers, and prism coupling characterization of multislot waveguide structures.

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8266-19, Session 5

Parallel-coupled dual racetrack silicon microresonators for quadrature amplitude modulation

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Advanced modulation formats such as quadrature phase-shift keying or M-ary quadrature amplitude modulation can provide higher spectral efficiency and other significant advantages compared to on-off keying. A parallel-coupled dual racetrack silicon micro-resonator structure is designed and analyzed for M-ary quadrature amplitude modulation. A distinctive feature of this structure is the coherent cross-coupling between the two racetrack micro-resonators mediated by the center waveguide. This cross-coupling drastically modifies the amplitude/phase characteristics of the resonances. A multi-waveguide coupled mode theory is introduced to study how the cross-coupling results in the largest coverage of all possible amplitude and phase states, which are essential for arbitrary M-ary quadrature amplitude modulation. The over-coupled, critically coupled, and under-coupled scenarios are systematically studied. Simulations indicate that only the over-coupled structures can generate arbitrary M-ary quadrature signals. Our study shows that the large dynamic range of amplitude and phase modulation of an over-coupled structure stems from the complex cross-coupling between two resonators, which can interpreted as the result of a delicate balance between the direct sum and the “interaction” terms. Asymmetries in the coupling constants and quality factors of two resonators may arise in real devices due to fabrication imperfections. Compensations for these asymmetries (up to 50%) by phase adjustment are shown feasible. The electrical power needed for modulation and phase compensation is investigated.

8266-20, Session 5

Optical signal processing using silicon resonance and slow-light structures

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Optical buffering is an indispensable function in optical packet switching networks. Silicon waveguide-based optical delay line is a promising candidate to achieve on-chip tunable delay, while it provides a compact size and potential monolithic integration with other silicon photonic and electronic devices. In order to obtain ns-scale continuous optical delay for broadband optical signals, we devise a novel scheme to fully utilize the waveguide routing and resonance-enhanced delay capabilities. Our delay structure is composed of two parts with the first one for long-range discrete coarse-tuning and second for short-range continuous fine-tuning. Silicon waveguides have a reasonable low propagation loss and low group delay dispersion, suitable for long-range optical signal delay. In our scheme, optical delay coarse-tuning is implemented by combing individual waveguide delay units with various lengths using a series of optical switches. The total delay that can be obtained by the signal routing structure exponentially increases with the number of waveguide stages. The continuous fine-tuning is implemented using a slow light structure in which a small refractive index change can result in a large delay variation due to the resonance effect. We use a novel reconfigurable waveguide self-coupling resonance structure to realize the tunable slow light. Its delay tuning mechanism is based on resonance coherent coupling, which has the key merit of low tuning power.

8266-32, Session 5

SOI-based trapezoidal waveguide with 45-degree microreflector for non-coplanar light bending

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SOI-based optical interconnect for silicon photonics have received attention in recent years. In order to achieve flexible interconnects between various micro-photonics and the compact integration into the optical-interconnect systems, making arbitrary directional changes in optical paths is essential for the waveguides.

SOI-based trapezoidal waveguide with a 45° micro-reflector is proposed for the three-dimensional optical bent path. The proposed structure is intended to connect input and output parts on the rear and front sides of SOI wafer, respectively. The input lightwave on the rear side impinges upon the Si-based 45 degree reflector and couple into the trapezoidal waveguide to become the output lightwave on the front side. The 45 degree sidewalls on the trapezoidal waveguide and the Si-based 45° reflector can be fabricated simultaneously using a single-step wet-etching process. The wet-etched waveguides with high quality sidewalls were demonstrated in literatures. However, the sidewalls were realized on {110} planes of silicon substrates. The high-quality 45 degree sidewalls on (100)-oriented silicon wafer are demonstrated using the wet-etching approach for the first time. As compared to the rectangular ridge waveguide using dry-etching approach, the proposed 45-degree trapezoidal waveguide is a cost effective structure and well suitable for mass production.

The transmittance efficiency of proposed structure is -4.51 dB, the propagation loss is -0.404 dB/cm, and misalignment tolerance are 42 µm at horizontal direction and 41 µm at vertical direction. The RMS roughness of waveguide sidewall and 45° micro-reflector is about 30 nm, and both of them are fabricated by wet etching at single process.

8266-21, Session 6

High speed silicon optical modulation using the silicon-on-insulator platform

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Optical modulator devices in silicon have experienced dramatic improvements over the last 7 years, with data rates demonstrated up to 40 Gb/s. However, the demands of optical interconnects are significant and the need for devices with compact real estate and broadband characteristics operating at high speed with extinction ratio above 5dB and working for one or both polarisation is of outmost importance. Here we describe the work at Surrey that led to the fabrication of novel devices as well as self aligned pn junction structures embedded in a silicon rib waveguide with an active length in the millimetre range producing high-speed optical phase modulation whilst retaining a high extinction ratio. We also describe recent work on Ge/SiGe quantum confined Stark effect devices for electroabsorption modulation, in which we have used strain engineering to target the commercially significant 1.3-µm communications 'window'.

8266-22, Session 6

Deep-level charge state control: a novel method for optical modulation in silicon waveguides

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The doping of silicon with deep-level impurities provides a means through which an efficient absorption mechanism may be introduced in optical waveguides; that is, the optical ionization of the impurity with sub-bandgap light. If the level of the dopant can be selected such that it provides an excitation mechanism which is dependent on its charge state, it is possible that optical absorption may be switched through the variation of the background doping concentration. In this presentation we will describe the fabrication and characterization of both passive and active waveguides (ie. modulators) which exploit this phenomenon to vary optical absorption. We will show that such control can be introduced using a depletion device and that the physical mechanism is significantly more efficient than for the case of free carriers. Modulation speed will also be discussed.

8266-23, Session 6

A compact high-speed and low-cost hyperspectral imager

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Although the potential of hyperspectral imaging has been demonstrated for several applications using laboratory setups, its adoption by industry has so far been limited due to the lack of high speed, low cost and compact hyperspectral cameras. To enable industrial hyperspectral imaging, we have developed a novel hyperspectral sensor with the following key innovations:

1.The development of a Fabry-Pérot interferometer, operating at minimal cavity sizes to optimize for free spectral range and minimize stray light. The main challenge to accomplish this is the strict control of the processing tolerances in combination with a design correcting some of these tolerances.

2.The organization of a series of Fabry-Pérot interferometers as a wedge, monolithically integrated on top of a standard off-the-shelve CMOS sensor, to reduce cost and improve optical throughput. The main challenge for this accomplishment was the production of the optical filters using tools and materials that are compatible with the standard CMOS process. Additionally, the materials' absorption indices had to be improved for a better light transmission.

3.The implementation of high speed software routines to remove higher-orders and improve image quality without additional optical filters further reduces the cost.

The result is a 2 megapixel sensor of 1.9 x 1.3 x 0.5 cm, a spectral range between 550 and 1000 nm, a spectral resolution lower than 10 nm, a dynamic range of 10 bit and a speed of 340 frames per second at illumination levels as used in machine vision applications.

8266-24, Session 7

Time-resolved photoluminescence and optical gain of Ga(NAsP) heterostructures pseudomorphically grown on silicon (001) substrate

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The development of integrated optoelectronic circuits on silicon is one of the most important challenges in the fields of electronics and photonics today. Such devices would provide high performance and unique novel functionalities. The key component of such photonic circuits is an electrically pumped laser capable of being integrated on silicon. The realization of such a laser is still a big challenge. One possible approach is the heteroepitaxial growth of direct III/V semiconductors on the indirect Si. However, the large lattice mismatch between such III/V materials and Si leads to a formation of high misfit and threading dislocation densities, reducing the efficiency and lifetime of the lasers dramatically. The new dilute nitride material Ga(NAsP)/(BGa)((As)P) is a very promising candidate to circumvent these problems. The combination of a high As fraction with dilute N fractions in Ga(NAsP) leads to a direct band gap material, which can be grown dislocation free on GaP and on exactly oriented (001) Si substrate. Here we investigate the optical properties of Ga(NAsP) multi-quantum well samples using time-resolved photoluminescence and optical gain spectroscopy. The results indicate that disorder-induced carrier localization has a significant impact on the optical properties of the material system. Its importance depends strongly on the growth and composition parameters of the active and surrounding layers. Samples with high nitrogen concentration grown on silicon in particular show reduced localization effects and high modal gain values up to 80 cm-1 at room temperature, demonstrating the suitability of GaNAsP/Si as an active material for laser on silicon.

8266-25, Session 7

NIR spectral characteristics of avalanche electroluminescent silicon CMOS light emitters

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The emission spectra of reverse biased CMOS light sources were measured for various device dimensions, current densities and temperatures.

In contrast to the previously reported narrow-band forward bias CMOS junction electroluminescence spectrum that peaks around 1.1 µm (1.1 eV) and reverse bias Si emission spectra that covered wavelengths between 400 and 950 nm (1.3 - 3 eV), our recently measured optical power spectra extended beyond 950 nm far into the NIR.

Since the photon energy decreases with increasing wavelength, this discovery of significant NIR radiation implies that the quantum conversion efficiency of Si avalanche light sources is appreciably higher than previously reported.

As avalanching junctions can be switched much faster than forward biased junctions, which are limited to about 100 kHz, practical implications include combining Si avalanche light emitters with waveguides that are currently employed for longer wavelengths and detectors other than Si in high-speed optical communication systems.

By calculating the photon flux at the emission source for various photon energies, the physical radiative processes responsible for the electroluminescence spectrum that extends from the UV through the visible and into the NIR are deduced and quantified with respect to silicon's electronic band structure. While three separate physical mechanisms are distinguished to be responsible for the wide avalanche spectrum, the NIR electroluminescence is attributed to electron relaxation within the conduction band.

The effect of current densities up to 106 A/cm2 and temperatures between -50 °C and 125 °C on the emission spectrum and consequently the physical light generation mechanism are also investigated and quantified.

8266-26, Session 7

Kinetics of energy transfer in Er-doped SiO2/ nc-Si multilayers

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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. In spite of intensive studies, a complete explanation and optimization of the energy transfer mechanism from Si nanostructures to Er is still under debate.

This work presents efficient infra-red photoluminescence (PL) and time-resolved photoluminescence (TR PL) from Er-doped SiO2/nc-Si multilayers. Multilayer samples were fabricated by the sequential deposition of silicon and silicon dioxide co-sputtered with Er on Si substrates by magnetron sputtering. The distance between erbium and silicon - one of the most important parameters for energy transfer was well controlled. A strong IR PL intensity was achieved with multilayers containing nc-Si compared to a uniform Er:SiO2 sample with the same Er concentration. The kinetics of the visible photoluminescence shows significant differences between undoped and Er-doped multilayers. In all samples, we observe fast and slow visible and IR PL time decay components. We also demonstrate a strong dependence of the decay time on the size and crystallinity (nc-Si or a-Si) in the Si layers. These results allow us to improve our understanding of energy transfer from a-Si and/or nc-Si to Er.

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8266-27, Session 7

Efficient infrared electroluminescence from Er-doped SiO2/nc-Si multilayers under lateral carrier injection

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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 and energy transfer from Si to Er has not been optimized.

This work presents current-voltage relationships, efficient infra-red electroluminescence (EL) and time-resolved electroluminescence (TR EL) from Er-doped SiO2/nc-Si multilayers with varies layer thicknesses. 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 wafers. 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 electrodes spacing, from 200 µm to 2.5 µm, reveal good rectifying properties and demonstrate that charges flow through the nc-Si layers in the p-i-n structure under forward bias. The similarity between the EL and PL spectra demonstrates that in both cases Er is excited by the carriers injected in the nc-Si layers. EL lifetimes below 1 µsec have been attained, which is 3 orders of magnitude faster than what is typically reported from Er doped SiO2 layers containing Si nanocrystals under vertical carrier injection. This result suggests that fast EL modulation might be possible in our novel structures.

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8266-28, Session 7

Silicon-based three-dimensional photonic crystal with enhanced spontaneous emission

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Silicon (Si) based optical circuits with integrated sources are of great technological interest since they would allow for the development of fast, chip level optical interconnects with CMOS compatibility. However, the indirect bandgap of Si is a major bottleneck that results in extremely low quantum efficiency. Significant effort has been invested into the development of Si-based three-dimensional photonic crystals (3D-PC) with defect nanocavities that allow for the use of cavity quantum-electrodynamics phenomena to enhance the spontaneous emission efficiency. In this contribution, we demonstrate an entirely group-IV 3D-PC nanocavity consisting of Si-components with deterministically embedded self-assembled Ge-islands as internal light emitters. We fabricated woodpile 3D photonic crystals using high purity molecular beam epitaxy grown passive Si-plates that were lithographically patterned into components that are subsequently assembled layer by layer using micromanipulation. Ge-islands are embedded into a single active plate into which a defect nanocavity is formed. The Ge-islands radiatively couple to the cavity modes, allowing us to directly probe them by detecting photoluminescence. Starting with a structure with ten passive plates below the active plate, we systematically increased the number of upper cladding plates and monitored the emergence of clear modes with Q-factors that exponentially increase up to a maximum of 13600 for ten upper cladding plates. By performing time resolved PL-measurements on the patterned active plate, both within and outside the 3D photonic crystal we directly observe a shortening of the radiative lifetime by a factor of 3.0±0.4; the first demonstration of Purcell effect for a 3D photonic crystal nanocavity.

8266-29, Poster Session

FDTD simulation method for silicon photonic elements

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Attempt to manufacture photonics devices on silicon requires theoretical and numerical prediction. This essay presents Compound FDTD (C-FDTD) method for comprehensive simulation of silicon photonics devices. Although this method is comprehensive, it maintains conventional Yee algorithm. In this method variation of refractive index due to nonlinear effects, is considered. With the help of this simulator, refractive index change due to free-carrier (that created through two photon absorption) and Kerr effect in silicon waveguide has been studied. Results indicate how to choose pump pulse shape to optimum operation of active photonics devices. Also conductivity variation of Si waveguide due to change in free-carrier density has been studied. By considering variations in conductivity profile, you be able to design better schemes for sweep free carriers away with reverse bias or nonlinear photovoltaic effect for fast devices and Raman amplifiers.

8266-31, Poster Session

Free-carrier electro-absorption and electro-refraction modulation in group IV materials at mid-infrared wavelengths

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Mid-infrared (MIR) group IV photonics has lately begun to attract attention as a promising technology for applications such as gas sensing, missile countermeasures and free-space communications. Silicon-on-insulator (SOI) is very popular at telecoms wavelengths, but is limited as a mid-infrared material to wavelengths lower than 3.6µm because of the high absorption of SiO2 at longer wavelengths. Work is therefore being undertaken by a number of groups to investigate different material platforms that might be used for the realisation of MIR integrated photonics, while taking advantage of mature silicon processing technologies.

Modulation would most likely be an important function in many MIR integrated systems. In active near-infrared (NIR) silicon devices, free charge-carrier electro-refraction is the most common modulation mechanism. Before MIR active devices can be designed, it is important to be able to predict the magnitude of free charge-carrier induced electro-absorption and electro-refraction in the candidate group IV material platforms.

Here we predict the magnitude of electro-absorption and electro-refraction effects in group IV materials including silicon and germanium. The approach of Soref and Bennett (1987), which produced accurate expressions for change in refractive index and change in absorption coefficient as functions of hole and electron concentration at telecoms wavelengths, is used here. Change in absorption is calculated directly from experimental absorption spectra found in the literature, and change in refractive index is calculated through Kramers-Kronig analysis of the absorption spectra.

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8267-01, Session 1

Development of electro-optical PCBs with polymer waveguides for high-speed on-board optical interconnects

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There are on-going initiatives for 25 Gbps per lane over copper backplane, like OIF CEI 25G/28G SR/VSR and IEEE 802.3ba 100G Copper backplane. Although technically possible, there is significant increase in cost, power consumption, design efforts, manufacturing challenges to achieve viable 20+ Gbps operation and beyond. Simultaneously, potentials of optical waveguides on printed circuit boards (PCB) for inter-chip/ inter-module interconnects are being evaluated. Technical maturity and supply-chain has not yet evolved in the level for commercial breakthrough, cost and reliability are the key issues hindering wider implementation.

We report here results of fabricating electro-optical PCBs (EO-PCB) on a production scale panels in a modern factory environment. Impacts on design and fabrication processes are evaluated with multiple test vehicles including optical outer or optical inner layer constructions. Process compatibility with accepted practices and challenges in production scale up for high volumes are key concerns. Results include material attenuation, waveguide transmission loss, misalignment tolerance, and effect of lamination and reflow soldering on the waveguides. Multimode channels with 25-µm to 50-µm cores with 125-µm and 250-µm pitch are fabricated on standard-loss FR4 (Panasonic R1755V), high-speed (Meg4 R5725) and high-speed halogen free (Hitachi MCL-HE-679G) laminates for comparison.

We report also results on terminating the polymer waveguides with an optical mid-board coupling device containing right-angle turn developed by a partnering connector supplier. To evaluate end-to-end link losses in 20-cm waveguide links, we designed point-to-point backplane test vehicle for multimode = 850 nm VCSELs/detectors provided via externally launched test source and fiber-optic ribbons. The link loss analysis, crosstalk performance, misalignment tolerance and eye diagrams are shown.

8267-02, Session 1

Injection molded optical backplane for broadcast architecture

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A low cost, blind-mate, injection molded optical backplane is presented. Each segment of the backplane incorporates 12 parallel waveguide channels positioned at a 250um pitch. The waveguides are intersected by six orthogonal slots spaced 1.75 inches (1U) apart. A pellicle beam splitter, coated with a dielectric thin film designed to produce equal optical power from all output 'taps,' is assembled into each slot. The parallel beams exiting the backplane assembly are collimated to enable position-tolerant coupling into blind-mate optical connectors developed in house. The backplane operates as a broadcast bus, allowing each connected transmitter to communicate with all connected receivers.

8267-04, Session 1

Design of a highly parallel board-level-interconnection with 320-Gbps capacity

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We present the design of an optoelectronic parallel board-level interconnect and consider its performance. For the realization of the onboard communications over short distances, the approach of planar-integrated free space optics (PIFSO) is used with its well known advantages. This approach offers the potential for complex interconnectivity, and yet compact size. By using free-space propagation, crossings of signal paths do not affect the quality of the transmission significantly. In addition, efficient coupling is possible to connect to input/output devices such as VCSEL arrays as the preferred light sources and fiber connectors, for example. The planar geometry lends itself to a well-defined mechanical layout of a bottom PCB, which holds the electronics and the active optical components.

Here, we show the integration of a 2D fiber-matrix for board-to-board interconnection with a total number of up to several hundred internal optical channels. The optical links work at 850 nm wavelength, each with a potential data rate of 10 Gbps. The optical system layout was simulated and optimized by an evolutionary algorithm to find the most efficient optical paths inside the PIFSO substrate.

The complete setup is demonstrated for a multicore computing system with separate cores. With this application, we want to demonstrate, in particular, the system modularity. A distributed layout of the components is used, which is of interest, for example, for the communication in high-performance embedded computing systems.

8267-49, Session 1

Evaluation of multimode optical waveguides for reconfigurable optical interconnects

A. X. Wang, Oregon State Univ. (United States)

No abstract available

8267-05, Session 2

3D optical interconnects: from research to reality

R. Houbertz-Krauss, S. Steenhusen, Fraunhofer-Institut für Silicatforschung (Germany); M. B. K. Riester, Maris TechCon Technology and R & D Consulting (Austria)

The continuous requirement of increasing performance of microelectronic devices is nowadays associated with a growing demand for manufacturable optical interconnect solutions. With increasing demand for high data rates, along with a miniaturization of devices and components the integration of optical interconnects on chip-to-fiber or fiber-to-fiber connection level is a rapidly growing field. For high-speed data transfer, materials and integration concepts are needed which account for miniaturized high-speed short-range connections, low cost, and which - preferably - enable free device design.

Non-linear absorption initiated by focusing ultra-short laser pulses into materials is particularly used for the 3D free-form fabrication of functional structures. Since the triggered reactions are strongly confined to the focal region, the fabrication of 3D microstructures is performed simply by moving the focal volume in 3D through the materials. The appeal of the method is that it provides an intrinsically scalable technology. The generation of complex free-form 3D structures in custom-designed multifunctional materials such as inorganic-organic hybrid polymers (ORMOCER®s) by a TPA-initiated two-photon polymerization process is particularly beneficial for 3D optical interconnects being used for chip-to-fiber or fiber-to-fiber coupling, where the design possibilities of 3D fabrication with the power of multifunctional materials are synergistically combined. The potential of TPA processes to be up-scaled from the sub-μm to the cm regime will be discussed with respect to the underlying material concepts and exposure strategies in the TPA process, and 3D optical interconnects will be demonstrated.

8267-06, Session 2

Polymer waveguide components and interconnection architectures for board-level optical communications

R. V. Penty, N. Bamiedakis, A. H. Hashim, Y. Hao, J. Beals IV, I. H. White, Univ. of Cambridge (United Kingdom)

No abstract available

8267-07, Session 2

Polymer optical waveguide based bi-directional optical bus architecture for high speed optical backplane

X. Lin, The Univ. of Texas at Austin (United States); A. X. Wang, Oregon State Univ. (United States); R. T. Chen, The Univ. of Texas at Austin (United States)

No abstract available

8267-08, Session 2

Characterization and analysis of graded index optical waveguides for the realization of low-power, high-density, and high-speed optical link

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This paper describes an advanced multimode waveguide based optical link model that is used to aid the development of low-power, high-density, high-speed multi-channel optical link. The model consists of VCSEL, multi-channel rectangular shape step index (SI) or graded index (GI) type optical waveguide, multimode fiber, and photo detector, and takes into account the connection of these components. For low-power optical links, the link power penalty has to be minimized. In this study, the benefits of GI waveguides, particularly for the coupling losses, are investigated and compared to SI waveguides. We start from the fundamental ray optics. The rays are emitted from a VCSEL with a Gaussian intensity distribution. Both between the VCSEL source and the waveguide (the Tx side), and between the waveguide and the photo diode (the Rx side), a 50-μm gap is assumed, which is corresponding to an optical VIA in a PCB. Hence, the gap is filled with a uniform medium with similar refractive index to the core center for the purpose of reducing the reflection loss. Furthermore, the two waveguides are connected by a 50-um core GI multimode glass fiber, which guides the light from the Tx side to the Rx side. The characteristics such as connection loss, ray invariant versus intensity distribution, and near field pattern are addressed. The calculated results show that GI waveguides confine the optical field near the core center more tightly than SI waveguides, which results in a lower coupling loss in the GI waveguide link (0.25 dB) between the 35-μm core size waveguide and the 35-μm diameter photo diode, compared to the SI-core waveguide link (1.34 dB). This calculation helps us to characterize the high performance optical link with a more reliable model.

8267-09, Session 3

Heterogeneous integrated photonic circuits

A. W. Fang, G. A. Fish, E. Hall, Aurrion, Inc. (United States)

Photonic Integrated Circuits (PICs) have been dichotomized into circuits with high passive content (silica and silicon PLCs) and high active content (InP tunable lasers and transceivers) due to the trade-off in material characteristics used within these two classes. This has led to restrictions in the adoption of PICs to systems in which only one of the two classes of circuits are required to be made on a singular chip. Much work has been done to create convergence in these two classes by either engineering the materials to achieve the functionality of both device types on a single platform, or in epitaxial growth techniques to transfer one material to the next, but have yet to demonstrate performance equal to that of components fabricated in their native substrates. Advances in wafer-bonding techniques have led to a new class of heterogeneously integrated photonic circuits that allow for the concurrent use of active and passive materials within a photonic circuit, realizing components on a transferred substrate that have equivalent performance as their native substrate. In this talk, we review and compare advances made in heterogeneous integration along with demonstrations of components and circuits enabled by this technology.

8267-10, Session 3

A 25-Gbps high-sensitivity optical receiver with 10-Gbps photodiode using inductive input coupling for optical interconnects

H. Oku, K. Narita, T. Shiraishi, S. Ide, K. Tanaka, Fujitsu Labs., Ltd. (Japan)

A 25-Gbps high-sensitivity optical receiver with 10-Gbps photodiode (PD) using inductive input coupling has been demonstrated for optical interconnects.

High-speed and cost-effective optical modules for optical interconnects are important technology in next-generation computer systems. One way to reduce in cost is to apply a PD for 10-Gbps application. This 10-Gbps PD has a large active aperture and facilitates module assembly with readily achievable alignment tolerances for optical coupling. However, the PD bandwidth is insufficient for a 25-Gbps receiver, because its capacitance (Cpd) is large due to its large aperture.

We introduced the inductive input coupling technique to achieve the 25-Gbps optical receiver using 10-Gbps PD. We implemented input inductor (Lin) between PD and trans-impedance amplifier (TIA), and optimized inductance to enhance the bandwidth and reduce the input referred noise current by simulating with RF PD-model. Near the resonance frequency of the tank circuit formed by Cpd, Lin, and TIA input capacitance, the PD photo-current through Lin into the TIA is enhanced. This resonance has effects to enhance the bandwidth at TIA input and reduce an input equivalent value of the noise current from TIA.

We fabricated the 25-Gbps optical receiver with 10-Gbps PD using an inductive input coupling technique. By an inductor being applied, receiver bandwidth is enhanced from 10 GHz to 14.2 GHz. Thanks to this wide-band and low-noise performance, we improved the sensitivity at an error rate of 1E-12 from non-error-free to -6.5 dBm. These results indicate that our technique is promising for cost-effective optical interconnects.

8267-11, Session 3

4 channels x 10-Gbps optoelectronic transceiver based on silicon optical bench technology

C. Chen, H. Hsiao, C. Chang, B. Shen, G. Lu, National Central Univ. (Taiwan); Y. Lee, Centera Photonics Inc. (Taiwan); S. Chang, Y. Lin, M. Wu, National Central Univ. (Taiwan)

In this paper, a bi-directional 4-channels×10-Gbps optoelectronic transceiver based on the silicon optical bench (SiOB) technology is developed. A bi-directional optical sub-assembly (BOSA) as an optical engine has been applied to this transceiver, which is composed of the silicon 45° micro-reflector, V-grooves, high-frequency electrical traces, and Au/Sn bumps, which can be monolithically integrated and fabricated by using micro-electro mechanical systems (MEMS) processes. This SiOB regarded as a silicon sub-mount can further integrate 4-channel VCSEL/PD and corresponding fiber ribbons with whole passive alignment achievable. The optical coupling of TOSA and ROSA is -3 dB and -2 dB, respectively without adding coupling optics due to working distance of 150 um from VCSEL to fiber (OM2) and fiber to PD. The 1-dB tolerance of optical signal level for TOSA and ROSA are both ± 15 um in the horizontal and vertical direction. That is very suitable for miss-alignment of fabrication and assembly.

The BOSA, fiber ribbon assembly, PCB with high frequency trace design, transmitter driver and receiver TIA IC are included in this transceiver. The BOSA and PCB also have some specific design for conventional chip-on-board (COB) process. In eye diagram measurement, the transmitter can pass 10-G Ethernet eye mask with 25% margin at room temperature; Bit error rate (BER) from transmitter to receiver via 10-meter fiber can achieve 10-12 order, which confirm the transceiver's ability of 10-Gbps data transmission.

8267-12, Session 3

Multigigabit optical transceivers for high data rate military applications

B. Catanzaro, CFE Services (United States); C. Kuznia, Ultra Communications, Inc. (United States)

Avionics has experienced an ever increasing demand for processing power and communication bandwidth. Currently deployed avionics systems require gigabit communication using opto-electronic transceivers connected with parallel optical fiber. Ultra Communications has developed a series of transceiver solutions combining ASIC technology with flip-chip bonding and advanced opto-mechanical molded optics. Ultra Communications custom high speed ASIC chips are developed using an SoS (silicon on sapphire) process. This circuits are flip chip bonded with sources (VCSEL arrays) and detectors (PIN diodes) to create an OEIC. These have been combined with micro-optics assemblies to create transceivers with interfaces to standard MT cabling technology. We present an overview of the demands for transceivers in military applications and how new generation transceivers leverage both previous generation military optical transceivers as well as commercial high performance computing optical transceivers.

8267-13, Session 4

Si-based optical I/O for optical memory interface

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We present a bulk-Si-based photonics platform suited for high-speed, low-cost, and low-power memory interfaces. In coming years, the existing electrical memory interface is expected to confront its technical limits of scalability and power cost, and may require the adoption of optical interconnects. The optical channels are already being introduced around the PC, but silicon photonics technology potentially featuring both of low cost and high speed should be developed to address the memory systems.

We present a photonics platform based on local oxide under-cladding and amorphous-Si waveguide core crystallized by solid phase epitaxy (SPE) or laser epitaxial growth (LEG). Since the platform does not require the silicon-on-insulator (SOI) substrate, it can be on-die integrated with most of existing electrical devices in a cost-effective manner.

The crystallization processes have allowed us to achieve propagation loss of -0.6dB/mm and coupling loss of 2.7dB, which are record low among the bulk Si-based results, to author's knowledge. On the bulk-Si platform, we have achieved modulators having active length of 200µm, modulation speed of 5Gbps, and power consumption of ~2 pJ/bit. The modulation speed has increased over 10Gbps with the pre-emphasis technique. 7Gbps Ge/Si photodiodes are also achieved in surface-illumination type. Furthermore, we have demonstrated a 10Gbps 1x4 optical link for CPU-DRAM interface indicating that optical interconnects can support large memory capacity and expandability at high speeds, unlike electrical ones.

8267-14, Session 4

Widely tunable photonic crystal filters for optical interconnects on Si chip

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The paper presents experimental and theoretical demonstration of integrated optical narrowband filters based on nondefect 1D Silicon Photonic Crystal (PC). The compact filters have ultra-narrow bandwidth of 0.4 nm and enable wide tuning of the passbands up to 100 nm. High extinction ratio exceeding 20dB at high modulation of reflection/transmission coefficient can be achieved. By infiltration of the central single groove of 1D PC with matching filler, an efficient Fabry-Pérot microresonator was realized in which the wide-band photonic band gap (PBG) was used for the frequency channel switching. By using nematic liquid crystal E7 as a filler, the precise tuning of the obtained resonance bands was experimentally achieved by either varying the temperature from 10° to 65°C or by application of electric field ranging from 0 V to 10 V. The PBG map approach was used as a core engineering tool to predict formation and separation of transmission channels within the PBG and, thus, to determine effectively the exact design parameters of the optical device. The experimentally obtained spectral characteristics in the NIR range around 1.55 µm validated the proposed method and its applicability for the wavelength selective switching (WSS) as well as for the wavelength division multiplexing (WDM) in Si chip optical interconnects.

8267-15, Session 4

Silicon nanomembranes for high performance flexible photonic interconnects and devices

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In this paper, we demonstrate the practicality of using silicon nanomembranes for use in high performance flexible photonic interconnects and devices. Compared with surface normal optical devices, in-plane photonic devices have stringent requirements on transfer precision because any shift in the position or breakage can affect the performance of devices. Therefore, using two silicon nanomembrane transfer schemes, we demonstrate successful transfer of several photonic building blocks including large aspect ratio (>4000) and long (>1cm) strip waveguides, band engineered slow light (ng > 30) photonic crystal waveguides, 1xN (1x6 and 1x12) multimode interference couplers etc, and photonic devices such as photonic crystal waveguide modulators, photonic crystal waveguide based true time delay lines, polarization splitters etc on a flexible Kapton polyimide substrate. The first method based on a modified stamp assisted transfer technique, utilizes a supporting layer consisting of a photoresist is exploited to protect the device during the transfer process. The second method based on a modified bonding technique involves a two step process - 1) bonding of silicon-on-insulator (SOI) wafer onto flexible substrate, and 2) removal of bulk silicon wafer. Both these methods have demonstrated their suitability for development of flexible photonic interconnects and devices. Unlike silicon nanomembrane components on a rigid substrate such as glass, silicon nanomembrane devices transferred on flexible substrates suffer from the lack of a reliable cleaving process for waveguide facet preparation. Therefore, a two-step cleaving method is developed and implemented to facilitate testing of the transferred in-plane flexible photonic components for the first time. This demonstration of true flexible photonic components opens limitless possibilities for the deployment of high performance flexible photonic components using silicon nanomembrane technology in a variety of applications including communication, sensing, medicine, agriculture etc

8267-16, Session 4

Photonic crystal cavity based cascaded modulators for WDM interconnects

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Wavelength division multiplexing (WDM) is the key technique for optical interconnects. Typical on-chip WDM systems consist of multiple lasers that are each modulated separately and then combined into a single channel by a multiplexer [1]. Such schemes suffer high losses at interfaces between sections and the complexity requires very precise fabrication, making the realisation of Tbit/s systems very difficult.

We have experimentally demonstrated a simple but more efficient technique to modulate and multiplex multiple channels. Our design is based on a bus waveguide (e.g. Silicon Oxynitride) vertically coupled to multiple Photonic Crystal (PhC) cavities, each of which modulates an individual channel in place. This coupling scheme is very efficient-potentially allowing 99% coupling into a cavity with Q=10,000. Light from a multi-wavelength laser may be coupled into the bus waveguide providing a compact, simple system with large tolerances. By using relatively large Q-factors (~10,000), modulation may be achieved using weak effects such as carrier depletion.

The PhC cavity modulators have a small footprint and very low switching energies (~fJ/bit). The frequency response is limited by the photon liftetime (<25ps) but may allow data transmission at rates above 20Gbit/s. Finally, the low index contrast bus and efficient coupling to the cavity allows low insertion (<0.5dB), high extinction ratio modulation (20dB+). Large arrays of single mode PhC cavities have been demonstrated [2], thus demonstrating the potential for 1 Tbit/s data transmission.

[1] Optics Express 16, 4413 (2008)

[2] Nature Photonics 2, 741-747 (2008)

8267-17, Session 5

Link power budget advantage in GI-core polymer optical waveguide link for optical printed circuit boards

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For further advancement of next-generation high-performance computers, low-power consumption, high-density, and low-cost optical interconnection technologies should be adopted, and thus, optical printed circuit boards (O-PCBs) implementing polymer optical waveguides would be a key device. In particular, for low-power consumption, the link power budget should be low enough. In the optical link that consists of two waveguides on PCBs and an MMF connecting the two PCBs, such a low power budget is expected when GI-core waveguides are utilized. Essentially low coupling loss between the GI-core waveguide and an MMF is one of the reasons of the low power budget, since the mode power profile mismatch between MMFs and GI-core waveguides is smaller than that between MMFs and SI-core waveguides.

In this paper, we compose an optical link of VCSEL-waveguide (SI or GI)-MMF-waveguide (SI or GI)-PD, and quantitatively evaluate the coupling loss at each connection point. When all the components are perfectly aligned, the total coupling loss is 1.9 dB in the link with GI-core waveguide. On the other hand, the SI-core waveguide link shows 0.8 dB higher coupling loss (2.72dB) than the GI-core waveguide link. When a misalignment of ±10 um is added at each connection and 50-um gaps are added at both VCSEL-waveguide and waveguide-PD connections, the GI-waveguide link demonstrates approximately 2-dB advantage in the power budget over the SI-waveguide link. Given limited power budget consideration for high bit rate optical links (~25 Gb/s), GI-core waveguide enabling low link power budget would be a promising component for O-PCBs.

8267-18, Session 5

Novel optical interconnect devices applying Mask-Transfer Self-Written method

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Optical interconnect is well-suited for high-capacity data transfer systems and large parallel processing computer systems. The success of the optical interconnects for practical use strongly depends on the development of sophisticated packaging and coupling technologies achieving both high coupling efficiency and easy alignment. One of the promising technologies to achieve this is the Self-Written Waveguide (SWW) technology with light-curable resin. The SWW technology enables fabrication of an optical channel waveguide growing from the end face of the optical fiber by the irradiating light, just like an icicle, which has very high coupling efficiency between the fabricated waveguide core and the optical fiber.

We have developed this “classic” fiber-SWW technology to a new method of the “Mask-Transfer Self-written (MTSW)” method. This new method enables fabrication of arrayed M x N optical channels at one shot of the light. Using this technology, several new optical interconnect devices have been tried. First, we will introduce plug-in alignment approach using the Optical Waveguide Plug (OWP) and the Micro-Hole Array (MHA) made of the light-curable resin. Plug-in alignment between a fiber and an OE-Printed Wiring Board (PWB), between a fiber and a VCSEL will be possible. Next, we will show a new three-dimensional (3D) branch waveguide. By controlling the irradiating angle through the mask aperture, it will be possible to fabricate 2-branch and 4-branch waveguide having a certain branch angle. The 3D branch waveguide will be very promising in the future optical interconnects.

8267-19, Session 5

Coplanar optical waveguides for optical interconnects

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For development of PCB-compatible optical interconnects, a hybrid metal coplanar optical waveguide is investigated theoretically and experimentally. By staking thick Cu strips in a homogeneous dielectric medium, the field of the guided mode is confined in the vertical and lateral directions. The propagation loss of the fabricated hybrid metal coplanar optical waveguide is slightly higher than that of conventional dielectric waveguide because of the loss due to metal strips. The 2.5 Gb/s optical signal is successfully transmitted via 10-cm-long hybrid metal coplanar optical waveguides.

8267-20, Session 5

Single-mode glass waveguide technology for optical interchip communication on board level

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The large bandwidth demand in long-distance telecom networks lead to singlemode fiber interconnects as result of low dispersion, low loss and dense wavelength multiplexing possibilities. In contrast, multimode interconnects are suitable for much shorter length up to 300 meters and are promising for optical links between racks and on board level. Active optical cables based on multimode fiber links are at the market and research in multimode waveguide integration on board level is still going on. Compared to multimode, a singlemode waveguide has much more integration potential because of core diameters of around 20% of a multimode waveguide by a much larger bandwidth. Of course light coupling in singlemode waveguides is much more challenging because of lower coupling tolerances. Together with the silicon photonics technology, a singlemode waveguide technology on board-level will be the straight forward development for chip-to-chip optical interconnects integration. Such a hybrid packaging platform providing 3D optical singlemode links bridge the gap between novel photonic integrated circuits and the glass fibers. We introduce our 3D photonic packaging approach based on thin glass substrates with planar integrated optical singlemode waveguides for fiber-to-chip and chip-to-chip interconnects. This novel packaging approach merges micro-system packaging and glass integrated optics. This kind of packaging consists of a thin glass substrate with planar integrated singlemode waveguide circuits, optical mirrors and lenses providing a platform for photonic IC assembling and optical fiber interconnects. Thin glass is commercially available in panel and wafer formats and characterizes excellent optical and high frequency properties. That makes it perfect for microsystem packaging. The paper presents recent results in waveguide technology on wafer level and waveguide characterization (cut-back, polarization dependence, coupling loss, numerical aperture). Also the integration in a hybrid packaging process and design issues are discussed.

8267-21, Session 5

Optical waveguide end roughness in correlation to optical coupling

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With the ever-increasing demand for board-to-board optical data communications, there should be a thorough understanding on the correlation between waveguide surface end roughness and coupling losses in order to mass produce optical waveguide boards cost-efficiently. In this study, end roughness of siloxane polymer optical waveguides will be studied and measured in terms of optical coupling losses as well as optical bit error rates.

Siloxane Polymers OE-414X available from Dow Corning were used to fabricate 50 x 50 µm rectangular waveguides through the photolithographic process. Edge roughness was controlled through various grades of fiber-optic polish films and measured using interferometric microscopy (IFM). Industry-grade 50 µm fibers with SC and MT connectors were utilized to inject and capture guided light. Electromagnetic modeling simulations were performed to correlate experimental and theoretical results. Controlled lab results are compared with industrial polishing techniques that are consistent with mass-production methods.

8267-22, Session 6

Next-generation high-density low-cost multimode optical interconnect

M. Hughes, D. Childers, J. Graham, US Conec Ltd. (United States)

This paper describes the development of a next generation optical interconnect passive component. This low cost, dense optical interconnect technology combined with recent advances in 10G/lane and beyond, miniature embedded Tx/Rx devices will help enable future bandwidth intensive applications.

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 incorporation of multiple rows of fibers into a single ferrule unit. The design supports up to four rows with as many as 16 fibers per row for a total potential lane count of up to 64 within in a single ferrule.

A low cost termination is achieved by securing precision-cleaved fiber arrays into the rear of the ferrule with a quick-cure, index matched, UV light activated epoxy. The elimination of a polished fiber array greatly reduces the cost and complexity associated with physical contact based multi-fiber interconnects. With the same overall footprint as an MT ferrule, the new, lens-based ferrule can be used in conjunction with MPO and other MT based connectors. However, by eliminating the need for physical contact via the use of collimated light beams, the connection force per ferrule required is greatly reduced, paving the way for high ferrule counts and mass insertion of dense optical backplanes.

Mated pairs of the new ferrule were tested for insertion loss with results for all channels supporting functional point to point links.

8267-23, Session 6

Rapid prototyping of interfacing microcomponents for printed circuit board-level optical interconnects

J. Van Erps, Vrije Univ. Brussel (Belgium)

No abstract available

8267-24, Session 6

Tailored hybrid materials for sub-100 nm two-photon lithography and micro-optical applications

S. Steenhusen, N. Tucher, R. Houbertz-Krauss, Fraunhofer-Institut für Silicatforschung (Germany)

The combination of two-photon polymerization (2PP) technology and specially designed hybrid polymers (ORMOCER®s) enables the route to the fabrication of arbitrary 3D structures and new photonic devices.

It is well known that, by employing the strongly confined volume of polymer solidification in 2PP, it is not only possible to create feature sizes beyond the diffraction limit, but also to fabricate freeform 3D structures in a single process step. Typically, however, mostly purely organic photopolymers lack mechanical, thermal, and chemical stability and, dependent on the polymer, their optical quality might not be sufficient for data- or telecom applications. Thus, ORMOCER®s are used as photoresists, which exhibit low optical losses and outstanding physical properties. Their material properties can be tailored by the choice of precursors for synthesis and reaction conditions, thus modifying the material on the molecular level and matching applications demands.

For the fabrication of 3D optical elements, different laser systems with adjustable repetition rate, power and wavelength were used to create microoptical elements such as diffractive optical elements, photonic crystals, phase plates, axicons, and freeform lenses using ORMOCER®s. Besides the fact, that some of these elements cannot be fabricated with conventional 2 or 2.5D lithography, we demonstrate that our choice of technology and material allows the creation of finest features (100 nm scale) and large structure sizes (> 1 mm²). Furthermore, first results on optical characterization will be shown revealing the performance and possible application potential of the structures.

8267-25, Session 6

Soft lithography fabricated polymer waveguides and 45-degree inclined mirrors for card-to-backplane optical interconnects

G. Jiang, S. Baig, M. R. Wang, Univ. of Miami (United States)

The 45° inclined waveguide mirror plays a significant role in the optical interconnects at the card-to-backplane level. Various techniques have been proposed for fabrication of 45° mirrors, such as blade cutting, laser ablation, reactive ion etching, and soft molding. Recently, soft molding shows obvious advantages as a convenient, effective and low cost fabrication technique for micro- and nanostructures. In the conventional soft lithography approach, the soft molding often results in a remnant layer between the anticipated waveguide and the substrate. This is a critical problem especially in the 45° waveguide mirror fabrication. The coupling efficiency of the waveguide modes to the surface normal output light beam through the waveguide mirror will be decreased due to poorer mode profile overlapping with the waveguide mirror structure. The return light coupling from the surface normal light beam to the waveguide may experience unwanted coupling to the residual polymer layer. In this paper, we present 45° inclined mirror fabricated by vacuum assisted microfluidic technique for card-to-backplane optical interconnect applications. Effective card-to-backplane waveguide interconnection will be demonstrated. The high coupling efficiency of the mirror can be realized because of eliminating the residual layer between the channel waveguide and the substrate.

8267-26, Session 7

Aspects of short-range interconnect packaging

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In short-range interconnect applications, one question arises frequently: When should optical solutions be chosen over electrical wiring? The answer to this question of course depends on several factors like costs, performance, reliability, availability of testing equipment and knowledge about optical technologies and last but not least, it strongly depends on the application itself. Networking in high performance computing (HPC) is one such example. With bit rates around 10 Gbit/s per

channel and cable length above 2 m, the high attenuation of electrical cables leads to a clear preference of optical or active optical cables (AOC) for most planned HPC systems. For AOCs, the electro-optical conversion is realized inside the connector housing, while for purely optical cables, the conversion is done at the edge of the board. Proceeding to 25 Gbit/s and higher, attenuation and loss of signal quality turn critical. Therefore, either significantly more effort has to be spent on the electrical side, or the package for conversion has to be integrated closer to the chip, thus requiring new packaging technologies. The paper provides a state of the art overview of packaging concepts for short range interconnects, it describes the main challenges of optical package integration and

illustrates new concepts and trends in this research area.

8267-27, Session 7

Novel coupling and packaging approaches for optical interconnects

B. Van Hoe, E. Bosman, J. Missinne, S. Kalathimekkad, G. Van Steenberge, P. Van Daele, Univ. Gent (Belgium)

Interconnecting fibers and optical waveguides to integrated optoelectronic sources and detectors is one of the most critical parts when building an optical interconnection scheme. Moreover, there is a need to integrate the optoelectronics and the waveguide structure in one thin and flexible packaging structure.

We present the design and fabrication of a full optical interconnection scheme including the optoelectronic package, containing driving VCSELs and read-out detectors, the coupling scheme of the fiber or waveguide interconnect and the fabrication of the waveguide structures itself. Both the optoelectronic package and the waveguide part are fabricated using polymer materials resulting in a low-cost, flexible interconnection scheme.

The optoelectronic package consists of an ultra-thin (25 µm) chip embedded in a polyimide based flexible polymer stack, connected through metalized microvias using thin film deposition steps. A 45° micromirror is used to couple this optoelectronic package to an optical fiber or an optical waveguide. The waveguiding structures can be integrated with the coupling plug leading to a 1 step alignment process which significantly reduces the coupling losses. Flexible and stretchable multimode polymer waveguides are also developed to end up with a fully flexible optical interconnect for short (waveguide) or long distance (fiber) communication.

Typical applications are investigated in this paper and include short-distance optical links in for example cellular phones or optical back panels. Integrated fiber sensing is another field of interest where an integrated, flexible package and coupling scheme has several advantages over the traditional optoelectronic sources. Ultra-thin optical sensors using the embedded optoelectronics are the last set of applications which are discussed in this paper.

8267-28, Session 7

Chip-to-chip interconnects based on 3D stacking of opto-electrical dies on Si

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We demonstrate error-free operation of a 10 Gb/sec photonic link incorporating a 850nm VCSEL and a photodiode integrated directly on silicon. The integration approach is based on stacking commmercial opto-electrical devices on CMOS substrates to maximize bandwidth density of the interconnect. In this very first proof of principal demonstration, we used a silicon substrate on which we evaporated gold co-plannar waveguides (CPW) to mimic a wire on the driver. The gold wires were later covered by a thick layer of SiO2 and narrow via's (2 micrometer) were etched in the SiO2 to provide vertical electrical connectivity through the isolating SiO2 layer. Electrical plating was used to metalize the via's and top bonding pads, creating a low resistance connectivity which was confirmed by comparing the V-I & L-I curves of a stacked VCSEL with those of a similar device probed directly. The VCSEL and photodiode chips are mounted to the contact pad with Epo-Tek ®H20E epoxy, which has been widely used for chip bonding in microelectronic and optoelectronic applications.

An optical link consisting of a VCSEL chip and a photodiode chip has been assembled and fully characterized using optical coupling into and out of a multimode fiber (MMF). The coupling loss between VCSEL and fiber is around 3 dB, and another 1 dB loss between fiber and photodiode. A 10 Gb/s 27-1 NRZ PRBS signal transmitted from one chip to another chip was detected error free. A 4 dB receiver sensitivity penalty is measured for the integrated device compared to a commercial link.

8267-29, Session 7

Proposal and FDTD simulation of reflective self-organizing lightwave network (R-SOLNET) using phosphor

M. Seki, T. Yoshimura, Tokyo Univ. of Technology (Japan)

We simulated self-organization of optical waveguides that connect two optical devices, where the reflective self-organized lightwave network (R-SOLNET) using phosphor is utilized, by the finite difference time domain (FDTD) method. In R-SOLNET using phosphor, optical devices with phosphor are placed in a photo-polymer. Write beams from some of the devices and luminescent write beams from the phosphors of the other devices overlap. In the overlap regions, the refractive index of the photo-polymer increases, pulling the write beams to the phosphor locations (the "pulling water" effect). By self-focusing, self-aligned optical waveguides are formed between the optical devices.

In the present work, we simulated self-organization between an optical waveguide and a phosphor target utilizing R-SOLNET using phosphor by the FDTD method.

Simulation models of R-SOLNET using phosphor are as follows. A waveguide was placed in a photo-polymer. A phosphor target was placed 6.4 µm away from the waveguide edge. The center of the phosphor target was misaligned from light axis of the waveguide. Refractive index of the photo-polymer varies from 1.5 to 1.7 with write beam exposure. Wavelengths of write beams, luminescence and probe beams are 351 nm, 400 nm and 633 nm, respectively.

From the simulation, it was found that R-SOLNET was constructed between the waveguide and the phosphor target and probe beams were guided to the phosphor target. Optical coupling efficiency was 95% when no misalignment exists between the phosphor target and the waveguide. Even when the misalignment is 800 nm, optical coupling efficiency of 60% was kept.

8265-01, Session 8

Requirements for optical interconnect and networking devices for low-energy communications within digital systems

A. L. Lentine, Sandia National Labs. (United States)

Information and communications technology (ICT) consumes 10% of the nation's electricity, with data centers comprising a 25% of the total. Interconnections between switching and routing equipment, between integrated circuits on a printed circuit board (PCB), and within integrated circuits are becoming a growing fraction of the total power consumption. The use of optical modules for interconnection between electronic sub-assemblies is increasing, but the approach will not scale as bandwidth needs increase.

Intimate integration of optics and electronics will be required for power consumption to decrease significantly over today's optical interconnect solutions. These future solutions are likely to require single mode operation to reduce receiver complexity and power dissipation, and dense wavelength division multiplexing to enable increased bandwidth density and waveguide technology to facilitate packaging in a manner compatible with today's electronic circuit boards.

Silicon photonics is well known to be a candidate for satisfying the requirements for these future systems. We will review the applicable devices and their requirements to enable reduced energy consumption in these systems. In particular, we will discuss the advantages and disadvantages of connecting processing or switching and routing subsystems with optical networks versus optical interconnections of electronic networks.

8265-02, Session 8

Multicore fiber link demonstrating large bandwidth density for future multimode optical interconnects

B. G. Lee, C. Baks, F. E. Doany, D. M. Kuchta, P. K. Pepeljugoski, C. L. Schow, IBM Thomas J. Watson Research Ctr. (United States)

Optical interconnects are now prevalent in high-performance computing (HPC) systems. Their superior bandwidth-distance product compared to electrical interconnects has been leveraged to facilitate performance scaling within the most aggressive machines in recent years. However, optical fiber systems in future HPC generations must meet growing bandwidth requirements, while maintaining feasible power and cost targets in addition to maintaining manageable volumes of fiber cabling. As a result, increasing bandwidth per fiber while only marginally increasing link cost and power is a primary goal for future optical interconnects. This presentation will describe recent results in multicore multimode fiber technologies, which may provide the added bandwidth per link required in next generation HPC systems.

A transmitter and receiver have been developed to interface to a seven-core graded-index multimode fiber constructed by OFS. The transmitter consists of a flip-chip packaged assembly with 130-nm CMOS driver ICs and custom VCSEL arrays (fabricated by Emcore Corporation) arranged to interface the multicore fiber. A silicon carrier with optical vias allows optical access to the VCSEL devices. The receiver consists of two wire-bond integrated 4-channel transimpedance amplifier ICs and a six-channel photodiode array (again fabricated by Emcore Corporation) to interface the multicore fiber. Aggregate data transmission of 120 Gb/s per fiber was realized. Bit-error rate measurements characterizing the amplitude and timing margins are performed to analyze the crosstalk experienced by the multiple channels within the link.

8267-30, Session 8

Optics in computers, servers, and data centers

H. J. S. Dorren, Technische Univ. Eindhoven (Netherlands)

No abstract available

8267-31, Session 8

Chip-scale integrated optical interconnects: a key enabler for future high-performance computing

M. W. Haney, Univ. of Delaware (United States)

Integrated Optical Interconnect (OI) technology is poised to provide the ultra-high chip-level bandwidths needed within future high performance computing (HPC) systems. Integrated OI will enable HPC to scale to the 50 GFLOPS/W level - far beyond the projected performance of HPC systems based on conventional metal trace-based interconnect fabrics. Emerging Si-photonics-based and hybrid III-V OI platforms are projected to enable this unprecedented HPC throughput scaling by providing channel densities that are higher, and link power requirements that are lower, than those provided by electrical interconnects. However, before the full benefits of integrated OI may be realized, efficient and cost-effective packaging must be developed that provides the desired "seamless" integrated OI fabric at the inter- and intra-chip levels, yet is compatible with conventional chip/package/board integration technology. Si-photonics, with its integrated single-mode waveguides fabrics, is projected to provide superior interconnect bandwidth densities, while hybrid multi-mode waveguide-based OI platforms may provide easier interfacing and packaging. But what platform will best enable Si-CMOS performance to scale to its full potential as the Silicon technology node approaches its ultimate limit? In this paper, the performance scaling benefits of chip-scale OI are reviewed and packaging/interface issues are discussed to highlight key remaining challenges to the high-impact deployment of integrated OI in future HPC systems.

8265-03, Session 9

Silicon photonics in computing applications

M. Watts, Massachusetts Institute of Technology (United States)

The continued Moore's Law scaling of microelectronics is driving not only compute power and storage, but the communications links required to feed the growing information capacity. The growth in information content is straining wireless networks, the wavelength division multiplexed (WDM) communications on telecom links, communications within the data centers that power the Internet and increasingly the processor-to-memory communication subsystems within personal computers. The exponential growth of Moore's Law scaling is sufficiently intense that even short reach electrical communication links to peripheral devices will be outstripped in the near future. Ultimately, it is conceivable that even on-chip electrical communications will need to be replaced with optical links.

With the demonstration of high-speed and low-power silicon modulators and germanium detectors, along with flattop filters on CMOS lines around the world, silicon photonics has emerged as a potential solution to each of these communication bottlenecks. Yet, despite these developments significant challenges remain. To date, no consensus exists for integration with CMOS nor has a WDM source to power these chips been clearly identified. Moreover, only a handful of devices have been effectively integrated together and cost-effective packaging solutions are years away. For silicon photonics to be widely adopted these and other challenges will need to be addressed. Here, we review recent results in silicon photonics and compare options for the addressing some of the remaining challenges.

8265-04, Session 9

Multiprocessor silicon photonic interconnects: a systems perspective

P. Koka, Oracle Labs. (United States)

The high bandwidth density and low power consumption characteristics of silicon photonics devices can provide a high performance interconnect solution for multiprocessor systems. At the same time his

technology also poses a new set of constraints and challenges in architecting, designing, and integrating such systems.

The 'macrochip' multiprocessor architecture leverages a photonically interconnected array of processor and/or memory chips to provide a flexible platform to build heterogeneous systems. The design considerations for such a system are influenced largely by the system architecture, the programming model and devices needed for their implementation. This talk will first describe the macrochip platform, technology constraints and potential interconnect solutions with the various device building blocks. Then it will present some topology choices that range from a WDM point-to-point interconnect to more complex switched data channel networks. It will close with a detailed analysis of these design choices and show the impact of the device constraints on performance and power consumption along with some recent ultra-low power device implementation results.

8267-32, Session 9

Chip-scale photonic interconnection networks for energy efficient processor-memory communications

K. Bergman, Columbia Univ. (United States)

No abstract available

8267-33, Session 9

Low-power integration of on-chip nanophotonic interconnect for high-performance opto-electrical IC

D. Ding, D. Z. Pan, The Univ. of Texas at Austin (United States)

No abstract available

8267-34, Session 10

Nanophotonics for information systems

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

This paper explores the role of nanotechnology with focus on dielectric, metal, and semiconductor inhomogeneous composites, devices and subsystems for information systems. We emphasize construction of optical subsystems directly on-chip, with same lithographic tools as the surrounding electronics. We present our work on monolithically integrated Si-photonic pulse compressor and heterogeneously integrated metal/dielectric/semiconductor nanolasers.

8267-35, Session 10

Energy-efficient high-speed 850 nm VCSELs for optical interconnects

J. A. Lott, N. N. Ledentsov, VI Systems GmbH (Germany)

Invited Talk

8267-36, Session 10

Design and experimental study on the grating outcouplers providing the controlled 2D-intensity profile of the output beam from a broad area laser diode

O. V. Smolski, V. O. Smolski, E. C. Browy, E. G. Johnson, The Univ. of North Carolina at Charlotte (United States); Z. A. Shellenbarger, SRI International Sarnoff (United States)

We present a method of designing the advanced grating outcoupler to obtain the desired 2D-intensity profile of the optical beam emitted by a grating coupled surface emitting laser. The method is based on the variation of grating parameters, such as the periodicity, duty cycle, and groove tilt angle, which is easily implemented by e-beam lithography. Grating design involves detailed analysis of the optical field propagated through the grating, applying simulating tool based on the Rigorous Coupled Wave Approach (RCWA) numerical method. RCWA has an advantage due to fast computation time and high accuracy and is specifically designed for analysis of the diffractive optics/structures. Experimental evaluation of the designed grating components was done by fabrication and testing the broad area semiconductor lasers with the monolithically integrated grating outcouplers. We present the obtained results along with Near- and Far-Field data demonstrating a hundreds microns scale, uniform optical intensity profile from the grating outcoupler with variable duty cycle. We also present a grating design provides spreading a single optical output into multi-beams at different outcoupling angles in the emitting plane. Such outcouplers are very attractive for designing optical elements based on coherent combining multiple phase-locked beams. Specific fabrication issues are also discussed.

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The views expressed are those of the author and do not reflect the official position of the Department of Defense or the U.S. Government.

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8267-37, Session 10

Novel VCSEL driving technique with virtual back termination for high-speed optical interconnection

M. Sugawara, Y. Tsunoda, H. Oku, S. Ide, K. Tanaka, Fujitsu Labs., Ltd. (Japan)

For developing optical interconnects for high-performance computing systems or high-end servers, high-density and high-speed optical modules are strongly required. An optical module with flip-chip bonding structure is effective for achieving compact size and speeds over 25-Gb/s. When the flip-chip structure is applied, the VCSEL is connected to the driver via the transmission-line. That is, developing the VCSEL driving technique which is able to make impedance matching to the transmission-line is a critical issue. In this work, we develop a simple and high-speed VCSEL driving technique with “Virtual back termination”.

To realize the flip-chip mounting, back termination has to be implemented to reduce the signal reflection via transmission-line. Additionally, the back termination must have simple dc-coupling, facilitated by removing large ac-coupling capacitors. Introducing a virtual GND to the circuit enables to satisfy these requirements. The virtual GND is made by a dummy-load connected to a complementary output and dc-coupled 50-Ω resisters between output and complementary output. The dummy-load has characteristics similar to the load VCSEL. Thanks for the virtual GND, the resisters act as the back termination.

We fabricated a driver circuit with the Virtual back termination by using SiGe Bi-CMOS technology, and evaluated the characteristics of our driving technique. The high-speed VCSEL was connected to the driver’s output via a 10-cm co-axial cable as a transmission-line. A clear eye-opening without reflectance effects was obtained up to 28-Gb/s despite using such a long transmission-line. These results show that our driving technique is suitable for high-speed optical interconnect applications.

8267-38, Session 11

Application of MIMO technology for next-generation optical and millimeter-wave interconnects

G. Chang, Georgia Institute of Technology (United States)

No abstract available

8267-39, Session 11

Device design for multiple-input multiple-output (MIMO) over multimode optical fiber

S. R. Bank, S. Vishwanath, K. Appaiah, S. Zisman, The Univ. of Texas at Austin (United States)

No abstract available

8267-40, Session 11

A high-speed 0.35um CMOS optical communication link

M. E. Goosen, INSiAVA (Pty) Ltd. (South Africa) and Univ. of Pretoria (South Africa); A. C. Alberts, P. Rademeyer, A. W. Bogalecki, INSiAVA (Pty) Ltd. (South Africa); M. du Plessis, P. J. Venter, Univ. of Pretoria (South Africa)

The idea of integrating a light emitter and detector in the cost effective and mature technology which is CMOS remains an attractive one. The light emitters, with an operating temperature range of -40 °C to 125 °C, are integrated in a standard 0.35 µm CMOS process utilizing no post processing. In this paper we discuss our recent advances and results towards an all-silicon optical data link solution. The directly modulated light emitter array is aligned to an optical fiber end and using a commercial silicon avalanche photodiode (APD), an optical link capable of multi-Mb/s data throughput is established. The utilized silicon light emitters are demonstrated to be able to switch at frequencies above 500 MHz and are electrically detected over a narrowband to negate the noise contribution of the APD which limits the received signal to noise ratio. Utilizing techniques such as increased array sizes and novel BEOL-stack reflectors, the power efficiency is improved in order to allow higher data rates.

In this paper we present an all silicon optical link capable of a data throughput in excess of 10 Mb/s at a bit error rate of less than 10-12, representing a tenfold increase over the previous fastest demonstrated all-silicon optical data link. Data rates in excess of 40 Mb/s is also demonstrated and evaluated. The quality of the optical link will be established using both eye diagram measurements as well as a digital communication system setup. The digital communication system setup comprises the generation of 232-1 random data, 8B/10B encoding and decoding, data recovery and the subsequent bit error counting.

8267-42, Poster Session

Design and fabrication of a compact 1-by-4 multimode interference power splitter

L. Ma, H. Zhu, Institute of Semiconductors (China); M. Chen, Tsinghua Univ. (China)

A compact 1-by-4 InGaAsP/InP multimode interference (MMI) power splitter based on multimode interference effects and useful for application with multiwavelength lasers was fabricated by using a strongly guided ridge structure.The effective index method (EIM)and the 2D FD-BPM method were applied for device design and simulation.In the design,single mode ridge waveguides and multimode interferences were connected by 25-um-long tapered waveguides to reduce the mode coupling loss between the two types of waveguides.By using a strongly guided ridge structure,the device had a small size,the MMI was 24 um wide and 308 um long.The simulation showed the designed structure had low excess loss and acceptable fabrication tolerance.The metal-organic Chemical Vapor Deposition(MOCVD)grown wafer was processed by conventional photolithography and optimized CH4/H2 reactive ion etchin(RIE)for device fabrication.An optimized 1.7 um thick InP cladding layer was epitaxial grown to obtain better device performence.In order to obtain extremely smooth sidewalls ,an O2 descumming process was used and the SiO2 mask was removed by ICP dry etching to control the width tolerance within 0.5 um.The propagation loss was as low as 3.2dB/cm for 2-um-wide straight waveguides at a 1.55-um wavelength. The insertion loss at each output port was measured as low as 6.4dB by automatic coupling test system.The uniformity of the four output port was 0.72.The fabrication tolerances and the wavelength sensitivity were also discussed.For the designed 1-by-4 multimode interference power splitter,the measured results were within the fabrication tolerances obtained from the FD-BPM simulation.Further improvements in device performances can be aciqured by more precise control of the photolithography and the etching processes.

8267-43, Poster Session

Transmitting part of optical interconnect module with three-dimensional optical path

C. Chang, P. Shen, C. Chen, H. Hsiao, National Central Univ. (Taiwan); Y. Lee, Centera Photonics Inc. (Taiwan); Y. C. Chang, M. Wu, National Central Univ. (Taiwan)

In this paper, transmitting part of optical interconnect module with three-dimensional optical path is demonstrated. In this module, electronic-device part and photonic-device part are separated on the different sides of SOI wafer. In the electronic-device part, VCSELs and PDs can be package on SOI rear side. Trapezoidal waveguide which is 40 um (width) x 40 um (height) and Si-based 45 degree micro-reflector are fabricated on device layer of SOI. Furthermore, optical modulator and WDM also can be combined in photonic-device part, and Driver and TIA ICs can be fabricated on electronic-device part of SOI by standard CMOS process. The VCSELs lightwave on the rear side of SOI pass through the substrate; impinge upon the Si-based 45 degree reflector and couple into trapezoidal waveguide. High frequency signal can be linked between electronic-device part and photonic-device part without through silicon via (TSV) technique. Using double-side alignment technology, photonic-device layer can be combined with electronic-device layer on the SOI wafer. The proposed transmitting part of optical interconnect module is a cost effective structure and well suitable for mass production in intra-chip.

In this work, the optical coupling efficiency of the transmitting-part module is -8.09dB. The degradation 1-dB tolerances are 30 µm and 19 µm on the horizontal and vertical direction, respectively. The module in the operating speed of 2.5Gbps without drive ICs, the eye height and eye width are 34 mV and 350 ps, which can verify the module for 2.5Gbps signal transmission is a certain feasible.

8267-44, Poster Session

Improved performance of traveling wave directional coupler modulator based on electro-optic polymer

X. Zhang, B. Lee, C. Lin, The Univ. of Texas at Austin (United States); A. Wang, Omega Optics, Inc. (United States); A. Hosseini, X. Lin, R. T. Chen, The Univ. of Texas at Austin (United States)

Polymer based electro-optic modulators have shown great potentials for a variety of applications, such as telecommunication, analog-to-digital conversion, phased-array radar, and electrical-to-optical signal transduction. Existing commercial LiNibO3 Mach Zehnder modulators have intrinsic drawbacks in linearity to provide high fidelity communication. In this paper, we present the design, fabrication and characterization of a polymer based electro-optic modulator, which is able to provide high linearity, high speed, and low optical insertion loss. Silver bottom electrode is used to reduce waveguide sidewall roughness due to scattering of UV light in photo-lithography process in addition to suppressing the RF loss. A 1×2 multi-mode interference 3dB-splitter, a photo-beached refractive index taper, and air trenches fabricated by nano-imprinting technique are used to reduce the optical insertion loss of the device. The symmetric waveguide structure of the MMI-fed directional coupler is intrinsically bias-free, and the modulation is obtained around 3-dB point regardless of the ambient temperature. By achieving low RF loss, characteristic impedance matching with 50Ω load, and excellent velocity matching between RF wave and optical wave, a travelling wave electrode is designed to function up to 62.5 GHz. Domain inversion poling with push-pull configuration is applied on a two-section directional-coupler to achieve a spurious free dynamic range of 110 dB/Hz2/3. The 3-dB electrical bandwidth of device is measured to be 10 GHz.

8267-46, Poster Session

80um-core graded-index multimode fiber for consumer electronic devices

D. Molin, M. Bigot-Astruc, P. Sillard, Prysmian/Draka (France)

Transmissions of 5 to 10Gbps over few meters delivered by the recently introduced USB 3.0 and Thunderbolt interfaces for consumer electronic devices are close to the limit of Copper-based solutions. Low-cost optical interconnects are the logical next-generation solutions to cope with the ever-increasing bandwidth demand.

The assembly cost of optical interconnects is mainly driven by alignment tolerances. An alignment tolerance up to 10-20µm can provide a significant cost reduction compared to the 1-5µm tolerance offered by 50µm-core multimode fibers (MMFs). 80µm-core MMF, with a larger NA of ~0.3, is expected to offer such a flexibility together with a higher channel capacity and/or longer reach potentials than Copper-based solutions.

High-NA 80µm-core graded-index MMFs, however, have not been extensively investigated, especially under restricted launches that are typical of VCSEL-based sources. Actually, there is no Standard that specifies such large-core MMFs for high-speed transmissions.

In this paper, we will detail the realization and the characterization of high-bandwidth 80µm-core MMFs. System simulations will also be presented, providing insights into the bandwidth requirements for error-free transmissions at both 10 and 20Gbps over 10s of meters. Finally, we will propose fiber specifications based on DMD measurements to guarantee these bandwidth requirements.

8267-47, Poster Session

Mode coupling due to isotropic random heterogeneities in graded-index plastic optical fibers

A. Inoue, K. Makino, A. Kondo, Keio Univ. (Japan); T. Sassa, RIKEN (Japan); Y. Koike, Keio Univ. (Japan)

A graded-index plastic optical fiber (GI POF) is a promising transmission medium in (ultra) short-reach communication networks because of its easy handling and low-cost installation. It has been reported that the bandwidths of GI POFs can be influenced by mode coupling. However, the origin of mode coupling have not been well understood. For glass multimode fibers (MMFs), the phenomena due to mode couplings were studied in 1970s. The density fluctuations in optical glasses result in uniform Rayleigh scattering since their characteristic scales are much smaller than the guided light wavelengths in glass MMFs. Therefore, the mode coupling in glass MMFs have been mainly attributed to structural imperfections such as microbendings. On the other hand, polymer materials inherently have larger-sized microscopic heterogeneous structures than those of optical glasses. The heterogeneities in POF cores can result in mode couplings due to more directional forward scatterings than those in glass MMFs. However, this intrinsic characteristics of polymer materials have not been considered in the analysis of optical transmission characteristics of POFs. In this report, we correlated the mode coupling to the microscopic heterogeneous structure in GI POF core by a modified coupled power equation. We derived the power coupling coefficient due to the isotropic random heterogeneities with Gaussian autocorrelation functions and investigated the influence of the correlation characteristics to the optical pulse propagation through the GI POFs. The results showed that the mode coupling between the guided mode pair is maximized for the specific correlation length of the heterogeneities.

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8267-48, Poster Session

Inverted-tapered mode-size converter for coupling of optical fiber with Si-photonics chip

D. Kim, G. Kim, Electronics and Telecommunications Research Institute (Korea, Republic of)

An inverted-tapered mode-size converter for the coupling of a single-mode optical fiber with a Si waveguide has been fabricated. It is processed with a silicon-on-insulator (SOI) wafer with top silicon thickness of 220 nm. It has a length of 115 µm, a height of 220 nm, a width of 500nm, and a tip width of 50 nm. The Si narrow tip was prepared by reactive ion etching (RIE) the top silicon layer in two consecutive steps. The second core was fabricated using Siliconoxynitride (SiON) with refractive index of 1.65@1550 nm. It was deposited by plasma-enhanced chemical vapor deposition (PECVD) and successively etched to have a dimension of 3 µm x 3 µm x 560 µm. Another laterally tapered SiON second core with minimum width of 500 nm was fabricated for comparison. Silicon dioxide (SiO_2) with refractive index 1.458@1550 nm was deposited for overcladding layer. The finite-difference time domain (FDTD) simulation analysis with TE-like mode shows quantitatively good coupling efficiency of the optical fiber with inverted-tapered mode-size converter.

The fabricated mode-size converter shows 2.5 dB of coupling loss. The coupling loss was measured by butt-coupling a lensed fiber with spot size of 3 µm to the second core port of the mode-size converter. TE-like mode wave was swept from 1520 to 1620 nm of wavelength. The coupling loss spectrum shows wavelength independency. The coupling loss is originated from the mode mismatch and misalignment between optical fiber and silicon tip. The large index contrast between second core and overcladding makes confinement of the mode in the tip better, which causes the mode mismatch to increase. The box type of second core showed a slightly better coupling efficiency compared with the laterally taper one.

Conference 8268: Quantum Sensing and Nanophotonic Devices IX

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8268-02, Session 1

Mid-infrared field concentration of electrically-generated surface plasmons polaritons

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Surface-plasmon polaritons (SPPs) are electromagnetic waves which are bound at a metal/dielectric interface. SPPs dispersion relation allows bent propagation and can lead to sub-wavelength energy concentration. These properties, well known in the visible and near-infrared, are lost at mid-infrared and THz wavelengths. Here we demonstrate an integrated device which is able to recover and exploit the confinement properties of SPPs. It operates in the mid-infrared wavelengths by electrical injection, It generates plasmonic excitations whose dispersion is artificially tailored via proper patterning of a purely metallic surface. We illustrate the power of this approach by demonstrating bending, focusing and sub-wavelength energy concentration. We demonstrate a compact (<0.1 mm2) device, which is electrically driven and is able to generate, couple, propagate on a chip over macroscopic distances, and focus mid infrared radiation into a sub-wavelength region. We employ a scattering near-field scanning optical microscope to directly probe the SPP presence, propagation and characteristics. The near-field measurements directly show guiding and focusing effects, and prove that the electromagnetic field is confined within sub-wavelength proximity of the artificially patterned metallic surface.

8268-03, Session 1

Analytic calculation for scattering of electromagnetic waves by linear slot array

D. Huang, D. Wellems, Air Force Research Lab. (United States)

We calculate the diffraction of an incident plane electromagnetic wave by a slotted metallic film,

using a general model for an arbitrary linear array of slots with variable slot width, slot separation and slot dielectric material. In contrast to conventional far-field optics, our model

shows that a planar metallic film containing a 1D slot array can be used for focusing polarized light in the near-field region when either the slot width or the slot dielectric material becomes spatially nonuniform. In addition, we also calculate the tunneling and scattering of surface-plasmon waves through a finite slit array on a metallic film filled with variable dielectric material, where the surface-plasmon waves are excited by a Gaussian beam incident on a slit below the array and detected at a slit above the array in the deep subwavelength regime. In comparison with a double-convex shaped lens with a finite radius of curvature, the proposed planar metallic lenses with a convex or a concave quadratic variation pattern for the slit dielectric material demonstrates very distinctive features in tunneling through and scattering by a slit array and trapping by array slits.

8268-04, Session 1

Binary nanoparticle dispersed metamaterial implementation and characterization

P. P. Banerjee, R. Aylo, G. T. Nehmetallah, H. Li, A. M. Sarangan, P. E. Powers, Univ. of Dayton (United States)

Metamaterials exhibiting a negative index of refraction in the visible are of recent interest due to many possible applications including cloaking and perfect lensing. Nanoparticle dispersed metamaterials have been researched due to their flexibility in operating frequency, electronic tenability, ease of fabrication and low cost. We propose binary polaritronic-plasmonic nanoparticles in a suitable host as candidates for metamaterials. Tunability is achieved through changing the nature, sizes and filling fractions of the nanoparticles, as well as electronically through changing the biasing of the host. SiC and Ag nanoparticles are used to obtain a negative index in the visible. The resulting metamaterial is optically isotropic. Experimental verification include surface plasmon resonance measurements for s and p polarizations for finding the effective permeability, permittivity and refractive index, and phase and group velocity measurement using a double Michelson interferometer.

8268-05, Session 1

Localized surface plasmon resonant photosensors for nano-spectroscopy

Z. Tanaka, Univ. of California, Santa Cruz (United States)

As nanotechnology applications push the limits of computing, , and sensing, a need arises for color sensitive optical nano-components. Most existing spectroscopic elements use far field gratings and filters to provide needed spectral sensitivity. We propose metallic nanoparticles that provide high localized electric fields embedded within nano-meter scale semiconducting mediums that can be probed as photodiodes with high sensitivity and low dark current. This miniaturized color-sensitive sensor can be used in lab-on-a-chip based flow cytometry, nano-fluorescence, and other spectroscopic applications.

8268-06, Session 2

Spectral filtering with subwavelength gratings: overview and latest advances

G. Vincent, ONERA (France); E. Sakat, ONERA (France) and Lab. de Photonique et de Nanostructures, CNRS (France); P. Ghenuche, S. Collin, N. Bardou, Lab. de Photonique et de Nanostructures, CNRS (France); S. Rommeluère, J. Primot, J. R. Deschamps, ONERA (France); F. Pardo, J. Pelouard, Lab. de Photonique et de Nanostructures, CNRS (France); R. Haïdar, ONERA (France)

For the past twenty years, far-field optics of subwavelength gratings has been the subject of numerous studies, particularly for spectral filtering purposes. These spectral properties are basically explained by wave-guided modes or strong resonances at subwavelength scales, and they interestingly led to “new principles for optical filters” [MAG1992][SHA1996][SEN2005]. Lately, following Ebbesen’s seminal work in plasmonics [EBB1998], purely metallic or hybrid metallo-dielectric structures have been proposed to achieve spectral filtering with enhanced efficiencies [POR1999][MOR2006].

In this talk, we will focus on the subwavelength structures developped in our laboratories to achieve band-pass filtering [COL2010][SAK2011] with quasi-perfect extinction out of the transmission band [EST2011], or cut-band filtering [GHE2011] with polarization selectivity. Such nanotechnology makes it possible to fabricate wide arrays of filters that, if integrated into a cooled infrared camera, can achieve real-time multispectral imaging [HAI2010]. These examples prove the tremendous interest of nanotechnology for spectral engineering and multispectral imaging.

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8268-07, Session 2

Plasmonic nanocavities for photovoltaics devices and biosensing

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Arrays of plasmonic nanocavities with very small volumes, down to $\lambda^3/1000$, have been fabricated by soft UV nanoimprint lithography. Nearly perfect omnidirectional absorption (3-70°) is demonstrated for the fundamental mode of the cavity (λ=1.15 µm). The second-order mode exhibits a sharper resonance with strong angular dependence and total optical absorption when the critical coupling condition is fulfilled (45-50°, λ=750 nm). It leads to high refractive index sensitivity (405 nm/RIU) and figure of merit (~21), and opens new perspectives for efficient biosensing experiments in ultra-low volumes.

It is also shown numerically that plasmonic nanocavities can be designed for multi-resonant, broadband absorption in ultra-thin solar cells. The predicted efficiency of 25 nm-thick GaAs solar cell is 17.5 %. This is a nearly 100-fold decrease in absorber thickness compared to most thin-film photovoltaic devices. This breakthrough in the conception of nanoscale solar cells should pave the way to the realization of extremely thin efficient solar cells, and allows to revisit the design of thin-film and third generation photovoltaic devices.

8268-08, Session 2

enhanced infrared detection using plasmonic mode-converters

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We present our recent modeling and experimental results for plasmonic structures that are designed to convert the impedance and polarization of free- propagating electromagnetic modes to match the sensing region. We show that the mode matching produced by such structures is capable of significant enhancement of quantum efficiency and reduction of the detector noise. Moreover, these structures can be designed to convert the polarization of the free-propagating modes to what is needed for electronic transition in quantum wells (e.g. QWIP) - almost independent of the initial polarization.

8268-09, Session 2

Semiconductor nanostructures towards optoelectronic device applications

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There has been a growing interest in the improvement of light extraction or absorption for optoelectronic device applications, such as light emitting diodes, flat-panel displays, solar cells, and optical sensors. In order to enhance the light trapping or absorption, there has been important progress made in the fabrication of nanostructures including nanorods, nanotips, hollow-tip arrays, naowire/nanocone arrays, nanopillar arrays, nanodomes by material growth, or etching process using polystyrene microspheres, silica nanospheres, and metal nanoparticles. On the other hand, the fabrication of nano-scale structures by integrating closely one-dimensional (1D) nanostructures on a 2D or 3D architecture has attracted intensive attention due to their fascinating properties for various device applications. Recently, the light scattering technique also has attracted intensive research interest because it is one of the most important means for increasing the overall absorption in photodetecting devices.

In this presentation, we report the nanostructure integrated structures to enhance the overall light absorption by extending the effective optical path and promoting the transmitted diffuse light for high-efficiency optoelectronic devices such as solar cells and light detecting devices. Additionally, antireflective surface relief nanostructures are useful for improved light trapping. Highly transparent sapphire micro-grating structures with largely enhanced diffuse transmittance are theoretically and experimentally studied. The nanostructures on the surface of biosensors as well as light emitting diodes are also investigated to improve the device efficiency.

8268-10, Session 2

Metamaterials and nanophotonic devices for energy and sensing

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Nanophotonics, the emerging field of photon-material interactions at the nanoscale, poses many challenges and opportunities for researchers engineering devices with subwavelength features. Plasmonic nanostructures and metamaterials exhibit optical properties not seen in conventional photonic materials and enable focusing, guiding, bending, and absorbing photons at the nanoscale. They are poised to revolutionize a broad range of applications including energy and sensing.

In this seminar, I will describe the design, nanofabrication and optical characterization of engineered nanophotonic materials that enable controlled and enhanced photonic functionalities. First, I will introduce frequency-tunable, hybrid infrared metamaterials, in which a dynamic optical response is achieved via a thermally induced phase transition in vanadium dioxide (VO2) nanostructures. I will also present how the mechanical actuation of flexible polymers can be used to control the nanoscale distances between coupled metallic resonators, in turn enabling frequency-tunable, compliant optical metamaterials. Such reconfigurable nanophotonic materials significantly enhance the infrared reflection signal from a C-H vibrational mode, and could find use in bio-chemical sensing and environmental screening applications. Finally, ultrathin, polarization-insensitive, broadband plasmonic super absorbers capable of absorbing light over the entire visible spectrum will be demonstrated. These uniquely shaped plasmonic nanostructures could be utilized in solar energy conversion applications for efficient light-trapping and photon management in photovoltaic and thermophotovoltaic cells.

8268-11, Session 3

Photonic crystal nanophotonic open sensor platform for highly sensitive highly specific high-throughput chip-integrated sensing and spectroscopy

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The unique dispersive properties of two-dimensional photonic crystal devices that enable confinement and manipulation of light on length scales of the optical wavelength have generated the prospect of chip-scale miniaturized nanophotonic devices in diverse applications in light emission, quantum optics, optical interconnects and sensing. While photonic crystal microcavities enable light to be trapped with very small mode volumes and high quality factors, photonic crystal waveguides enable light to be slowed down by 2 orders of magnitude compared to free space. In recent years, photonic crystal slot waveguides have added another dimension of enhanced light-matter interaction with a narrow low index slot within a photonic crystal waveguide where the electric field intensity is significantly enhanced. The enhanced light-matter interactions enable a nanophotonic open sensor platform that is extremely versatile and can be tailored for diverse applications in chemical and biological sensing.

In this invited paper, we present our work with photonic crystal devices for on-chip sensing and spectroscopy. On-chip sensing by absorption spectroscopy signatures with 300 micron long photonic crystal slot waveguides have enabled the detection of greenhouse gases (100ppm methane in nitrogen) and volatile organic compounds (100ppb xylene in water) with high sensitivity in the near-infrared. Integration with quantum cascade lasers for chip-scale absorption spectroscopy with the same normalized design at longer wavelengths will be discussed.

We also present our high sensitivity and high throughput photonic crystal microarray platform for chip-scale medical diagnostics, pathogen detection and explosives detection. Potential for enhanced electromagnetic wave sensing will also be discussed.

8268-12, Session 3

Quantum cascade laser enabled nano-liter polymer waveguide sensor

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Polymers have been long recognized as an alternative sample preparation and spectroscopy platform for IR sensing and chemical analysis, for its capabilities in repelling water while preferentially adsorbing and pre-concentrating chemicals of interest, in both liquid and gas phases[1]. However, when only used in surface evanescent wave sensing scheme, the effective absorption path length is greatly reduced to 10s of microns; the simple transmission type of IR absorption scheme could have longer path length, but it is also compromised due to the much longer time required for chemicals to diffuse into the thick polymers.

Here, we first coupled Quantum Cascade (QC) laser into a CaF2 Whispering Gallery Resonator[2] with a 40 nm thick layer of polyethelene coating. Also with prism coupling, we coupled QC laser into a single mode Mid-IR slab polymer waveguide with ~10 microns thickness. Due to high brightness, only QC lasers could be efficiently coupled into these two waveguides with good signal to noise ratio. These ultra thin polymer waveguides minimizes the time of adsorption to second level while providing preconcentration and water repelling; at the same time they have effective path lengths well over several millimeters for QC lasers. Thus they could realize better than 10^(-3) Hz^(1/2)of loss accuracy in the Mid-IR absorption measurements, i.e. sub ppm level of samples in nano liters of volume could be detected and identified by QC lasers.

Other forms of thin polymer waveguide and innovative applications, including selective laser desorption and adsorption, will also be discussed.

8268-13, Session 3

Long wave infrared on-chip absorption spectroscopy with photonic crystal slot waveguides

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A lab-on-chip integrated infrared spectrometer for remote, in situ sensing and spectroscopic identification of gases taking advantage of the large absorption cross-sections in the long wavelength infrared is highly desired. Quantum cascade lasers in mid-infrared and far-infrared wavelengths can probe fundamental molecular vibrations of most molecules. However, requirement of a gas cell still makes on chip integration difficult and heterogeneous integration cumbersome and expensive. Here, we demonstrate detection of triethylphosphate on-chip by absorption signatures at 9.5 micron. The chip integrated slot serves the function of gas cell. Based on Beer-Lambert absorption law, the photonic crystal slot waveguide device combines slow light in photonic crystal waveguides with large optical field intensity in a low index slot at the center of the photonic crystal waveguide to enhance interaction between the optical field and the analyte and thus effectively increases the optical absorption path length. Fabrication of photonic crystal slot waveguides in long wavelength infrared transparent germanium with barium fluoride cladding has been performed. Light from a transverse magnetic polarized quantum cascade laser is coupled through a transverse electric mode guiding photonic crystal slot waveguide and transmitted intensity measured by a MCT detector. Output intensity is measured in presence and absence of triethylphosphate as a representative gas and its absorbance determined on chip from the difference in transmitted intensity. The principle of photonic crystal slot waveguide spectroscopy has been demonstrated before to detect 100ppm methane with a 300 micron long photonic crystal slot waveguide by near-infrared absorption signatures.

8268-14, Session 3

Sensitive detection of nitric oxide using a 5.26 µm external cavity quantum cascade laser based QEPAS sensor

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The development and performance of a CW, TEC DFB QCL based sensor for quantitative measurements of nitric oxide (NO) concentrations will be reported. Human breath contains ~ 400 different chemical species, usually at ultra low concentration levels, which can serve as biomarkers for the identification and monitoring of human diseases or wellness states. By monitoring NO concentration levels in exhaled breath a fast, non-invasive diagnostic method for treatment of patients with asthma and COPD is feasible.

The NO concentration measurements are performed with a 2f wavelength modulation quartz enhanced photoacoustic spectroscopy (QEPAS) technique [1,2], which is very suitable for real time breath measurements, due to the fast gas exchange inside a compact QEPAS gas cell (~5 mm typical dimensions). A Maxion Technologies, Inc. air-cooled DFB-QCL was operated at 20.5oC, targeting the NO absorption line at 1900.08 cm-1 (λ~5.263 µm), with ~ 100 mW of QCL power. The sensor includes a 5 cm long reference cell, filled with a mixture of 0.11 % of NO in N2 at 175 Torr, which is used for line-locking. A minimum detection limit (1σ) for the line locked NO sensor is ~6 ppbv with a 1 sec update time of the control electronics. This NO sensor will be clinically evaluated at Baylor College of Medicine in a side to side comparison with an FDA approved chemiluminescence based instrument (NIOX- MINO, Aerocrine AB Solna, Sweden).

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8268-15, Session 3

Spectral selective absorption enhancement from stacked ultra-thin InGaAs/Si Fano resonance membranes

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Photonic crystals (PCs) with periodic modulation of the refractive index provide phase matching for the out of plane radiation modes allowing the continuum of the radiation modes into the discrete in plane modes which is not possible with a bulk material. This coupling of the out of the plane radiation mode to the in-plane discrete mode is a resonant phenomenon called Fano resonance [1-2]. At resonant coupling there is strong localization of the fields and hence the energy inside or on the surface of a layer is of great interest for applications like bio sensing, light sources, frequency converters, optical traps, detectors, etc [3].

Photonic crystals have the ability to manipulate the photon density of states, alter the light matter interaction and control the spontaneous emission [4]. Most of the work related to enhanced absorption is based on epitaxial quantum dot system [5-6] or metallic photonic crystals [7-8]. Little work is done in the area of enhanced absorption in 2D PC cavities. We report a stacked ultra-thin InGaAs/Si Fano resonance membrane in the IR regime with enhanced absorption with absorption enhancement factor ~26. The impact of the change in the InGaAs absorptive layer thickness is investigated in terms of spectral tunability and absorption enhancement factor. The spectral location of the resonance can be tuned by changing the fill fraction (ratio of the air hole radius to the lattice constant (r/a)), the refractive index and Fano membrane thickness, and the absorption layer properties. This important feature ensures flexible design for infrared photodetectors incorporating photonic crystal cavities. We will conclude the paper by presenting a practical idea of stacked ultra-thin InGaAs/Si Fano resonance membrane based spectrally selective absorption enhanced photoconductive photodetector in the IR region.

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8268-17, Session 4

III-V-N alloys grown by MOVPE in H2 and N2 mixed carrier gases

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The III-V-N type alloys are attractive material for the infrared applications because they have the huge bandgap bowing that gives a significant bandgap reduction with N incorporation. To obtain the III-V-N films with a higher N content, however, is difficult due to the low N solubility. In this work, the InAsN and GaAsN films were grown in the H2 and N2 mixed carrier gas to control the N incorporation, and the effect of N2 on the MOVPE growth of the III-V-N films was investigated in detail.

The InAsN and GaAsN films were grown by the low-pressure (160 Torr) MOVPE. Tertiarybutylarsine and 1,1-dimethylhydrazine were used as the As and N precursors, respectively. The group-III precursors were trimethylindium and trimethylgallium. The N2/(N2+H2) carrier gas ratio was varied from 0 to 0.75 with the constant As/III ratio and the DMHy flow rate.

With increasing the N2/(N2+H2) carrier gas ratio, the N content in the InAsN and GaAsN films increased from 1.5% to 2.0% and from 2.8% to 3.7%, respectively. Namely, it is found that the increase of the N2 carrier gas ratio enhances the N incorporation into III-V-N films. The calculated boundary layer thickness in H2 is about 2.6 times as thick as that in N2 due to the large difference in the viscosity and the density of the gas between N2 and H2. Therefore, the increase of the N content may be explained by the increase of the concentration gradient of the precursors that suppresses the N desorption from the III-V-N surface.

8268-18, Session 4

MBE growth of Sb-based type-2 quantum dots for the application to long wavelength sensors

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Type-2 quantum dots (QDs) have attracted large attention, because long wavelength IR detector operated at room temperature can be expected without the carrier leakage problems caused by fabrication process. However, until now, few researchers published on this topic. JPL groups extended cutoff wavelength up to ~ 6μm with InSb QD barriers in InAsSb matrix (type-2) grown by MBE and exhibited operation of photodetector at 225K [1]. However, they did not reveal the structural properties of type-2 QDs. Moiseev et al. [2] showed structural and electrical properties of InSb QDs in InAs(Sb,P) matrix grown by LPE.

In this talk, we will present the physical properties of InSb migration enhanced epitaxial QDs in InAsSb matrix prepared on AlGaSb/GaAs wafers and InSb QDs in InAs matrix on InAs wafers. Cross-sectional TEM images show reduction of InSb QDs in InAsSb matrix. With them we will discuss the effect of growth sequence on the structural properties of InSb QDs. Finally, the optical properties of InSb QDs in InAs matrix will be discussed.

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8268-19, Session 4

Study of the valence band offsets between InAs and InAs1-xSbx alloys

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InAs/InAs1-xSbx strain-balanced type-II superlattices (T2SL) on GaSb are a viable alternative to the well-studied InAs/(In)GaSb T2SL for infrared detectors. The valence band offset between InAs and InAs1-xSbx is necessary for designing T2SLs with desirable wavelengths. Recent PL studies of InAs/InAs1-xSbx T2SL with $x \leq 0.27$ used a type-II alignment with the conduction band edge of InAs1-xSbx higher than that of InAs and reported 60-70% of the bandgap bowing occurring in the valence band. However, higher Sb compositions are essential to maintain high electron-hole wave function overlaps for strong absorption in the mid- and long-wavelength infrared regions. In this work, the effective bandgap energies of InAs/InAs1-xSbx T2SLs with x=0.28-0.40 are designed using the Kronig-Penney model with 65% of the InAsSb bandgap bowing attributed to the valence band. Multiple 0.5 μm-thick superlattice samples are grown by MBE on GaSb substrates. Detailed structural characterization of these samples using XRD and AFM reveals consistent excellent crystalline properties with SL0 peak FWHMs between 30 and 40 arcsec and 20x20 μm2 area RMS roughness of 1.6-2.7 Å. Initial optical spectroscopy study shows the samples cover a very broad wavelength range from 5 to 10 μm, as designed, and give strong PL intensities, some very close to that of an InAs/(In)GaSb T2SL reference sample. The band offset and bowing parameter of InAs1-xSbx alloys are obtained by fitting the measured effective bandgaps and alloy compositions to the theoretical values calculated using the Kronig-Penney model.

8268-20, Session 5

Nonlinear GaInAs/AlInAs/InP quantum cascade laser sources for wavelength generation in the 2.7-70 μm wavelength range

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GaInAs/AlInAs/InP quantum cascade lasers have established themselves as reliable laser sources in the mid-infrared region (3.8-10) μm, where they operate at room-temperature in continuous-wave with Watt-level output powers. However, wavelengths below and above this wavelength region are difficult to generate. At short-wavelengths, the finite conduction band offset and the position of indirect conduction band valleys lead to increased carrier leakage into continuum and into the indirect valleys. At long wavelengths, devices suffer from large free-carrier absorption and poor population inversion due to the short upper laser state lifetime. An alternative way to extend the spectral coverage of GaInAs/AlInAs/InP QCLs is to use intra-cavity nonlinear frequency mixing.

We demonstrate that using intra-cavity frequency mixing, room-temperature short-wavelength limit can be pushed down to 2.7 μm with devices based on quasi-phase-matched second-harmonic generation. Similarly, the process of difference-frequency generation is utilized for long-wavelength generation. In the latter case, devices emitting up to ~ 70 μm are demonstrated. The theoretically estimated power levels that can be achieved with our approach are in the range of several mW at short-wavelengths, and up to 0.1 mW in the THz range, which are suitable for main applications, such as gas sensing, spectroscopy, radio-astronomy, etc.

8268-21, Session 5

Linewidth broadening caused by intrinsic temperature fluctuations in quantum cascade lasers

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The intrinsic narrow linewidth of quantum cascade lasers (QCLs) in the mid-infrared and Terahertz (THz) ranges promises wide applications in the field of sensing such as high-sensitive trace-gas detection. However, so far limited work has been reported in intrinsic linewidth characteristics of QCLs. In this paper, we theoretically investigate the fundamental frequency noise and the linewidth broadening caused by intrinsic temperature fluctuations in both mid-infrared and THz QCLs. The analytical derivation is based on the Green function analysis and the Van Vliet-Fassett theory. The results show that the fundamental frequency noise caused by temperature fluctuations is prominent in the low frequency range (below a few kHz) and is sensitive to the temperature, heat conductivity and the thickness of the active region/substrate. It also shows that this fundamental frequency noise does not show a 1/f trend in the whole frequency spectra for both THz and mid-infrared QCLs. For mid-infrared QCLs, this frequency noise leads to the linewidth broadening from 14.74 Hz to 62.02 Hz as the temperature increases from 200 K to 400 K. When the microscopic features of the refractive index variations associated with the intersubband gain transition, the self-heating-induced thermal expansion and energy level broadening in mid-IR QCLs are considered, an estimation shows that the linewidth broadening increases greatly by a factor of at least a few times.

8268-22, Session 5

Substrate emission quantum cascade ring lasers with room temperature continuous wave operation

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We demonstrate room temperature, continuous wave operation of quantum cascade ring lasers around 5 micrometer with single mode operation up to 220 mW output power. Light is coupled out of the ring cavity through the substrate with a second order distributed feedback grating. The substrate emission scheme allows for epilayer-down bonding, which leads to room temperature continuous wave operation.

8268-23, Session 5

Active layer design and power calculation of nitride-based THz quantum cascade lasers

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III-V nitrides with its enhanced thermal and transport properties provide an interesting alternative for the realization of high power THz QCLs operating at room temperature. The active layer of design of GaN-based RP/QCLs requires the incorporation of spontaneous and piezoelectric polarizations and their modifications due to stress and applied bias. The application specific generation of THz radiation by tailoring material systems to include active layers consisting of AlxGa1-xN/GaN/ AlxGa1-xN, InxGa1-xN/GaN/ InxGa1-xN and AlxGa1-xN/ InyGa1-yN will be addressed in the talk. Generation and tuning of THz radiation ranging from 1THz to over 15THz by tailoring the material system or by the variation of applied bias will be discussed. The talk will conclude with estimation of the system gain and overall efficiency.

8268-24, Session 6

GaN-based nanowire photodetectors

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Semiconducting one-dimensional nanostructures have a huge potential as building blocks for quantum electronics, optoelectronics, and sensor applications. In this work, we present a comprehensive study of the photocurrent phenomena in single defect-free GaN nanowires (NWs), analyzing the effect of the contact nature, excitation power, light polarization, measuring frequency, and environment. GaN NWs present high photocurrent gain, in the range of 1E5-1E8, with the photocurrent increasing sublinearly with the excitation power. The spectral response is relatively flat for excitation above the GaN bandgap and presents a visible rejection of more than six orders of magnitude. In depleted nanowires (diameter < 100 nm), the photocurrent time response is in the milisecond range, far from the persistent photoconductivity effects (seconds, minutes) observed in larger NWs or two-dimensional layers. From the above-described results, we confirm that the photoresponse is dominated by the redistribution of charge at the surface levels. However, the total depletion of the NW active region reduces the surface band bending preventing persistent photoconductivity effects and granting insensitivity to the chemical environment. Furthermore, the m-plane crystallographic orientation of the NW sidewalls is characterized by the absence of occupied states within the band gap, which prevents the degradation of the spectral response observed in GaN two-dimensional photoconductors. In summary, their unique combination of properties, namely giant photocurrent gain, huge ultraviolet/visible contrast, reasonable bandwidth and environment insensitivity, renders GaN NWs particularly attractive for reliable and robust photodetector applications.

8268-25, Session 6

III-V nanowires by self-assembly MOVPE technology for novel and efficient opto-electronic and photovoltaic devices

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Free-standing nanowires (NWs) of III-V semiconductors are being considered ideal building blocks for the realization of novel and efficient nanophotonic devices and solar cells. Self-assembly of III-V NWs by metalorganic vapor phase epitaxy (MOVPE) through the Vapor-Liquid-Solid mechanism, is a most promising technology for the synthesis of NW-based devices.

We report on self-assembly MOVPE growth and properties of GaAs-AlGaAs NWs, as case study. The growth of GaAs, AlGaAs and GaAs-AlGaAs core-shell and multi-shell NWs will be presented, focusing on the NW properties (morphology, size, growth rate, inner composition, defects content, and luminescence) and their dependence of MOVPE conditions. Strategies to achieve p- and n-type doping in these NWs will be also addressed.

The fabrication of MOVPE-grown single-NW devices based on GaAs and GaAs-AlGaAs core-shell nanostructures will be reported. Metal-semiconductor-metal (MSM) photodetectors based on Schottky-contacted core/shell GaAs/AlGaAs NWs exhibit relatively strong polarization anisotropy (varying from 0.1 to 0.55 depending on absorption wavelength) of their spectral photocurrent, and high quantum efficiency values (about 10% at 600 nm). Core/shell devices exhibit significantly improved dc and high-speed performances over GaAs NWs, and comparable to planar MSM photodetectors. Picosecond temporal response coupled with picoampere dark currents, demonstrates their potential for high-speed imaging arrays and on-chip optical interconnects.

The potentials of self-assembly MOVPE technology towards photovoltaic applications of NWs will be presented and discussed. Growth of large area and dense arrays of well-aligned GaAs and GaAs-AlGaAs NWs on Si. and alternative low-cost substrates will be demonstrated, and their characteristic optical (visible) properties reported.

8268-26, Session 6

III-V nanowires in photonic crystal microcavities: toward vertical emitting nanolasers

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Monolithic integration of efficient light sources at the nanoscale is one of the great challenges in modern photonics. The recent progress in the bottom-up growth of functional III-V semiconductor nanowires has allowed the synthesis of one dimensional structures with unprecedented flexibility for the design of optical nanoemitters. Specifically, the possibility to control nanowire morphology, positioning, and bandgap engineering through the formation of heterostructures and doping directly during the synthesis make III-V nanowires excellent candidates for the development of ultra-compact on-chip light emitters, unrestricted by some of the limitations of conventional top-down technology. Despite the tremendous effort devoted to the synthesis of active nanowire structures, single vertical nanowires are usually considered as a basic optical Fabry-Perot cavity with limited output efficiency due to the low refractive index contrast with their original substrate. In order to boost emission performance, we propose an original approach where a single vertical nanowire is grown on top of a two dimensional photonic crystal cavity with large quality factor and small mode volume, aimed at increasing light-matter interaction. Strategies to enhance spontaneous emission and optimize lasing based on the coupling between a strong resonant cavity mode with the gain medium or specific guided modes into the nanowire will be illustrated by theoretical evaluation of the Purcell factor, modal gain, and far field radiation pattern. The latest developments toward a practical realization of such devices will also be presented and discussed.

8268-27, Session 6

Photovoltaic devices based on quantum dot functionalized nanowire arrays embedded in an organic matrix

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Quantum dot (QD) functionalized nanowire arrays are attractive structures for low cost high efficiency solar cells. QDs have the potential for higher quantum efficiency, increased stability and lifetime compared to traditional dyes, as well as the potential for multiple electron generation per photon. Nanowire array scaffolds constitute efficient, low resistance electron transport pathways which minimize the hopping mechanism in the charge transport process of quantum dot solar cells. However, the use of liquid electrolytes within such scaffold device structures as a hole transport medium have led to significant degradation of the QDs.

In this work, we first present the synthesis uniform single crystalline ZnO nanowire arrays and their functionalization with InP/ZnS core-shell quantum dots. The resulting structures are characterized using electron microscopy, optical absorption, photoluminescence and Raman spectroscopy. High resolution transmission electron microscopy (HRTEM) is used to reveal the atomic interface between the ZnO and the QD. A combination of HRTEM and energy dispersive x-ray spectroscopy mapping allows observation of the core-shell QDs as well as the co-localized presence of indium, phosphorus, and sulphur. Photoluminescence shows the successful attachment of quantum dots. The functionalized nanowire arrays are subsequently embedded in a poly-3(hexylthiophene) hole transport matrix with a high degree of polymer infiltration prior to device fabrication. The electrical characteristics and optical response of the resulting devices will be reported.

8268-28, Session 7

Optimization of InAs/GaSb superlattice pin photodiode design for the high temperature operation in the midwave infrared range

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In order to improve temperature operation in the mid-wavelength infrared (MWIR) domain, several InAs/GaSb superlattice pin photodiodes showing different active zone period designs were fabricated by MBE on p-type GaSb substrate. These SL structures exhibited cut-off wavelength between 4.5µm and 5.5µm at 80K.

Electro-optical characterizations including dark current, noise measurements, capacitance-voltage measurements, spectral response and quantum efficiency were performed on single detectors in the temperature range [10K-300K]. Measurements revealed carrier concentrations of about 7x1014 cm-3 at 80K, dark current densities of 1.5x10-5 A/cm2 at 100K and J = 0.33A/cm2 at 200K for Vbias =-50mV while the measured R0A product reaches 1x106 Ohm.cm2 at 77K.

Analysis of dark current characteristics shows that the R0A value is improved by more than one decade in the best configuration. These results obtained help us to determine the optimized SL structure design suitable for high temperature operation.

8268-29, Session 7

High operating temperature XBn-InAsSb bariode detectors

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A bariode is a new type of “diode-like” semiconductor photonic device, in which the transport of majority carriers is blocked by a barrier in the depletion layer, while minority carriers, created thermally or by the absorption of light, are allowed to pass freely across the device. In an n-type bariode, also known as an XB_nn structure, both the active photon absorbing layer and the barrier layer are doped with electron donors, while in a p-type bariode, or XB_pp structure, they are both doped with electron acceptors. An important advantage of bariode devices is that their dark current is essentially diffusion limited, so that high detector operating temperatures can be achieved. In this paper we report on MWIR n-type bariode detectors with an InAsSb active layer and an AlSbAs barrier layer. These devices exhibit a cut-off wavelength of ~ 4.1 micron and operate with Background Limited Performance (BLIP) up to at least 160K at F/3. Different members of the XB_nn device family are investigated, in which the contact layer material, “X”, is changed between n-InAsSb and p-GaSb. In all cases, the electro-optical properties of the devices are similar, showing clearly the generic nature of the bariode device architecture. Focal Plane Array detectors have been made with a pitch of 15 or 30 micron. We present radiometric performance data and images from our Blue Fairy (320x256) and Pelican (640x512) detectors, operating at temperatures up to 180K. We demonstrate that detector performance can be achieved which is close to “Rule 07”, the benchmark for Mercury Cadmium Telluride (MCT) devices.

8268-30, Session 7

Thermal distribution in high power optical devices with power-law thermal conductivity

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The cross-plane thermal conductivity of a type II InAs/GaSb superlattice (T2SL) is measured from 13 K to 300 K using the 3-omega method. Thermal conductivity is reduced by up to 2 orders of magnitude relative to the GaSb bulk substrate. The low thermal conductivity of around 1-8 W/m.K may present a challenge for T2SL quantum cascade lasers and high power light emitting diodes, while serving as an advantage for possible thermoelectric applications. We introduce a power-law approximation to model the non-linear thermal conductivity of such superlattices, and show a simple analytical correction which predicts increased or decreased peak temperature for negative or positive exponents, respectively.

8268-31, Session 7

Barrier engineering in quantum dots in a well detector

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In the third generation of IR detectors, there is an increased emphasis on obtaining higher operating temperature (HOT). In particular, there have been a lot of research efforts in engineering the barriers for reducing the dark current in the infrared detectors. We have been undertaking research on infrared detectors based on InAs/GaAs quantum dots in a well (DWELL) and InAs/GaSb superlattices. We will discuss approaches to incorporate unipolar barriers in the superlattices to prevent noise generating mechanisms. Using barrier engineering with confinement enhanced (CE) barriers, we will show how the operating transition of the dots in a well detector can be engineered to produce higher signal to noise ratios.

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8268-32, Session 7

Low frequency noise in 1024x1024 long wavelength infrared focal plane array based on type-II InAs/GaSb superlattice

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Recently, the type-II InAs/GaSb superlattice (T2SL) material platform is considered as a potential alternative for HgCdTe technology in long wavelength infrared (LWIR) imaging. This is due to the incredible growth in the understanding of its material properties and improvement of device processing which leads to design and fabrication of better devices. In this paper, we report electrical low frequency noise measurement on a high performance type-II InAs/GaSb superlattice 1024×1024 LWIR focal plane array.

8268-33, Session 7

High-performance LWIR superlattice detectors and FPA based on CBIRD design

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The nearly lattice-matched InAs/GaSb/AlSb (antimonide) material system offers tremendous flexibility in realizing high-performance infrared detectors. Antimonide-based superlattice (SL) detectors can be tailor-made to have cutoff wavelengths ranging from the short wave infrared (SWIR) to the very long wave infrared (VLWIR). SL detectors are predicted to have suppressed Auger recombination rates and low interband tunneling, resulting in the suppressed dark currents. Moreover, the nearly lattice-matched antimonide material system, consisting of InAs, GaSb, AlSb and their alloys, allows for the construction of superlattice heterostructures. In particular, unipolar barriers, which blocks one carrier type without impeding the flow of the other, have been implemented in the design of SL photodetectors to realize complex heterodiodes with improved performance.

We report our recent efforts on advancing of antimonide superlattice based infrared photodetectors and demonstration of focal plane arrays based on a complementary barrier infrared detector (CBIRD) design. By optimizing design and growth condition we succeeded to reduce the operational bias of CBIRD single pixel detector without increase of dark current or degradation of quantum efficiency. We demonstrated a 1024×1024 pixel long-wavelength infrared focal plane array based on the CBIRD design. An 11.5 μm cutoff focal plane without anti-reflection coating has yielded noise equivalent differential temperature of 53 mK at operating temperature of 80 K, with 300 K background and cold-stop. Imaging results from a recent 10 μm cutoff focal plane array are also presented. These results advance state-of-the art of superlattice detectors and demonstrated advantages of CBIRD architecture for realization of FPA.

8268-34, Session 7

World's first demonstration of type-II superlattice dual band 640 x 512 LWIR focal plane array

E. K. W. Huang, M. Razeghi, Northwestern Univ. (United States)

High resolution multi-band infrared detection of terrestrial objects is useful in applications such as long range and high altitude surveillance. In this paper, we present a 640 by 512 type-II superlattice focal plane array (FPA) in the long-wave infrared (LWIR) suitable for such purposes, featuring 100% cutoff wavelengths at 9.5μm (blue channel) and 13μm (red). The dualband camera is single-bump hybridized to an Indigo 30μm pitch ISC0905 read-out integrated circuit. Test pixels revealed background limited behavior with specific detectivities as high as ~5x10(11) Jones at 7.9μm (blue) and ~1x10(11) Jones at 10.2μm (red) at 77K.

8268-35, Session 7

Free-space optical communication using mid-infrared or solar-blind ultraviolet sources and detectors

R. P. McClintock, A. Haddadi, M. Razeghi, Northwestern Univ. (United States)

Free-space optical communications is considered as a promising solution to the "last mile" bottleneck of high-speed access to data networks. Conventional near infrared-based free-space optical communication systems suffer from atmospheric scattering losses and scintillation effects which are limiting the performance of the data links. Using mid- and long-wavelength infrared, we can improve the quality of the data links and increases their range. The reason is the lower susceptibility to atmospheric affects in these wavelengths. Because of the low scattering, the data link cannot be intercepted without a complete or partial loss in power detected by the receiver. This type of communications provides ultra-high bandwidth and highly secure data transfer for both short and medium range data links.

Quantum cascade lasers are one of the most promising sources for mid- and long-wavelength infrared and type-II superlattice photodetectors are strong candidates for detection in these regimes. Using combination of room-temperature, continuous-wave, high-power quantum cascade lasers and high operating temperature type-II superlattice photodetectors offers the benefits of mid- and long-wavelength infrared systems as well as practical operating conditions for next generation free-space communications systems.

8268-36, Session 7

Suppression of surface leakage in gate controlled type-II InAs/GaSb mid-infrared photodetectors

G. A. Chen, B. Nguyen, A. M. Hoang, E. K. W. Huang, S. R. Darvish, M. Razeghi, Northwestern Univ. (United States)

Type II InAs/GaSb superlattice (T2SL) has been shown great progress in infrared detection from mid-infrared (MWIR) to very long wavelength infrared (VLWIR) regimes. However, for very high bulk performance T2SL p-[pi]-M-n heterostructure mesa-isolated detectors, their electrical performances strongly depend on devices' sidewall quality because surface roughness or residual byproducts cause strong surface leakage current. Moreover, surface leakage current screens other important bulk dark current mechanisms, and brings difficulty and uncertainty to the material optimization and bulk intrinsic parameters extraction such as carrier lifetime and mobility. Most of surface treatments were attempted beyond the MWIR regime because compared to the bulk performance, surface leakage in MWIR was considered to be a minor factor. However, in this

paper, we show that even for very high bulk performance MWIR p-[pi]-M-n detectors, surface leakage still strongly affects their performance below 150K, and with gating technique, we can effectively eliminate the surface leakage in a controllable manner.

8268-37, Session 8

Physical properties of heteroepitial and homoepitaxial wurtzitic heterostructures grown along arbitrary orientation: III-nitrides and II-oxides

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The quests for high power and one hundred percent quantum efficiency today constitute a real issue for designers of optoelectronics devices susceptible to operate in the upper part of visible or in the near ultraviolet portions of the electromagnetic spectrum. Such devices may be realized by assembling strained layers of several group III element-nitrides or alternatively several group II element- oxides. These two families of compounds both preferentially crystallize under the wurtzitic point symmetry, which indicates that they display a spontaneous polarization (along the six-fold symmetry axis) and a piezoelectric one. Thus strained layer heterostructure may be or not subject of Quantum Confined Stark Effect (QCSE), depending on the growth orientation of the heterostructures. QCSE reduces the efficiency of light matter interaction (brightness of the device) and red shifts the recombination energy if using thick carrier confining layer. We present the different partners ruling the optical properties of quantum well LEDs and LDs in the cases of both nitrides and oxides and we demonstrate that using semi polar orientations may be a plus for nitrides and for ZnO-ZnCdO heterostructures whilst it is not for ZnO-ZnMgO. In the specific case of InGaN-GaN for green and yellow light emission, a substantial and fortunate reduction of the density of elastic energy paves the way to utilization of a very thick active region, which may be a plus for increasing the optical confinement or for increasing the indium incorporation without creating too many dislocations. We then review the robustness of the photoluminescence intensity for both nitrides and oxides and we demonstrate how impacting the homoepitaxial option is. We finally discuss the nitrides cases and the specific situation of ZnO-ZnMgO deposited on non polar, M-Plane oriented ZnO. In this specific case the stability of the photoluminescence measured in the context of both cw and time resolved experiments indicate the lack of non radiative recombination channels in such samples, a situation also reported in nitrides although not so readily.

8268-38, Session 8

Magneto-optical spectroscopy of MOVPE grown narrow gap III-Mn-V ferromagnetic semiconductors

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Narrow gap ferromagnetic semiconductors (NGFS) have significant potential for applications in both infrared spin photonics and spin transport devices due to their lighter holes, smaller energy gaps, and much higher carrier mobilities compared to other III-Mn-V ferromagnetic semiconductors. A Rudermann- Kittel-Kasuya-Yosida (RKKY) mechanism, where free holes mediate the ferromagnetism, is favored in NGFS and a small hole effective mass results in a long interaction distance and effective exchange coupling. The calculated hole effective Bohr radius in NGFS indicates sufficient overlap of the hole wave functions to stabilize ferromagnetism for hole concentrations greater than 10^18 cm^-3. In this work, several time resolved differential transmission and magneto-optical spectroscopy techniques were employed to provide insight into both the time scales and the nature of microscopic interactions in MOVPE grown ferromagnetic InMnAs and InMnSb with the Curie temperatures above room temperature.

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8268-39, Session 8

Optical properties of the periodic polarity-inverted GaN waveguides

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[Invited Speaker]

Based on the recent improvement on the crystallographic qualities, nitride semiconductors are widely used for the current optoelectronic applications such as light emitting diodes and lasers. However their potentials have not been fully utilized, in terms of their nonlinear optical properties originated from their strong polarization field applied within the crystal. Exploring the new application to the quantum optics, the periodic polarity-inverted GaN waveguides were fabricated using molecular beam epitaxy (MBE).

All the growths were performed using a MBE system equipped with rf-plasma-enhanced nitrogen plasma sources and effusion cells. Firstly, nitrogen-polarity GaN templates with a thickness of 50 nm were grown on c-plane sapphire substrates using a low temperature nitridation. Next the templates were periodically patterned by electron-beam lithography and reactive ion etching, in which the parts of the sapphire substrates were exposed. Finally the above stripe-patterned templates were loaded into the growth chamber and a growth was proceeded to obtain gallium-polarity GaN area onto the sapphire exposed parts, while the regrown GaN onto nitrogen-polarity GaN underlayer remained the same polarity.

A successful periodic inversion of the crystallographic polarities was confirmed by piezoelectric force microscopy and Kelvin force microscopy. In addition to the reversal of the crystallographic orientations, periodic grating structures were formed on the surface due to the slight difference of the growth rates for different polarities, which gives the occurrence of the photonic band structures. In this work, the results on the linear optical properties is presented, which was investigated utilizing the variable-angle optical reflectance measurements.

8268-40, Session 8

Growth and applications of ammonothermal bulk GaN substrates

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Gallium Nitride opens new horizons for modern optoelectronics and electronics. The technological parameters of devices can be boosted by the use of truly bulk Gallium Nitride wafers. Recently, large interest has been devoted to ammonothermal method. In this technique GaN containing feedstock is dissolved in one zone of the high pressure autoclave, then transported by convection in the temperature gradient to the second zone, where GaN is crystallized on native seeds due to the supersaturation of the solution. This presentation shows general information about the method and the properties of the obtained crystals and the parameters of various optoelectronic devices grown on ammonothermal GaN substrates.

Currently, 2-inch substrates can be achieved. In the crystals considered, a low dislocation density (5 x 103 cm-2) is attained. At the same time the crystal lattice is extremely flat, and the (0002) rocking curve is very narrow (FWHM=16 arcsec). In case of n-type substrates the carrier concentration of the crystals can be controlled by appropriate doping and varied in the range 2*1017 - 2*1020 cm-3 The crystals are useful to cut wafers of any orientation: polar c-plane, non-polar and semipolar. The latter two ones are extremely important from the point of view of their applications in green InGaN quantum well lasers, due to the largely reduced level of piezoelectric field. The surface of the wafers can be polished with atomic smoothness with RMS factor of below 2Å obtained

GaN epilayers deposited on any type of substrate (polar, non-polar or semi-polar) exhibit very good structural properties and the intrinsic narrow exciton lines in optical measurements. The aforementioned results clearly indicate that ammonothermal substrates fulfill requirements for the epitaxy of stress free GaN-based optoelectronic devices. In this respect, this communication shows also recent results on performance of devices (light emitting diodes and laser diodes) grown on AMMONO-GaN substrates. As one of example, a violet 3-stripe laser of 2.5W output power will be shown.

References:

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8268-41, Session 8

Lasing in GaN microcavities

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III-V nitride semiconductors are well suited for short-wavelength optoelectronic devices such as blue light emitting diodes and laser diodes thanks to their direct bandgaps that range from 0.7 eV (InN) to 6.2 eV (AlN). In addition, III-V nitrides are quite promising for the physics of cavity-polaritons. This comes from some GaN material specificities related to light-matter interaction. In particular one does stress an oscillator strength 10x larger than that of GaAs and an exciton binding energy as large as 27 meV in bulk and 50 meV in quantum wells (QWs). Consequently, light matter-interaction is greatly enhanced, which allows to achieve the strong coupling regime (SCR) between a cavity mode and an exciton at room-temperature (RT). Optical pumping experiments carried out on GaN based microcavities (MCs) have already shown the potential of III-V nitride semiconductors for polariton lasing at 300K [S. Christopoulos et al., Phys. Rev. Lett. 98, 126405 (2007)]. Recent results indicate polariton condensation at 300K with a very low threshold. This is accompanied by a strong non-linear light emission ascribed to polariton stimulated emission. As expected, the threshold depends on both the temperature and the detuning of the cavity mode with respect to the exciton mode. Perspectives of GaN for polariton laser working under electrical injection will be discussed.

8268-42, Session 9

Manufacturing of 100mm diameter GaSb substrates for advanced space based applications

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Antimony based III-V semiconductors are of significant interest for advanced applications in optoelectronics, high speed transistors, microwave devices, and photovoltaics. GaSb and InSb demand is increasing due to its lattice parameter matching of various ternary and quaternary III-V compounds, as their bandgaps can be engineered to cover a wide spectral range. For these stealth and spaced based applications, larger format IRFPAs benefit clearly from larger diameter starting substrates. In this study, we have manufactured and tested larger diameter substrates of both GaSb and InSb. The objective of this work was to provide the best possible 150mm InSb and 100mm GaSb material for advanced IRFPA and SLS epi growth. The analysis of substrate orientation by multiple crystal XRD, AFM surface roughness, oxide desorption using XPS, FTIR, bow and warp, and SLS based epitaxy quality are examined for these substrates. By implementing subtle changes in our substrate orientation and surface finishing, we show that a thin, desorbable surface oxide is routinely provided (t-oxide 50% transmission. Post-MBE CBIRD structures on the 100mm ULD GaSb were examined and reveals a high intensity, 6.6nm periodicity, low (15.48 arcsec) FWHM peak distribution that suggests low surface strain and excellent lattice matching. The Ra for both InSb and GaSb is a consistent ~0.2-4nm, with average batch wafer warp of <4 µm to provide a clean, flat antimonide template critical for advanced epi growth.

8268-43, Session 9

Multiwafer production of epitaxy ready 4" GaSb substrates: requirements for epitaxially growth infrared detectors

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In this work we describe the multiwafer production of GaSb substrates that are used in the epitaxial growth of advanced III-V infrared detector structures. Results will be presented on the crystal growth of 4" GaSb ingots produced by the Czochralski method. Wafer surface quality assessments have demonstrated low levels of surface roughness (rms <0.2 nm), tight oxide thickness control (<30 Angstroms) and very flat surfaces (bow, warp and TTV < 5 µm). Epitaxially grown detector structures were evaluated via Nomarski optical microscope and atomic force microscope (AFM). The requirements for larger diameter GaSb substrates are also discussed with a view to enabling future 6" production technologies.

8268-44, Session 9

Surface chemistry improvement of 100mm GaSb for advanced space based applications

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As size requirements and pixel viabilities for infrared focal plane arrays (IRFPAs) continue to increase, resolution and sensitivity requirements for high performance advanced imaging systems must meet or surpass stringent demands. Strain layer superlattice (SLS) grown by molecular beam epitaxy (MBE) on large diameter antimonides has necessitated changes in crystal processing and finishing parameters, as device layer growth by epitaxy or other means requires a thin (2-5 nm) and highly desorbable surface oxide. This study compares three different chemo-mechanical (CMP) finishes on large diameter GaSb and examines the surface for IRFPA applications. Surface and chemical analysis was implemented by spectroscopic ellipsometry (SE), X-ray photoelectron spectroscopy (XPS), Surfscan haze and particle (LPD) count. Three distinct CMP and final clean finishes on GaSb(100) substrates were examined. By implementing subtle changes in surface finishing, we show that a thin, desorbable surface oxide can be provided. This study has shown that a significant reduction in oxide thickness and a decreased haze with a substantial lowering of LPD count is realized with a final clean process incorporating a novel surface finishing chemistry. Results are consistent with a desorbable oxide composition as determined by the analyzed XPS surface oxides. Molecular beam epitaxy (MBE) growth testing of these 'epitaxy-ready' GaSb surfaces indicate high levels of surface quality. With wafer warp measured at <5um for an average wafer batch, the resultant surface finish and excellent epitaxy-ready quality shows a benefit for larger diameter GaSb IRFPA applications.

8268-45, Session 9

Manufacturable MBE growth process for Sb-based photodetector materials on large diameter substrates

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Antimony-based photodetector structures have received considerable attention recently for their potential and demonstrated performance in infrared detection and imaging applications. Heterostructures based on InAs/Ga(In)Sb strained layer superlattices (SLS) create a type-II band alignment that can be tailored to cover a wide range of the mid-wave and long wave infrared (MWIR and LWIR) absorption bands by varying the thickness and composition of the constituent materials. Through careful design, the Sb-SLS can realize desirable detector features such as higher operating temperature, better uniformity, suppression of Auger recombination, reduction of tunneling currents, and higher quantum efficiency.

The manufacturing challenge is the reproducible growth of high-quality Sb-based SLS epiwafers due to their complex designs including large numbers of alternating thin layers with mixed group V elements. In this paper, we discuss the manufacturability of such epiwafers by molecular beam epitaxy (MBE) using multi wafer production tools. Various techniques were used to characterize the material properties of these wafers, including high resolution x-ray diffraction, cross-sectional transmission electron microscopy, low-temperature photoluminescence, Nomarski optical microscopy, and atomic force microscopy. Photodiodes were fabricated from these Sb-SLS epiwafers, and discussions will include device characteristics such as I-V curves, dynamic impedance, responsivity, and quantum efficiency. For large-format focal plane array applications, production quantities will require growth on large-diameter substrates. We will present two approaches to achieve this goal: growth on 4" diameter GaSb substrates which are in the development stage at the substrate vendors; and growth on latticed-mismatched GaAs substrates as an alternative path to extend this technology up to 6" diameter wafers.

8268-46, Session 10

Arrays of Geiger-mode avalanche photodiodes

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Arrays of InP-based avalanche photodiodes operating at 1.06-µm wavelength in the Geiger mode have been fabricated in various formats. The arrays have been hermetically packaged with precision-aligned lenslet arrays, bump-bonded read-out integrated circuits, and thermoelectric coolers. Such arrays may be suitable for both laser radar and laser communication applications.

8268-47, Session 10

Indirect Time-of-Flight 3D ranging based on SPADs

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High-speed imaging sensors are the enabling technology for a great number of applications. One of these fields is the distance measurement of a scene for safety purposes, for example in automotive field to monitor the environment around the vehicle and help the driver to avoid accidents. These sensors are based on amplitude modulated light hitting the scene and, depending on the covered distance, undergoing a time delay proportional to distance information. These techniques are named Time-of-Flight (TOF) measurement and can be classified as direct-TOF and indirect-TOF. In the former the distance is obtained from the time interleaving between a narrow light pulse emission and the detection of its reflection. In the latter the TOF is obtained from the phase delay of a periodic waveform using a 2D imaging sensor. We conceived two sensors for two different indirect time-of-flight techniques, named respectively pulsed iTOF (piTOF) and continuous wave iTOF (cwiTOF). The sensitive element within every pixel is a Single-Photon Avalanche Diode (SPAD), which ensures high sensitivity hence requiring low power illuminators. To study the performances of the two methods we will use SPADs with different diameter (10, 20 and 30 µm) and different form factor (circular or squared). With these two methods and sensors we will acquire 3D scenes with a maximum distance of 20 m and with a distance resolution down to few centimeters for both sensors.

8268-48, Session 10

Planar technologies for SPAD arrays with improved performances

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In the last years many progresses have been made in the field of Silicon Single Photon Avalanche Diodes (SPAD) thanks to the improvements both in device design and in fabrication technology. For example, the use of custom fabrication processes has allowed a steadily improvement of SPAD performance in terms of active area diameter, Dark Count Rate (DCR), and Photon Detection Efficiency (PDE). Although a significant breakthrough has been achieved with the recent introduction of a new device structure capable of combining a good timing resolution with a remarkable PDE in the near infrared region, nevertheless there is still room for further improvements.

In this paper we will discuss further modifications to the device structure aimed on one hand at improving the device performance and on the other hand at allowing the fabrication of arrays with red enhanced photon detection efficiency.

8268-49, Session 11

Quantum well lasers emitting between 3.0 and 3.4 µm for gas spectroscopy

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The 3 to 4 µm range had long appeared inaccessible to quantum well lasers made on GaSb. Despite having excellent performance in the 2 to 3 µm range, GaInAsSb/AlGaAsSb quantum well lasers rapidly show their limits when crossing the 3 µm barrier (the highest wavelength reached with such a device was 3.04 µm under cw operation at 20°C). This situation was all the more regrettable because several gases have their strongest absorption lines in the 3 to 4 µm range: methane, for example, has a peak of absorption at 3.26 µm overhanging a weaker peak at 2.31 µm by a factor 40.

Works carried out in the University of Munich in 2005 gave new hopes to the world of laser diode spectroscopy. By replacing the quaternary AlGaAsSb barrier by a quinary AlGaInAsSb barrier, researchers were able to reach laser operation at 3.26 µm and room temperature in the pulsed mode. Since then, several teams have engaged in the objective of reaching cw operation at room temperature with such structures. We will detail the difficulties associated with the growth of these materials by molecular beam epitaxy and give an insight into the phenomena responsible for the increase of threshold current with growing wavelength. Finally, we will present results obtained with a monomode DFB laser diode emitting at 3.38 µm having a threshold current of 140 mA at 18°C. Thanks to the Quartz Enhanced PhotoAcoustic Spectroscopy technique, a limit of detection of 50 ppb was reached for methane.

8268-50, Session 11

Physics of interband cascade lasers

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While the interband cascade laser (ICL) has a somewhat analogous geometry to the quantum cascade laser, key differences, in addition to the interband vs. intersubband active transitions, include the ICL's distinctive internal generation of electrons and holes for the population inversion and its slower non-radiative relaxation that allows thermal quasi-equilibrium to be established within the carrier populations. We describe and analyze the physical principles governing ICL operation, and discuss specific modifications to the active-region, electron-injector, hole-injector, and waveguide designs that have demonstrably improved device performance.

8268-51, Session 11

Silicon emission in and out resonant coupling with high Q optical mode

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Coupling silicon emissive centers to subwavelength optical cavity mode offers the possibility of enhancing radiative recombination. It represents an interesting new pathway toward turning Si into an optical gain medium. Two point defects, the G center and the W center, have been shown to be good below-bandgap emitters in crystalline silicon. But both are limited to cryogenic temperatures because they loose to competitions from non-radiative recombinations at higher temperatures.

Generally, point defects in silicon give rise to highly localized states in the band gap and some of these pairs of states in the band gap have a non-vanishing electric dipole matrix element. Theory shows that the rate of spontaneous emission can be enhanced by placing emissive centers in the optical microcavity with high quality factor (Q). A greatly enhanced radiative recombination in turn would compete more effective for the carriers and thereby lead to higher temperature operations.

We show that coupling a silicon emission line to a high Q silicon microdisk mode is technically feasible by electrical or thermal tuning of modal index. However, in the case of the G-center emission, we found that the coupling effect may not always give rise to an enhanced emission but may result in a Rabi splitting instead, depending on the coupling strength. In the case of the W-center emission, we present results of a numerical and experimental study that show an order of magnitude increase of emission intensity in a microdisk over that of a bulk reference sample. The peaks of the increase is reached when the W-line is matched with a cavity mode. Whereas the science behind the couplings in two cases is intriguing, the potential applications are equally inviting and range from low-noise silicon detection at telecom wavelength (for quantum cryptography) and ultrafast IR LED in low-cost silicon.

8268-52, Session 11

Coherent integration of photonics on silicon through the growth of nanostructures on GaP/Si

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The monolithic integration of III/V compound materials on silicon substrates has received a renewed interest due to the development of Opto-Electronic Integrated Circuits (OIECs), and their potential use in optical interconnects, and the future development of low-cost multijunction Photovoltaics. One of the key components for OEICs is a direct bandgap III/V based laser structure for efficient light emission integrated onto Si, due to the dominance of Si in microelectronics. Among the different strategies for producing efficient and long-term stable electrically-pumped lasers on Si substrates, lattice-matched growth is highly preferred, due to lower dislocation generation. In recent years, this route has been optimised through the growth of GaPN-based compounds lattice matched with a few percent of N. GaPN-based compounds are known to develop a pseudo-direct-band gap character and can act as efficient light emitters. However, the improvement of the GaP/Si interfacial layer structural quality remains one of the major stumbling blocks in the development of efficient electrically-pumped laser devices onto Si.

First, we present a comprehensive study of GaAsPN/GaPN quantum wells (QWs) onto GaP substrates, in the light of a comparison with their N-free GaAsP/GaP QWs counterpart system. To this end, both structural (XRD and TEM, with a particular care for typical III-V/Si defect characterisation) and electroluminescence studies will be presented as well as calculated bandstructures. Finally, RT photoluminescence properties of GaAsPN/GaPN QWs onto Si substrate will be presented and discussed in term of carrier injection efficiency.

8268-53, Session 11

GaSb-based laser monolithically grown on Si substrate by molecular beam epitaxy

J. Rodriguez, L. Cerutti, J. Reboul, E. Tournié, Univ. Montpellier 2 (France)

The Antimony-Based Compounds Semiconductor (ABCS), e.g. InAs, AlSb, GaSb, InSb and their relative alloys, offer a great variety of band lineups from type I to type III that are useful for both electronic and photonics devices in the mid infrared wavelength range. Recently efforts have been made to monolithically grow these devices by molecular beam epitaxy (MBE) onto Si in order to integrate the devices with CMOS technology and / or silicon photonics circuitry. However, the lattice mismatch of ABCS with Si is around 11%. This lattice mismatch normally results in formation of high threading dislocation densities not compatible with the fabrication of high performance devices. However, it was demonstrated using ABCS materials that under appropriate growth conditions it is possible to relieve this high strain by the formation of an interfacial 2D arrays of dislocations which greatly reduces the density of threading dislocations.

Using this particular relaxation mode, we have already demonstrated that it is possible to fabricate edge emitting lasers operating in pulsed regime at 1.55 µm and 2.3 µm, with a buffer layer thickness of only 1 µm. We will present the substrate preparation, growth conditions and technological processes allowing to improve the laser performances. We demonstrate cw laser operation near 2µm up to 35°C which is the first demonstration of an Sb-based laser operating in CW on Si. This preliminary result paves the way to the possible integration of Sb-based laser monolithically grown on Si.

8268-54, Session 12

Quantum optics with quantum dots in photonic nanowires

J. Claudon, M. Munsch, J. Bleuse, Commissariat à l'Énergie Atomique (France); P. Lalanne, Lab. Charles Fabry (France); N. Gregersen, Technical Univ. of Denmark (Denmark); J. Gérard, Commissariat à l'Énergie Atomique (France)

No abstract available

8268-55, Session 12

Quantum sensing in integrated photonic devices

J. C. F. Matthews, A. Politi, D. Bonneau, J. L. O'Brien, Univ. of Bristol (United Kingdom)

On-chip integrated photonic circuits are crucial to further progress towards quantum technologies and in the science of quantum optics. We have previously reported precise control of single photon states and multi-photon entanglement directly on-chip [1], following a scheme that was previously implemented in bulk optics [2]. Here we report the heralded generation of multi-photon entanglement for quantum metrology using a reconfigurable integrated waveguide device in which projective measurement of auxiliary photons heralds the generation of path entangled states [3]. From four and six photon inputs we heralded two- and four-photon "NOON" states-a superposition of N photons in two paths, which enable phase supersensitive measurements at the Heisenberg limit. Realistic devices will include imperfections and we demonstrate phase super- resolution with a state that is robust to photon loss. These results can be generalised to generate arbitrarily large entangled states of light for quantum metrology in an integrated optics architecture. Finally we show how such devices can be used to probe real samples.

[1] J. C. F. Matthews, A. Politi, A. Stefanov, and J. L. O'Brien, Nature Photon. 3, 346 (2009).

[2] T. Nagata, R. Okamoto, J. L. O'Brien, K. Sasaki, and S. Takeuchi, Science 316, 726 (2007).

[3] J. C. F. Matthews, A. Politi, D. Bonneau, and J. L. O'Brien, arXiv:1005.5119

8268-56, Session 12

Cavity solitons and nonlinear dynamical regimes in semiconductor microcavities

R. Kuszelewicz, S. Barbay, T. Elsass, Ctr. National de la Recherche Scientifique (France)

Cavity solitons (CS) are localized optical states forming in the transverse plane of a large Fresnel number (micro)resonator, under the competition of the nonlinear susceptibility of the cavity material and transverse effects such as diffraction and eventually carrier diffusion. They form as particular states of a larger family of structures, emerging from the translational invariance symmetry breaking, such as hexagonal or roll patterns. CSs have bistable properties in specific regions of the phase space and can therefore be written or erased independently in any location of the transverse plane provided they are distant one from each other of more than their diameter. At shorter distances they can form compound states or clusters. Moreover, an original property of CS resides in their possibility to be manipulated by controlled gradients of the external parameters. All these properties not only reveal fascinating mechanisms of the light-matter interaction in a resonator but also open the way to quite powerful functionalities that can translate into quite efficient all optical processing schemes.

This presentation will concentrate and develop on the experimental observation of such CSs obtained in III-V semiconductor based microresonators systems such as optically injected amplifiers or lasers defined by a gain/saturable absorber competition. Both cw and pulsed regimes are investigated in various geometrical configurations. The conditions in which stable periodic pulses can be observed and controlled is analyzed. Possible applications of such temporal regimes are finally considered. Extension to more complex excitable or nonlinear wave regimes will be investigated and prospective applications envisaged.

8268-57, Session 12

Anomalous evolution of quantum systems in the ultrastrong coupling regime

A. Arab, Univ. of Dayton (United States); S. Khorasani, Georgia Institute of Technology (United States)

Free running waveforms which are completely sinusoidal, has been considered the flawless answers of the JCP Hamiltonian for a long time. In yielding these answers, Rotating Wave Approximation, which neglects the anti-rotating terms in the interaction Hamiltonian, has been used.

In contrary to this conventional solution, we have dismissed the RWA and solved the JCP without any approximation. We have written a MATLAB code that solves the Schrödinger's equation in the most general case in which both the dipole-dipole and atom-field interactions are included. This code is capable of solving the Schrödinger's equation for any arbitrary system that user defines. In addition, the code generates another code regarding the parameters user has defined and automatically calculates and plots the concurrency. Furthermore, we have not used any numerical method to solve the equation and the results are mathematically exact.

A system including of a two-leveled quantum dot interacting with a single mode cavity, which are in resonant with each other, has been studied. The initial Fock state has been analyzed to determine the effect of anti-rotating terms that had been dismissed in RWA. It shows that as coupling constant increases, the effect of these terms becomes stronger and ultimately it cannot be neglected in UCR. In addition, system has been put in the coherent state and amplitude and phase of expectation values of photon annihilation operator and atomic ladder operator have been calculated and plotted. It has been depicted that even in Weak Coupling Regime the time variation of atomic ladder and photon annihilation expectation values are not sinusoidal at all, and also their phases have not varied linearly. As a result, the outcome of the code for these two operators is far from conventional free running solutions. Concurrency, showing the amount of entanglement that presents in the system, has been illustrated for several cases.

8268-58, Session 13

Standoff detection of explosives with broad band tunable external cavity quantum cascade lasers

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Due to the threat of terrorist bomb attacks, stand-off detection of trace explosives has become an important issue. Optical detection techniques based on IR - laser backscattering spectroscopy represent a promising approach, as organic chemical compounds typically exhibit strong characteristic absorbance patterns in the mid-infrared spectral range. Quantum cascade lasers are robust, compact and wavelength-versatile semiconductor lasers and therefore ideal illumination sources for this task.

Within the collaborative project IRLDEX, funded by the German Federal Ministry of Education and Research (contract number FKZ 13N4543), a mobile system has been developed that can detect traces of explosives on surfaces using hyperspectral IR-image analysis. On the hardware side, the key component of the system is a external cavity quantum cascade laser (EC-QCL) with a wide tunable range around 300 cm-1.

We present a QCL-based imaging system for stand-off detection of explosives on surfaces. Traces of almost all common explosives as well as various non-hazardous substances such as flour or skin cream on different substrate-materials were analyzed by illuminating them with the EC-QC laser and collecting the diffusely backscattered light. By tuning the EC-QCL across the characteristic absorption spectra in the thermal IR we were able to detect the explosives with excellent discrimination against other non-hazardous substances. For medium distances (< 3 m) trace concentrations down to the range of some 10 µg/cm2 can be detected. For higher material concentrations we demonstrate detection distance up to 28 m.

8268-59, Session 13

Angle-resolved scattering spectroscopy of explosives using an external cavity quantum cascade laser

J. D. Suter, M. C. Phillips, B. E. Bernacki, Pacific Northwest National Lab. (United States)

Infrared laser spectroscopy using quantum cascade lasers shows great promise for the standoff detection of explosives. However, interpretation of the spectral signals from explosives is often complicated by variations in relative contributions to the received signal from absorption, reflection, and scattering.

We present a study of the spectral and angular dependence of the diffuse scatter of mid-infrared (MIR) laser light from explosives residues on realistic surfaces. Experiments were performed using an external cavity quantum cascade laser (ECQCL) tunable between 7.1 and 7.9 microns (1270 to 1400 wavenumbers) to illuminate a surface and a mercury cadmium telluride (MCT) detector to detect backscattered spectra as a function of surface angle. Residues of RDX, tetryl, and TNT were examined on surfaces including a painted car door at a distance of 2 meters for angles between zero (specular) and 50 degrees. We observe distinct spectral signatures of the explosives in the scattering geometry which differ significantly from those observed in specular reflection or transmission geometries. The total scattered power depends strongly on collection angle, decreasing by as much as 4 orders of magnitude for scattering angles as small as 5 degrees from specular. Scattered light spectra of explosives were resolved for large angles, often with higher relative contrast than observed in the specular reflection spectra. We have used this characterization to analyze the differences between scattered and reflected spectra, which will be essential for understanding the performance of standoff explosives detection instruments and developing robust spectral analysis techniques.

8268-60, Session 13

Detecting contamination with a QCL spectrometer

F. G. Haibach, A. Mazurenko, E. Deutsch, Block Engineering, LLC (United States)

Block Engineering has developed a widely tunable quantum cascade laser (QCL) spectrometer, a probe, and algorithms specific to detecting low levels of surface contamination. This paper discusses the basic technology of the QCL spectrometer both in a standoff and probe based configuration. It provides information on the algorithms and probes developed for this application. The paper compares the QCL based technique to other approaches for detecting surface contamination. In addition to the data, we describe how this work is directly applicable for pharmaceutical cleaning verification, aerospace bonding surfaces, explosive detection, and potentially biological contamination.

8268-61, Session 13

Hollow fiber based quantum cascade laser spectrometer for fast and sensitive drug identification

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Sensitive and fast identification of drugs or drug precursors is important and necessary in scenarios like baggage or container check by customs or police. Fraunhofer IPM is developing a laser spectrometer using external cavity quantum cascade lasers (EC-QCL) to obtain mid-infrared (IR) absorption spectra in the wavelength range of the specific vibrational bands of amphetamines and their precursors. The EC-QCL by Daylight Solution covers a tuning range of about 200 cm-1 within 1 s.

The system could be used for different sample types like bulk samples or wipe tests or preconcentrated air particles. A sampling unit evaporates the sample. Because of small sample amounts a 3 m long hollow fiber with an inner volume smaller than 1ml is used as gas cell and wave guide for the laser beam.

This setup could be used as a detector of a gas chromatograph instead of a standard detector (WLD or FID). The advantage is the reliable identification of drugs by their IR spectra in addition to the retention time in the gas chromatographic column. In comparison to Fourier Transform IR systems the EC-QCL setup shows a good mechanical robustness. Because of the good fiber incoupling performance of the EC-QCL it is possible to use hollow fibers. So, a good absorption signal is achieved because of the long optical path in the small cell volume without significant dilution. In laboratory measurements a detection limit in the nanogram range is shown.

The project “Portable system for rapid detection of illicit Drugs and key precursors by InfraRed Absorption spectroscopy and gas Chromatography” (DIRAC) is funded by the EU (Grant agreement no. 242309).

8268-62, Session 13

Hyperspectral microscopy using an external cavity quantum cascade laser and its applications for explosives detection

M. C. Phillips, J. D. Suter, B. E. Bernacki, Pacific Northwest National Lab. (United States)

Hyperspectral imaging using broadly tunable external cavity quantum cascade lasers (ECQCLs) offers the potential for high-speed chemical imaging of gas, liquid, and solid compounds over a wide range of magnifications. Operating in the mid-infrared (MIR) “fingerprint” spectral region of 3-14 µm, ECQCLs provide a high-brightness tunable laser source for infrared spectroscopy and imaging. We have previously demonstrated hyperspectral imaging using ECQCL illumination in both transmission and reflection geometries; however, the spatial resolution of these systems was limited as they were designed for imaging large fields-of-view. We have recently adapted these hyperspectral imaging techniques to microscopy applications, in which the infrared absorption spectra of small particles or spatial features can be studied.

Using infrared hyperspectral imaging, we demonstrate microscopy of small particles of the explosives compounds RDX, tetryl, and PETN with near diffraction-limited performance. The custom microscope apparatus includes an external cavity quantum cascade laser scanned over its tuning range of 9.13-10.53 µm in four seconds, coupled with a microbolometer focal plane array to record infrared transmission images. We use the hyperspectral microscopy technique to study the infrared absorption spectra of individual explosives particles, and demonstrate sub-nanogram detection limits.

8268-63, Session 14

InGaAs/InP single-photon counting module running up to 133 MHz

A. Tosi, A. Della Frera, A. Bahgat Shehata, C. Scarcella, F. Acerbi, F. Zappa, Politecnico di Milano (Italy)

More and more photon-starving applications, ranging from biotechnologies to physics, from secure telecommunications to materials science, require the detection of single photons in the 900 - 1700 nm wavelength range. High performance Single-Photon Avalanche Diodes (SPADs) made in InGaAs/InP technology have been successfully developed to fulfill such needs. Yet, dedicated high-speed low-jitter electronics is needed in order to fully exploit such photodiodes in different applications, each requiring very peculiar operating conditions.

We present new circuital solutions for operating InGaAs/InP SPADs at high speed with very fast avalanche quenching time. A compact wide-band pulse generator (mounted close to the detector) is able to gate the SPAD at a repetition frequency from 200 Hz up to 133 MHz. An adjustable amplitude gate-driver allows to trade-off between photon detection efficiency and dark count rate, while a variable gate-width precisely selects the time interval during which the detector is ON. A fast avalanche-quenching scheme, working on both SPAD's anode and cathode, is able to minimize quenching action to less than 1 ns, thus effectively reducing afterpulsing through a decreased total charge flowing through the junction.

We integrated all such circuits into a compact detection module, together with a previously-reported differential read-out electronics for low time-jitter response. We show the performance of the overall module in many different setting points, just to proof its suitability for a wide variety of applications.

8268-64, Session 14

Detecting single photons with superconducting nanowires

S. N. Dorenbos, I. E. Zadeh, V. Zwiller, Technische Univ. Delft (Netherlands)

We will report on the characterization of Superconducting Single Photon Detectors (SSPDs) systems fabricated with NbTiN on a silicon substrate. This type of SSPDs shows an unprecedented signal to noise ratio, making them the detector of choice for quantum optics experiments.

We have developed a fiber coupling technique which makes it straightforward to implement the detectors in experiments. This we show by performing antibunching measurements with different types of single photon emitters.

8268-65, Session 14

Fast-gated single-photon detection module with 200 ps transitions running up to 50 MHz with 30 ps resolution

G. Boso, A. Dalla Mora, A. Tosi, A. Della Frera, F. Zappa, Politecnico di Milano (Italy)

We present a novel instrument able to quickly time-gate a silicon Single-Photon Avalanche Diode (SPAD) to be used in advanced gated Time-Correlated Single-Photon Counting (TCSPC) setups, like time-resolved optical spectroscopy, optical mammography, optical molecular imaging. The detection module boosts the photon counting dynamic range, thanks to the fast transitions between the OFF and the ON state of the detector.

The module embeds into a single box (11 cm x 15 cm x 24 cm) all components needed to operate a SPAD detector in fast time-gated mode and to output a standard NIM timing signal. The module includes: i) an ultra-fast pulse generator, based on MMIC components, to enable and disable the detector in less than 200 ps for very short and well-defined time slots, ranging from less than 1 ns up to 10 ns with 10 ps steps, at a repetition rate up to 50 MHz; ii) the silicon SPAD itself together with optical assembly to focus photons from the optical fiber onto the active area; iii) a passive quenching/active reset electronics, needed for optimal detector operation; iv) a low time-jitter ultra-fast comparator, to detect avalanche ignitions with less than 30 ps (FWHM) jitter and to generate a standard NIM output; v) a service board containing power supply, microcontroller, and USB link, to remotely set and control all instrument parameters.

8268-66, Session 14

Spectral dependence of ultra-low dark count superconducting single photon detector for the evaluation of broadband parametric fluorescence

S. Subashchandran, R. Okamoto, A. Tanaka, M. Okano, Hokkaido Univ. (Japan) and Osaka Univ. (Japan); L. Zhang, L. Kang, J. Chen, P. Wu, Nanjing Univ. (China); S. Takeuchi, Hokkaido Univ. (Japan) and Osaka Univ. (Japan)

Superconducting nanowire single photon detectors (SNSPD), have unique characteristics of ultra low dark counts and wide spectrum sensitivity. These natures are indispensable for the evaluation of ultra-broadband parametric fluorescence, which will be used for the quantum optical coherence tomography and novel optical non-linear experiments. Here we report the spectral dependence of a SNSPD over the spectral range of 500nm - 1600nm, in steps of 100nm. The meander type device was fabricated using 50nm narrow width and 6nm thick NbN nanowires patterned over a MgO substrate with active area of 10 x 10μm2¬. We used a white light source and a laser line Bragg tunable band pass filter which can select a wavelength with a band width of ≤1nm. We observed a maximum efficiency of 32% at 500nm, 30% at 600nm, 16% at 800nm, 10% at 1000nm, and 1% at 1550nm with the normalized bias current of 0.95 and dark counts as minimum as 2 Hz. The device exhibits ultra low dark count of 0.01Hz without appreciable decrease in the detection efficiency in the visible region (32% at 500nm and 30% at 600nm) and decreased to 0.1% at 1550nm. We observed almost exponential dependence of detection efficiency with the incident wavelength and noise equivalent power (NEP) of the order 10-19 WHz-1/2 in the visible region and 10-17 WHz-1/2 in the near IR region. We are planning to use this device for the detection of ultra-broad band parametric fluorescence.

8268-67, Session 15

Electroluminescence from p-type thin film/n-type nanostructures aligned by non-uniform electric field

J. Kim, Korea Univ. (Korea, Republic of)

P-type thin film / n-type nano(micro)structures have been demonstrated by using dielectrophoretic force. Various combinations of ZnO, GaN and Si materials successfully formed p-n heterojunction after aligned by non-uniform electric fields. Also, the electroluminescence was observed from the various p-type thin film / n-type nano/micro-structures under forward bias condition. From n-type GaN microwire / p-type Si thin film, the wave-guiding effects were also observed, which showed that this structures can be used as both the interconnects (optical waveguide) and the point LEDs. The details of the fabrication methods and the electrical/ optical characterizations will be presented.

8268-68, Session 15

Full-scale self-emissive blue and green microdisplays based on GaN micro-LED arrays

J. Day, Texas Tech Univ. (United States); J. Li, III-N Technology, Inc. (United States); D. Lie, Texas Tech Univ. (United States); C. E. Bradford, U.S. Army Night Vision & Electronic Sensors Directorate (United States); J. Lin, H. Jiang, Texas Tech Univ. (United States)

Since their inception, micro-size light emitting diode (µLED) arrays based on III-nitride semiconductors have emerged as a promising technology for a range of applications. Until now, semiconductor microdisplays were incapable of delivering video images due to the fact that it is nearly impossible to connect the huge number of required drive circuits and only one row could be accessed at any one time within a passive monolithic µLED array. We report the successful integration of III-nitride µLED array with Si CMOS to accomplish a high-resolution solid-state self-emissive microdisplay operating in an active driving scheme. The fabricated blue and green video graphics array (VGA) microdisplays (640 x 480 pixels) have a pixel size of 12 µm, a pitch distance of 15 µm and are capable of delivering real time video graphics images. An energy efficient active driving scheme is accomplished by integrating micro-emitter arrays with CMOS active matrix drivers that are flip-chip bonded together via indium metal bumps. The luminance level of III-nitride microdisplays is much higher than those of liquid crystal and organic-LED displays. The pixel emission intensity was almost constant over an operational temperature range from 100 to -100 oC. Our results indicate that III-nitride microdisplays are a favorable competing technology compared to conventional liquid crystal display, OLED, digital light processing, and laser beam steering based microdisplay technologies for ultra-portable products such as next generation pico-projectors, wearable displays, and head-up displays. This success also means that InGaN µLED arrays could play crucial roles in emerging fields such as optogenetics.

8268-69, Session 15

Flexible GaN LED on a polyimide substrate for display applications

H. G. Yoo, K. Park, M. Koo, S. Kim, S. Lee, S. H. Lee, K. J. Lee, KAIST (Korea, Republic of)

III-V LEDs have superior characteristics, such as long-term stability, high efficiency, and strong brightness compared to OLED. However, due to the brittle property of inorganic materials, III-V LED limits its applications for the flexible electronics. This seminar introduces the first flexible GaN LED on plastic substrates that is transferred from bulk GaN wafers. The superb properties of the flexible GaN LED in terms of its wide band gap and high efficiency enable the dramatic extension of not only consumer electronics but also the biosensing scale. The flexible white LEDs are demonstrated for the feasibility of future flexible BLU. Finally a water-resist and a biocompatible PTFE-coated flexible LED biosensor can detect PSA at a detection limit of 1 ng/mL. These results show that the nitride-based flexible LED can be used as the future flexible display and a type of implantable LED biosensor.

8268-70, Session 15

Light emitting diodes: the future lighting source with high efficiency

H. K. Kwon, LG Electronics Inc. (Korea, Republic of)

Advanced technologies to improve the light emitting diodes are presented. A technique to measure the internal quantum efficiency is introduced to extract the extraction efficiency in LEDs. The measured internal quantum efficiency is correlated with the defect properties better than before by considering not only defect density but also defect type and size. The relationship between the internal quantum efficiency and the defect properties is explained by measuring the four commercial products. To improve the extraction efficiency in vertical LED, the surface roughening made by photo-enhanced chemical etching is inspected in details. The The role of silicone encapsulation is reviewed. The way to protect the reflecting surface of LED package and its effect on reliability is explaind by measuring the 1000hr life time test. By integrating the advanced technology, the improved lighting device can be fabricated in terms of performance and reliability.

8268-71, Session 16

Nanoscale metrology of graphene

K. F. Kelly, Rice Univ. (United States)

In this talk, I will review our recent success in applying probe microscopy to understanding the chemistry of graphene and graphitic nanoparticles. We have used STM to compare the morphology and defect density in graphene grown on copper foils by liquid-phase epitaxy to that produced by other methods such as mechanical exfoliation and pyrolysis of silicon carbide. In addition, we have applied a similar analysis to the characterization of chemically suspended graphitic nanoparticles. Coupled with these studies, we also performed chemical characterization of these systems using Raman microscopy. Lastly, I will discuss the role of different electron tunneling spectroscopies to understand both the layering and doping in these graphene systems.

8268-72, Session 16

Direct graphene growth on dielectric substrates: enabling technology for industrial development of graphene electronics and spintronics

J. Kelber, M. Zhou, F. L. Pasquale, Univ. of North Texas (United States); P. A. Dowben, Univ. of Nebraska-Lincoln (United States)

Direct deposition, by practical and scalable methods, of graphene on dielectric substrates is a critical step toward the industrial-scale development of graphene-based devices. We have demonstrated direct growth of macroscopically continuous graphene films on h-BN(0001)/Ru(0001) by chemical vapor deposition, on MgO(111) by both chemical and physical vapor deposition and on Co3O4(111)/Co(111) by molecular beam epitaxy. In each case, strong chemical interfacial interactions induce significant changes to graphene electronic structure. Photoemission/inverse photoemission and scanning tunneling microscopy/spectroscopy measurements show that graphene on BN retains its basic electronic structure, but charge transfer from the substrate fills the π^* band. For graphene/MgO, photoemission/inverse photoemission measurements reveal a ~0.5 eV-1 eV band gap, consistent with observed C3V LEED symmetry, and suggesting a reconstructed, commensurate oxide/graphene interface. For graphene/Co3O4(111), an incommensurate interface is observed by LEED, as well as significant graphene-->oxide charge transfer, as indicated by a C(1s) photoemission binding energy of 284.9(±0.1)eV for 3 monolayer graphene. These results demonstrate that electronic properties of directly grown graphene are fundamentally impacted by graphene/substrate interactions, and that these properties may be “tunable” by variation of the substrate thickness or the number of graphene layers. Challenges/opportunities for development of “synergistic” graphene/dielectric heterojunction-based devices will be discussed.

8268-73, Session 16

Oxygen sensors made by monolayer graphene

S. C. Hung, C. W. Chen, National Central Univ. (Taiwan); M. D. Yang, C. W. Yeh, C. H. Wu, Institute of Nuclear Energy Research (Taiwan); G. Chi, National Chiao Tung Univ. (Taiwan); F. Ren, Univ. of Central Florida (United States); S. J. Pearton, Univ. of Florida (United States)

Graphene is a promising material in lots of applications, such as transparent contact layer for optoelectric devices and biosensor. In our previous work, we demonstrate a minipressure sensor made by functionized gated AlGaN/GaN HEMTs. In this study, we will demonstrate another minipressure sensor made by CVD grown graphene with metal contact. The sheet resistivity of graphene is highly dependent with different concentration of oxygen in the testing chamber. The results shows the potential of the application of graphene in oxygen gas sensor.

8268-75, Session 17

Two-photon conductivity in semiconductors: a new tool for the study of the quantum properties of light

E. Rosencher, ONERA (France) and Ecole Polytechnique (France); F. Boitier, A. Godard, ONERA (France); C. Fabre, Univ. Pierre et Marie Curie (France)

Photons emitted by optical sources display temporal correlations, i.e. photon coincidence rates, which are a signature of their emission mechanism. Since the very beginning of quantum optics in the 1960's, it has been suggested that two photon absorption (TPA) could measure these photon temporal correlations in the femtosecond timescale, since it involves an almost simultaneous absorption of two photons, within a maximum delay given by the Heisenberg principle. Here, this long searched prediction is experimentally demonstrated using the association of interferomery setups and two photon conductivity (TPC) in a GaAs photon counting module.

Using this new tool, that we call TPC interferometry, we have been able to unravel the spectacular behaviour of photons emitted by different optical sources, in agreement with the predictions of quantum optics.

For instance, we have observed bunching of photons emitted from blackbody sources in the femtosecond range,i.e blackbody photons tend to be detected in pairs.

We have also applied this technique to the study of twin beams originating from parametric down convertion, which are the workhorse of quantum optics engineering today. We have unambiguously shown that twin photon are effectively produced in pairs within few femtoseconds, giving rise to extrabunching, originating from exact coincidences between down converted pairs of photons, travelling in unison.

TPC interferometry is opening new opportunities in Photonics, such as quantum cryptography, ghost imaging, optical diagnostics of combustion, or monitoring optical quantum statistics at the femtosecond timescale.

8268-76, Session 17

Semiconductor sources of two-photon states at room temperature in the telecom range

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The miniaturization of quantum information technology is a subject attracting a growing attention; different approaches are currently under study going from superconducting qubits, to microtraps for ions and atoms, to sources and detectors of single and multiple photon states.

In this context the exploitation of spontaneous parametric down conversion in AlGaAs waveguides to fabricate integrated sources of photon pairs presents several advantages: high nonlinear susceptibility and well-mastered growth technique, room-temperature operation and high emission directionality in the telecom range.

Different geometries of phase matching can be used depending on the researched properties of the two-photon state.

In this work we will present our recent results on three different kinds of AlGaAs devices.

1) A microcavity-based source, in which a transverse pump beam generates two counterpropagating, orthogonally polarized signal and idler guided photons (A. Orieux et al., J. Opt. Soc. Am. B 28, 45(2011))

2) A selectively oxidized source, based on form birefringence phase matching, for which we have demonstrated the strongest second harmonic generation ever reported in semiconductor waveguides (M. Savanier et al. Opt. Letters 36, 2955 (2011))

3) A waveguide based on modal phase matching among a Bragg mode and two modes confined by total internal reflexion.

We will discuss and compare the figures of merit characterizing the three devices in the aim of their application for quantum information and communications: conversion efficiency, optical losses, spectral characteristics and versatility of the generated two-photon state.

8268-77, Session 17

Laterally confined photonic Tamm states: a new approach for single photon sources and cavity-enhanced photodetectors

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Laterally confined photonic Tamm states : a new approach for single photon sources and cavity-enhanced photodetectors.

Photonic Tamm states1 (or Tamm plasmons) are strongly localized optical modes formed due to the specific boundary conditions at the interface between a periodic stack of dielectric materials (a Bragg mirror) and a metallic layer. They are an electromagnetic analog to the electronic Tamm states formed at the interface between a crystalline solid and vacuum. When the lateral size of the electrode is reduced, efficient 3 D confinement of light is obtained. In spite of absorption in the metal, the quality factor of these original microcavities can be large enough (>1000) for cavity quantum electrodynamics applications. Compared to alternative solutions such as photonic crystal or micropillar cavities, Tamm plasmon cavities are considerably easier to fabricate and allow natural coupling to an electrical circuit for current injection or detection. We investigate this new type of « hybrid » metal-semiconductor microcavities and demonstrate their potential by fabricating a single photon source formed by a single quantum dot deterministically coupled to a Tamm plasmon cavity2. We further anticipate their advantages in the context of cavity-enhanced photo-detection.

1 M. Kaliteevski et al., Phys. Rev. B76, 165415 (2007)

2 O. Gazzano et al., Archiv 1106.4437 (2011)

8268-78, Session 18

Reliable GaN-based resonant tunneling diodes with reproducible room-temperature negative differential resistance

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Recently, III-nitrides have gained interest for intersubband (ISB) devices. This is because large electron effective mass (m* ~ 0.2-0.3×m0) and longitudinal optical phonon energy (~ 90 meV) enable ultrafast ISB relaxation offering very high speed devices. Specifically, wide bandgap, large conduction band discontinuity [~ 2.1 eV in AlN/GaN], high carrier mobility, and thermal stability promise high power, high frequency room-temperature operation for GaN-RTDs. Demonstrating NDR and understanding the transport in AlGaN/GaN double-barrier (DB) RTDs will enable room-temperature terahertz oscillators and quantum cascade lasers. Despite these promises, there were no reports of reliable NDR in GaN-based DB heterostructures until our demonstration.

In this talk, we will discuss the challenges addressed and techniques employed to achieve highly reliable GaN-based RTDs. Employment of low dislocation density substrate, polarization-free design, and low aluminium content active layer approach were shown to increase reliability and reproducibility of NDR in RTDs. This is the world's first reliable and reproducible negative differential resistance demonstration in GaN-based RTDs. GaN-based RTDs possessed R of -67 Ω, CPVR of 1.08, and PMAX of 0.52 mW at room temperature. Our work motivates further research towards low aluminum content polarization-free AlGaN/GaN DB-structures grown on low dislocation density substrates.

8268-79, Session 18

Tunable surface emitting THz quantum cascade structure based on cyclotron emission

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The application of a strong magnetic field along the growth axis of a quantum cascade structure (QCS) gives rise to a spectrum of discrete energy states, the Landau levels (LLs) |i,j> which are separated by the cyclotron energy. Cyclotron emission (inter-LL emission) has a polarization ε_x and thus photons can be emitted through the surface of the sample contrary to intersubband transition where the light has a polarization ε_z and is emitted through the side of the device. It has been theoretically demonstrated that in the vicinity of crossing LLs which belong to different subbands, the redistribution of the electron population between them occurs in a subpicosecond scale. In this study we conceived a QCS in which electrons are injected in the first excited LL |2,0> of a large quantum well. By exploiting an elastic scattering mechanism, electrons are transferred in the LL of the first subband |1,j> and subsequently generate photons by spontaneous emission between |1,j> and |1,j-1>.

Spectra as a function of magnetic field exhibit a wide variety of peaks at different energies. In addition to cyclotron emission at energy $\hbar\omega_c$, other peaks appear. We assume that they are the result of activated optical transitions that are normally forbidden in ideal structures. Voltage as a function of magnetic field clearly shows that electron-electron interaction is the dominant mechanism. This study is very promising for extending the present emitter concept to the realization of the LL-laser.

8268-80, Session 18

Room temperature terahertz detectors based on semiconductor nanowire field effect transistors

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No abstract available

8268-81, Session 18

Surface phonon polaritons for active THz devices

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The THz gap is a frequency domain (1011 to 1013 Hz) where sources, detectors and modulators are to a large extent not available [1]. Compact solid-state devices operating at room temperature are still missing, with one remarkable exception[2], based on electrically modulated absorption by metamaterials at frequencies around 1 THz. Here, we introduce a novel modulation mechanism based on an unconventional use of a single GaAs quantum well placed below a gold grating. The 22 nm thick GaAs layer absorbs more than 45% of the incident radiation by the resonant excitation of surface phonon polaritons at 8.74 THz, an absorption largely due to a near-zero dielectric constant in the GaAs layer. By adjusting the intersub-band transition frequency in the quantum well to the surface phonon polariton resonance, an electrical control of the electron density allows to tune the refractive index. This new scheme permits an electrical control of the reflectivity. A relative modulation of the THz reflectivity (ΔR/Rmin) of 54% is demonstrated at room temperature. The ideas put forward in this work can be extended to design new optoelectronic devices in the infrared and THz domains.

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8268-82, Session 18

Phase-locking of a 2.5THz quantum cascade laser to a frequency comb using a GaAs photo-mixer

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Compact, terahertz (THz) sources with high spectral purity are required as local oscillators for applications in high-resolution spectroscopy and broad-band wireless telecommunications. In this respect THz quantum cascade lasers (QCLs) are competitive sources, emitting tens of mW in CW in the ~2-4.5 THz range. Recently THz QCLs have been phase-locked to the repetition rate of fs-fibre combs, using electro-optic sampling.

A well-established method to extend the accuracy of optical frequency combs to the THz region relies on the use of semiconductor photomixers (PMs). With this technique the fs-pulses from an optical mode-locked laser produce a photo-carrier THz comb in the PM, composed of a set of lines oscillating at a harmonic of the fs-laser repetition rate. The PM can then be used as a multi-frequency local oscillator. This system has been used to measure the emission frequency of electronic sources emitting at ~100GHz.

In this work we show how a PM-based THz frequency comb produced by a 1550nm fs fiber-laser, can be used to phase-lock the emission of a 2.5THz QCL. With 10 mW emitted by the quantum cascade laser, the phase-locked signal at the intermediate frequency yields 80 dB of signal-to-noise ratio in a bandwidth of 1 Hz. Such a hybrid QCL-optoelectronic system takes advantage of the QCL inherent high power, producing an increase of the signal-to-noise ratioby three to four orders of magnitude at ~2.5THz compared to state-of-the art continuous-wave photo-mixing systems.

8268-83, Session 18

LT GaAs nanophotoswitches for microwave sampling

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It is well-known that Low Temperature growth GaAs (LT GaAs) is a convenient material for very high speed photoconductive detectors, due to its high resistivity in darkness and very short recombination time of photocarriers. Included in a microwave coplanar line, this photoconductor, constituted of a LT GaAs gap in the central metal ribbon, can act as an optically controlled switch (or photoswitch) of the microwave signal propagating along the coplanar line: in darkness the impedance of the gap (photoswitch) is high and the microwave signal cannot pass through (OFF state); under illumination the photoswitch acts as a short-cut for the microwave signal which propagates along the coplanar line (ON state). By illuminating the photoswitch with very short laser pulses periodically emitted, it has been recently demonstrated the sampling of microwave signals: samples of the microwave signal injected at the input of the coplanar line are collected at the output of the line during the light pulse (ON state). Compared to the all-electronic method, the photonic one can take advantage of the very low jitter of the laser sources to reach better performance for analogue to digital conversion of microwave signals. Nevertheless, conventional (in size) photoswitches need too much optical power to be competitive with electronics in size, compactness, consumption...

It is the reason why we designed, fabricated and characterized a new LT GaAs nano-photoswitch, which active region (the gap) has a 3D submicron size. Thanks to a reduce volume, the impedance of the LT GaAs gap can be controlled with a few milliwatts range mean optical power for devices top illuminated with a lens-ended fiber or through a dielectric (SiO2/Si3N4) optical waveguide to localize the impinging light in the active region. Experiments carried out with an impulse laser (2 and 4 ps pulse width, 80 and 320 MHz repetition frequency rate, 1.6 and 0.6 mW mean optical power) demonstrated sampling and re-building of microwave signals for frequencies up to 20 GHz with this nanophotoswitch associated to a DAC for monitoring. In the conference, details on the design and technology of this new microwave - photonic integrated circuit will be given, together with the experiments dedicated to its characterization and sampling demonstration.

8268-114, Session 18

Generation and amplification of ultrafast THz pulses using gain switching in quantum cascade lasers

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Laser action normally is initiated by the amplification of spontaneous emission. As spontaneous emission is a random process, the carrier phase of a laser is different each time a laser is turned on. As a consequence, it is not possible to measure the time-resolved field of a free-running laser using coherent detection techniques [1, 2]. Here we show [3] that it is possible to fix the carrier phase of a quantum cascade laser (QCL) by using injection seeding. Terahertz (THz) pulses with a fixed phase are injected into the QCL cavity and coincide with the gain of the QCL being turned on rapidly to avoid gain clamping (gain switching). The externally injected THz pulses are greatly amplified through multiple passes [4] and can initiate laser action (instead of the spontaneous emission) and set the carrier-phase. Consequently, as well as the generation of large THz fields, this enables the electric field of the laser emission to be measured as a function of time, from initiation of lasing to the steady-state lasing regime using coherent sampling techniques. The phased-resolved field of the QCL is thus directly measured in the time-domain. This work enables the laser emission to be measured in the time domain and the QCL to be used as a powerful source for time-domain spectroscopy. We also use this scheme to imprint a fixed phase relationship between the multiple longitudinal modes of a THz QCL, resulting in the emission of ultrashort THz laser pulses.

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8268-84, Session 19

Optical heterodyne detection in the mid-infrared: capabilities and new molecular sensing applications

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The mid-infrared spectral region gives access to the most intense molecular ro-vibrational bands of many species and is of particular importance for spectroscopic chemical sensing. On the other hand, performance of optical photodetectors in the mid-infrared becomes strongly limited by the thermal noise causing direct photodetection at the fundamental shot noise limit to be difficult without cryogenic cooling of the detector element. Thus optical heterodyne detection (OHD) that can achieve shot-noise limited performance without cryogens becomes an important alternative in the mid-infrared. In this paper several techniques that take advantage of mid-infrared OHD will be presented.

A coherent nature of an OHD process allows for optical phase measurements. A chirped laser dispersion spectroscopy (CLaDS) introduced recently uses this capability to detect refractive index changes in the vicinity of ro-vibrational transitions. A two-color dynamic interferometric OHD enables fast quantitative trace-gas detection with large immunity to optical power fluctuations (particularly important in remote sensing applications). Overview of CLaDS theory and spectral measurement examples targeting atmospheric pollutants such as NO or N2O using mid-infrared quantum cascade lasers (QCLs) will be discussed.

Another example of an OHD-based remote chemical sensing is a thermal infrared laser heterodyne spectro-radiometer employing a broadly tunable external cavity QCL as the local oscillator. This system capable of simultaneous monitoring of five atmospheric species (H2O, CH4, N2O, O3, and CCl2F2) was operated in a solar occultation mode. In this instrument the OHD enabled photodetection at 7x the fundamental shot-noise limit. Examples of laboratory and field tests will be presented.

8268-85, Session 19

Spectroscopic measurements of isotopic water composition using a new modulation cancellation method

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To determine the isotopic composition of selected chemical species it is necessary to measure the deviation of the concentration ratio R of two related isotopes with respect to the ratio in a reference sample Rst. The most common application is the isotopologue abundance quantification and the deviation from the reference $\delta[^0/_{00}]$ is expressed as $\delta[^0/_{00}]=((R-R_{st})/R_{st})\times1000$

Existing spectroscopic approaches to measure δ are based on precise separate measurements of the selected absorption lines with the subsequent numerical calculation of δ. For isotopic characterization of samples practically important δ values range from few $^0/_{00}$ to $0.1^0/_{00}$. Making such precise measurements is challenging due to small variations in pressure, laser power and other external factors. To address these issues, we have developed a novel modulation spectroscopic technique (MOCAM) [1, 2], which relies on the physical cancellation of the measured sensor response if R=Rst. In this case, the signal from the analyzed sample will be proportional to the deviation of the absorption line strength ratio from the reference one. We used quartz enhanced photoacoustic spectroscopy as the detection technique and water as the target species. The variation of the sample isotopic composition can be calculated using the following equation:

$$\delta^{18}O[^0/_{00}]=(U_A/U_{A1})\times1000$$

Here UA is the signal detected from the analyzed sample when the signal from the reference is zero; UA1 is the signal detected from the analyzed sample when the laser resonant with the H218O absorption line is switched off. We achieve a sensitivity in measuring $\delta^{18}O$ of $1.4^0/_{00}$, with a 200 sec of integration time.

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8268-86, Session 19

Heterodyne-enhanced Faraday rotation spectrometer

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Faraday rotation spectroscopy (FRS) has been used for sensitive and selective detection for multiple paramagnetic species in gas phase (NO, O2, NO2 etc.). However due to a large low frequency (<10 kHz) laser source relative intensity noise (RIN) and limited performance of mid-IR photodetectors, the sensitivity of the quantum cascade laser based FRS systems is far from the fundamental limits. Therefore new photodetection techniques are still required to improve the sensitivity of the mid-IR FRS. To achieve the shot-noise limited sensitivity we developed new method employing a heterodyne enhanced FRS detection (H-FRS). The system is based on a conventional (so-called 90 degree) FRS measurement method and uses an additional interferometer configuration that recycles the extraordinary beam from the Rochon polarizer after the FRS cell for heterodyne measurement. Since the ordinary beam carries the entire (relatively weak) FRS signal the high power extraordinary beam after acousto-optic frequency shift can serve as the local oscillator. The AOM is modulated at 30MHz as the laser RIN is largely suppressed, so we can obtain better signal-to-noise ratios at this heterodyne frequency.

Although the current system performance is still limited by the laser RIN observed at 30MHz, the measurements show a total noise level of only 2.8X the shot-noise. For comparison a QCL based FRS system cannot achieve better than 10X the shot noise limited performance. Further reductions of the RIN are being implemented and improvements of the H-FRS sensitivity are expected. Comparisons between a conventional FRS and H-FRS systems will be discussed in details.

8268-87, Session 19

A modular architecture for multi-channel external cavity quantum cascade laser-based chemical sensors: a systems approach

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A multi-channel Herriott cell-based chemical sensor platform is presented, in which a modular architecture allows the exchange of complete sensor channels without disruption to overall operation. Each sensor channel contains custom optical and electronics packages, which can be selected to access particular laser wavelength regions, cell path lengths and modulation techniques optimal for given applications or missions. Although intended primarily to accommodate mid-infrared (MIR) external cavity quantum cascade lasers (ECQCLs) and astigmatic Herriott cells, sensors using visible or near infrared (NIR) lasers, or other gas cell architectures can also be used, making this a truly versatile platform. Analog and digital resources have been carefully chosen to facilitate small footprint, rapid spectral scanning, low-noise signal recovery, fail-safe autonomous operation, and finally in-situ chemometric data analysis, storage and transmission.

A prototype two-channel version of this platform is discussed in detail. Both channels use ECQCLs, with operating wavelength ranges of 7.35 to 8.20 µm (1220 - 1360 cm^-1) and 9.35 to 10.42 µm (960 - 1070 cm^-1), and astigmatic Herriott cells with optical path lengths of approximately 50 and 90 meters respectively. These sensors routinely distinguish between multiple chemicals, and between broad and narrow spectroscopic features simultaneously, with sensitivities at a one-second time resolutions for many chemicals in the low parts-per-billion. The prototype is housed in a 28x19x16 inch aluminum case, weighs 77 lbs, and draws 250 Watts of electrical power.

8268-88, Session 19

Sub-ppb detection of nitrogen dioxide with an external cavity quantum cascade laser

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Faraday Rotation Spectroscopy (FRS) has been recognized as a sensitive and zero background technique for trace gas measurements of the paramagnetic molecules [1,2]. Moreover, the FRS technique is well suited for atmospheric detection of prominent air pollutants (NO, NO2) or for exhaled breath analysis (NO). This is because interferences from diamagnetic species, such as water and carbon dioxide, are effectively eliminated.

In this paper an ultra-sensitive detection of NO2 at sub-ppb concentration levels will be reported based on a FRS sensor platform employing a widely tunable external cavity quantum cascade laser (EC-QCL). With available EC-QCL mode-hop free frequency tuning, between 1600 cm-1 and 1650 cm-1, the optimum FRS 441<-440 Q-branch NO2 transition at the 1613.25 cm-1 was accessed with an optical power of ~135 mW. To improve detection sensitivity and reduce the size of the FRS system, a custom made multipass gas cell (MPC), with total effective optical path of 10 m for 22.47cm separation between the multipass mirrors, was implemented. The whole optical sensor platform, including the MPC surrounded by a 15 cm long air core solenoid and placed between two MgF2 Rochon polarizers with an extinction ratio of less than 10-5, was installed on 18" by 24" optical board. To-date a NO2 detection sensitivity of 400 pptv (1σ) for a 1 second lock-in time constant was obtained at an optimal pressure of 30 Torr and magnetic field of 200 Gaussrms. Performance details of such a FRS based sensor and preliminary results of atmospheric NO2 measurements for both scan and line-locked modes will be presented.

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8268-89, Session 19

Progress towards compact broadly tunable laser modules for high-resolution mid-IR spectroscopy and commercial applications

M. J. Weida, E. Fotheringham, T. Day, Daylight Solutions Inc. (United States)

Many important gas-phase molecules for environmental and health monitoring have sharp spectral features that remain resolved at atmospheric pressure. Molecules such as CH4, CO2, NO, NH3, and others, can be monitored via direct absorption spectroscopy, but require continuous tuning, CW laser sources for enhanced sensitivity. Due to the wide availability of telecom diode lasers, these molecules have traditionally been monitored in the near-infrared (IR) (0.8 to 2.0 µm) with distributed feedback (DFB) diode lasers, even though the mid-IR spectral region (2 to 20 µm) is known to be ideal for its much stronger molecular absorptions. Quantum cascade (QC) lasers are now capable of providing continuous, CW radiation throughout much of the mid-IR. DFB versions of QC lasers have already seen success in environmental and health monitoring applications, using the strong chirp in pulsed operation to scan over several spectral features. Here we present progress towards new compact mid-IR laser modules that allow for much broader continuous CW tuning than available with the DFB intra-pulse technique. Broad continuous tuning has already been demonstrated in larger QC laser modules, but they require water cooling and have a form factor not ideal for inclusion in commercial instrumentation. Recent advances in higher efficiency, lower power consumption QC devices have enabled new laser modules with compact form factors and performance that is promising for realizing a new set of commercial applications involving sensitive spectroscopic detection of multiple light molecular species.

8268-90, Session 20

Realisation of innovative quantum imaging protocols at INRIM

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Innovative Quantum Imaging protocols

Marco Genovese, Giorgio Brida, A.Meda, I. Degiovanni, Ivano Ruo Berchera

Quantum properties of the optical field represent a resource of the utmost relevance for the development of quantum technologies, allowing unprecedented results in disciplines ranging from quantum information and metrology to quantum imaging.

In particular, in the last case various protocols have been proposed ranging from ghost imaging [1] to quantum illumination [2].

In particular Ghost Imaging can have very interesting practical applications [3].

Another kind of protocols of interest for possible application is offered by the possibility of sub shot noise measurements with quantum optical states.

In particular a very interesting example is provided by the detection of weak objects by exploiting the quantum correlations of parametric down conversion (PDC) emission: a result that could have important practical applications. A little more in detail the principle of this technique is to take advantage of the correlation in the noise of two conjugated branches of PDC emission : in fact, subtracting the noise measured on one branch from the image of a weak object obtained in the other branch, the image of the object, eventually previously hidden in the noise, could be restored [4].

In this talk, after a general summary of quantum imaging techniques, firstly we will show how we have reached a sub shot noise [5] regime and then improved this result up to reach a regime where it was possible to achieve the first experimental realisation of sub shot noise imaging of a weak absorbing object [6].

Then we will present some recent experiments addressed to realise improved ghost imaging protocols in view of practical applications.

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8268-91, Session 20

Recent advances in quantum cascade lasers in the InAs/AlSb material system

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The InAs/AlSb material system is very attractive for the development of short wavelength quantum cascade lasers (QCL) due to the high conduction band offset of 2.1 eV. Using these materials we have demonstrated first QCLs operating below 3 µm and extended the short wavelength limit of QCL operation down to 2.6 µm. Performances of InAs/AlSb QCLs are expected to degrade at short emission wavelengths due to increasing electron leakage into the L-valley of the InAs quantum wells. We have nevertheless demonstrated InAs-based QCLs emitting close to 3.0 µm at room temperature which can be operated in pulse mode up to 400K.

Molecular spectroscopy is one of the main applications of mid-infrared lasers. We fabricated and studied distributed feedback InAs/AlSb QCLs operating around 3.3 µm. Details and results of this study, which allowed us to obtain stable single frequency emission in this spectral region, will be presented.

The InAs/AlSb system is also attractive for the development of long wavelength lasers because of the small electron effective mass in InAs resulting in higher QCL gain compared with other materials. We have realized InAs/AlSb QCLs emitting above 8 µm. A double-metal waveguide was used in the lasers with emission wavelength close to 20 µm.

Prospects of InAs-based QCLs will be discussed in the conclusion.

8268-92, Session 20

Infrared imaging with quantum wells and strained layer superlattices

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In the last few years infrared focal plane arrays based on Type-I GaAs/AlGaAs quantum well infrared photodetectors (QWIPs) have been commercialized, providing excellent cost-effective imaging for security and surveillance and gas imaging applications. A second cooled infrared sensor technology that has made significant advances in recent years are photodiodes based on Type-II InAs/(In)GaSb strained layer superlattices (SLS). Imaging chips with upto a million pixels, quantum efficiency exceeding 50%, and cutoff wavelength exceeding 10 microns have been recently demonstrated. SLS offers the promise of the high quantum efficiency and operating temperature of mercury cadmium telluride (MCT) at the price point of QWIP and midwave indium antimonide (InSb). That promise is rapidly being fulfilled. This talk will review the current state-of-the-art of both these sensor technologies at this critical stage of their evolution.

8268-113, Poster Session

Graphene-based quantum hall effect infrared photodetectors

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Graphene [1] is a promising material for optoelectronics and photonics [2]. Recent experiments demonstrated graphene photodetectors based on interband transitions working at Mid and Near-IR/Visible regions. Extension of the spectral range to longer wavelengths requires alternative photoresponse mechanisms. One of the mechanisms which has been proven to be efficient for THz range for "classical" semiconductor materials is the optically-induced breakdown of quantum Hall effect. The major limitation for "classical" quantum Hall effect photodetectors made in GaAs or MCT is the low (liquid Helium) operation temperatures required.

In our work we successfully demonstrated a graphene-based QHE photodetector working at liquid Nitrogen temperatures. Our result demonstrates the potential of graphene as a material for Far-IR photodetectors. Further improvement in device design and the use of more efficient radiation coupling solutions should enable graphene photodetectors with broader spectral range, higher sensitivity, and elevated operating temperatures for a variety of applications.

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8268-93, Session 21

QWIP status and future trends at Thales

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Since 2005 the Thales Group is successfully manufacturing QWIPs in high rate production through III-V Lab. All the early claimed advantages of QWIPs are now demonstrated. The versatility of the band gap engineering allows the custom design of detectors to fulfill specific application requirements in MWIR, LWIR or VLWIR ranges. The maturity of the III-V microelectronics based on GaAs substrates gives uniformity, stability and high production rate. In this presentation we will discuss the specific advantages of this type of detector and particularly the majority carrier nature of QWIPs. We will discuss also the new potentialities opened by the R&D work in the field of the optical solutions initially developed in order to cope with the intrinsic polarization selection rules forbidding normal incidence illumination. An overview of the available performances and production status will be presented including under-development products such as dual band and polarimetric sensors.

8268-94, Session 21

Optically-addressed multiband photodetector for infrared imaging applications

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Multiband infrared focal plane arrays (FPA) with small pixel pitch has increased processing complexity since they often need more than two terminals per pixel for readouts. Simpler FPA is enabled by our newly demonstrated optically-addressed two-terminal multiband photodetector architecture. The device consists of a series connected photodetectors, each with a different cutoff wavelength. Incident photons pass through all junctions whose bandgap has higher energies than the photons'. Photons in different wavelength bands are absorbed at corresponding junctions. All junctions except one are illuminated by a series of LEDs with their corresponding detection wavelengths, and the non-illuminated junction remains the only active photodetector since it limits the total current. To further improve the multiband photodetector architecture for long wavelength infrared (LWIR) and mid wavelength infrared (MWIR) imaging applications, the use of quantum well infrared photodetectors (QWIP) has been investigated. The results show that the utilization of unipolar QWIPs with bipolar near infrared (NIR) devices is feasible with this new optical addressing scheme. Using an equivalent ac-circuit model, our analysis of the potential device performance, including signal to noise ratio, reveals that the operating point of each photodetector can be tuned with optical and electrical bias, so that signal and noise of each band contribute with different weights to the single output terminal. Adequate impedance design will be adopted to eliminate some illumination LEDs, and to make it voltage tunable. Proposed design maximizes fill factor and enables small pixel-pitch FPA with single indium-bump per pixel for NIR/MWIR/LWIR multiband detection capability.

8268-95, Session 21

Electromagnetic design of resonator-QWIPs

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Rigorous electromagnetic field modeling is applied to design resonant cavities that are suitable for narrow band imaging between 8 - 9 microns. For this application, the cavity should exhibit a strong and sharp resonance. We investigated several detector geometries that can give rise to such a strong resonance and they are generally referred to as the resonator-QWIPs (R-QWIPs). These detector structures contain circular features, which are made of GaAs and are fabricated on top of square QWIP pixels. The unit cell of the pattern can be a circle (R1 design), a ring (R2 design) or a circle surrounded by a ring (R3 design) and is covered by metal. The diameter and height of the unit cells are adjusted to give the maximum integrated vertical electric field inside the QWIP active volume. The modeling result shows that while the R1 design offers a wider bandwidth of 1.5 microns, the peak quantum efficiency is highest for the R3 design with a bandwidth of 0.67 microns. For 20 micron pitch arrays, each pixel contains four unit cells and the calculated QE for R3 is 82% over an 1.5 microns-thick QWIP material. Even when the pitch is reduced to 12 microns, which contains only one unit cell, a 51% QE is obtained. Combined with a relatively large gain offered by the thin detector material, a high conversion efficiency is expected. In this work, we also investigated the effects of different metal covers on the detector performance. Experimental result will be presented if available.

8268-96, Session 21

Evolution of QWIP focal plane development at the NASA/Goddard Space Flight Center

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The development of GaAs quantum well infrared photodetectors (QWIPs) at NASA's Goddard Space Flight Center began in the late 1980s and has continued ever since. Initial developments produced single element detectors and shortly thereafter in 1990 a 128 x 128 element array was developed in collaboration with AT&T Bell Labs and Rockwell Science Center. Since that time we have developed numerous generations of QWIP arrays most recently resulting in the multi-QWIP focal plane for the next NASA-US Geological Survey Landsat mission to be launched in December of 2012. This paper will describe the technological evolutionary process from concept to a space flight qualified infrared detector system. Included will be descriptions of the four band multi-spectral/hyperspectral QWIP array, the 1k x 1k QWIP array, the broad band, space-qualified 640 x 512 QWIP arrays developed for the Landsat Data Continuity Mission (LDCM) and the current development of a 512 x 3k and 2k x 2k QWIP arrays for the next generation of high resolution earth observing missions. Result of QWIP camera airborn experiments will also be presented.

8268-97, Session 21

Responsivity enhancement of QWIPs by photonic crystal slabs

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We present a photonic crystal slab (PCS) fabricated from a quantum well infrared photodetector (QWIP). In the mid-infrared region (MIR) the dielectric out-of-plane confinement of photons in the slab wave guide inflicts much lower losses compared to a plasmonic wave guide. By using a QWIP with a low doping concentration in the quantum wells we have shown, that the noise due to the dark current can be reduced, while a high responsivity can be maintained due to the high lifetime of photons in the PC resonances [1]. We observed an increase of the maximum operation temperature from 110K for a standard QWIP up to 170K for a low-doped PCS-QWIP with a peak absorption at λ=8µm.

When designing such PCS devices the thickness of the slab is of crucial importance. For slabs with a high slab-to-PC ratio d/a we have shown, that additional peaks can be found in the photocurrent spectrum, which correspond to higher order modes of the slab wave guide [2]. By variation of the slab-to-PC ratio we are able to precisely identify the order of the slab mode of a resonance as well as the polarization by the magnitude of the resulting peak shift. In conjunction with the established photonic band structure mapping technique [3] we present a detailed characterization of multi-mode PCSs. The measured band structures are in good agreement with simulation results of the revised plane wave expansion method (RPWEM) with an effective refractive index approximation for the slab wave guide.

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8268-98, Session 22

Semiconducting hexagonal boron nitride for deep ultraviolet photonics

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Among the members of the III-nitride material system, hexagonal boron-nitride (hBN) having a band gap comparable to AlN (Eg ~ 6 eV), is the least studied and understood. Due to its extraordinary physical properties, such as high chemical stability, thermal conductivity, melting temperature, electrical resistivity, and band gap, BN appears to be the material of choice for many emerging applications, including deep UV (DUV) optoelectronics. hBN has been well known both as an excellent electrical insulator and thermal conductor. The ability to synthesis wafer-scale semiconducting hBN epitaxial layers with high crystalline quality and electrical conductivity control is highly desirable for the fundamental understanding and the exploration of emerging applications of this interesting material. Here, we report on the successful synthesize of large area hBN epitaxial films (up to 2-inch in diameter) by metal organic chemical vapor deposition. P-type conductivity control was attained by in-situ Mg doping. Basic structural, optical and transport properties of undoped and Mg doped hBN epilayers will be presented. A remarkable observation is that the band edge emission intensity is about 500 times stronger than the dominant band-edge emission of a high quality AlN epilayer. Furthermore, compared to Mg doped wurtzite AlN, dramatic reductions in Mg acceptor energy level and p-type resistivity (by about 6-7 orders of magnitude) have been realized in hBN epilayers. The ability of conductivity control and wafer-scale production of hBN opens up tremendous opportunities for emerging applications, ranging from revolutionizing p-layer approach in III-nitride deep ultraviolet optoelectronics to graphene electronics and photonics.

8268-99, Session 22

Tuning of internal gain, dark current and cutoff wavelength of UV photodetectors using quasi-alloy of BGaN-GaN and BGaN-AlN superlattices

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Recently, solar-blind ultraviolet photodetectors (PD) fabricated from wide band gap semiconductors, such as III-N and MgZnO alloys, have been attracting more and more attention due to their huge potential for applications in missile plume early warning, flame/engine control, air/water purification, etc. Some of these PDs exhibit an apparent external quantum efficiency exceeding 100%, indicating large internal gain.

Schottky and MSM PDs are not expected to exhibit gain. Several physical mechanisms were proposed to explain such gain, which is mainly attributed to the existence of trapping states at the active layer-metal interface, due to threading dislocations, and having acceptor-like nature, which can trap photogenerated holes, thus reducing the Schottky barrier height (SBH) and producing a “secondary” photocurrent. It has been shown that, higher are the dark current and the SBH decrease, higher is the internal gain. Nevertheless, a high dark current is generally a drawback for PDs.

In this paper, we aim to develop large internal gain MSM PD with reduced dark current based on quasi-alloy of BGaN/GaN superlattice. We show that, the dark current can be lowered with keeping high DC internal gain (up to 105 for optical power in the nW range) and low time response (few tens of ns) in AC regime and large optical power (W range). Moreover, thank to the boron incorporation, the UV cutoff wavelength can be also tuned.

8268-100, Session 22

The electrical properties of transparent conducting- and semiconducting oxides

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The oxides SnO2 and In2O3 are widely used as transparent conducting oxide (TCO) contact in optoelectronics devices and as chemical (gas) sensors --- based on high doping (e.g. In1.8Sn0.2O3=ITO) and poly-crystalline films. Both these applications require only a low material quality compared to semiconductor standards. When synthesized to a high material quality and purity these oxides can become transparent semiconductors in their own right. Not only can such In2O3 and SnO2 be used in high-performance transparent electronics but it also allows us to study their intrinsic physics and to improve the traditional applications.

Plasma assisted molecular beam epitaxy was used to growth sytematically-doped and undoped, continuous, high quality SnO2 and In2O3 films whose transport characteristics were investigated. Typical for these oxides is the unintentional n-type conductivity, difficulty to achieve p-type conductivity, and the presence of a surface electron accumulation layer.

Structural investigations and high electron mobilities at low uid donor concentrations suggest a high material quality. The uid donors were found not to be hydrogen in SnO2 and likely oxygen vacancies (or metal interstitials) in In2O3. A surface electron accumulation layer and its depletion by an oxygen plasma was demonstrated for SnO2 and In2O3. Despite optimistic theoretical predictions, In- or Ga doping did not lead to p-type SnO2. Sb in SnO2 acts as a well behaved donor with 100% doping efficiency up to at least 3e20cm^-3. Sn-doping of In2O3 allowed to increase the electron concentration even up to the low 1e21cm^-3, typical for ITO.

8268-101, Session 22

Nanophotonics devices based on magnetic materials

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Magneto-optics and nanophotonics offer promising developments for applications in various technological sectors like data manipulation and storage, bio-imaging or optical sensors. Towards such purposes it is advantageous to combine ultrafast magnetism performed with ultrashort laser pulses together with nanophotonics performed on various magnetic materials. Firstly, we will give examples of magneto-optical patterning which can be used for switching or for realizing diffractive magneto-optics. For example, individual ferromagnetic CoPt3 dots can be manipulated at the femtosecond time scale using confocal magneto-optical Kerr microscopy. Alternatively one can pattern such dots and control their size and shape. Patterning magnetic arrays on ferromagnetic metals with light pulses is also potentially very attractive for diffractive structures. Secondly, we will describe several situations showing the great advantages of performing coherent magneto-optics. In particular, transparent magnetic materials like Garnets are well adapted for making self diffractive magneto-optical devices. Finally we will describe some of the important physical mechanisms underlying the control of these magneto-optical nanodevices with femtosecond laser pulses.

8268-102, Session 22

Practical rules for spin-orbit engineering of [110]-oriented III-V heterostructures

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Transport phenomena in solid state physics have to be mastered for efficient engineering of electronic and photonic devices. A robust theory for the probability current in solids has been formulated since a long time; However the study of spin-related phenomena, especially in the field of spintronics, devoted to semiconductors, revealed that a novel formulation of probability and spin current is mandatory when Spin-Orbit Interaction (SOI) is involved. [1,2]

Here, we present a systematic construction of the probability current operator, based on momentum power series expansion of the Hamiltonian. We prove that this procedure is valid not only when the Rashba [3] term is included beside the kinetic term, but also when the D'yakonov-Perel [4] (DP) contribution is taken into account.

We apply this formalism to the interface of an heterostructure, consisting of a free electron-like material and a barrier material with SOI. We show that the BenDaniel and Duke approach,5 that relies on the continuity of the envelope function and the continuity of the velocity of the particle at the interface, can still be applied only when first order (Rashba) term and second order (kinetic) term are involved in the effective Hamiltonian. When a third order (DP) term is introduced it is necessary to find out new boundary conditions to solve the Schrödinger equation associated to the effective Hamiltonian. The key point is to ensure the continuity of the probability current, but in this case the envelope function can no longer be continuous, in line with the ideas of Harrison.[6]

We illustrate these results in the model case of the GaAs [110]-oriented barrier, a direction where the spin-splitting of the real conduction band is maximum.[7]

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8268-103, Session 23

HgCdTe photon trapping detectors for mid-wavelength infrared (MWIR) high operating temperature (HOT) focal plane arrays

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Raytheon Vision Systems (RVS) is developing HgCdTe 3D photon trapping or photonic crystal resonance structures for high operating temperature (HOT) broadband mid-wavelength (MWIR) infrared detection in the 0.5-5µm spectral range. The concept of using photonic crystals is relatively well understood and has been demonstrated for applications like VCSELs, which have a very similar device structure to a photovoltaic detector1; Krishna et al.2 have showed application of photonic crystals to infrared detectors. This paper will describe ongoing work at RVS related to realizing high performance, elevated operating temperature MWIR focal plane arrays (FPAs) with an approach that utilizes Molecular Beam Epitaxy (MBE) on Silicon growth of p-on-n HgCdTe detector designs, and deep dry-etching to form a photonic crystal that substantially reduces active detector and junction volume, and associated dark current, while also maintaining high quantum efficiency (QE).

In this paper results for the following will be reported: photonic crystal detector design, process improvements that enable photonic crystal detector and FPA fabrication, and both detector and 512 x 512 FPA results at elevated operating temperatures (200 K) that employ these novel detector design and process improvements. Figure 1 shows example photonic crystal detector simulations using Synopsys TCAD SDevice software upgraded with an EMW package that enables fully functional finite-difference-time-domain (FDTD) electromagnetic FEM simulation. Figure 2 shows dark current as a function of temperature for 30 µm unit-cell detectors with varying absorber volume, which compares a regular detector design with two photonic crystal detector designs. The feature of the photonic crystal designs is that dark current can be significantly reduced due to a reduction in detector absorber volume but without the loss of detector quantum efficiency (QE).

8268-104, Session 23

Theoretical and experimental investigation of MWIR HgCdTe nBn detectors

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Infrared detector technology continues to rely heavily on high-performance HgCdTe p-n photodiodes for applications spanning the short to long wavelength infrared (SWIR-LWIR) spectral ranges. However, thermal generation and processing technicalities put some limitations on the usage of this technology at elevated temperatures and low photon background fluxes. To address these challenges, two alternative HgCdTe detector structures are proposed in this work: 1) a unipolar HgCdTe implementation of the nBn structure and 2) a novel Auger-suppressed unipolar hybrid nBn-n HgCdTe structure. Both structures rely on bandgap engineered barrier layers to suppress SRH and Auger processes that contribute to the dark current density and performance limitations. The unipolar devices provide the additional benefit of a simplified fabrication process, where p-type doping requirements are eliminated. Numerical physics-based device simulations utilizing established HgCdTe material parameters and incorporating tunneling contributions and generation-recombination mechanisms are used to study the performance characteristics of both devices. Near equivalent performance characteristics of nBn devices to those achieved by ideal pn heterojunction devices are predicted. Alternatively, the nBn-n device is expected to exhibit both SRH and Auger suppression due to the nature of the structure, thus, achieving a lower dark current density than that observed in current detector technology for the same temperatures. We report on the fabrication and device characterization of the HgCdTe nBn and nBn-n structures grown by molecular beam epitaxy and present current-voltage and spectral response measurements that demonstrate unipolar behavior and Auger suppression in these structures. This demonstration has significant implications for high temperature detector operation regarding reduction in power and cooling requirements without sacrificing device performance and for the manufacturability of the technology.

8268-105, Session 23

Wide-area SWIR arrays and active illuminators

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Invited Paper.

This paper will review recent progress on large wide-area Shortwave Infrared (SWIR) arrays for imaging sensor applications. Several detector configurations (for example PIN, APD, SLS) and material systems (for example InGaAs, HgCdTe) will be described, including the latest performance data affecting noise, sensitivity, efficiency and spectral response. Advantages and disadvantages of each approach will be discussed from a performance and fabrication perspective. Progress on matching high power SWIR laser illuminators will be reviewed as well, describing the variety of laser configurations under evaluation (for example Vertical Cavity Surface Emitting Lasers (VCSELs) and Edge Emitting Lasers (EELs)) and material systems being pursued (for example GaAs and InP based). Data regarding SWIR sensor performance with and without illumination will be discussed, as it applies to defense and commercial sensor applications. Optimum illumination requirements for best sensor system performance will be described.

8268-106, Session 23

Colloidal quantum dots for mid-infrared detection

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Infrared imaging could benefit from reduced cost and higher operating temperatures. One possible novel direction is thin films of colloidal quantum dots. These provide high packing density, ease of processing, and a simple tuning of the infrared absorption edge. We show that HgTe colloidal dots provide absorption and luminescence tunable across the mid-IR by adjusting the growth conditions and final particle sizes. Films made by drop-casting the colloidal solutions on patterned electrodes substrates show detectivity past 5 µm. We report on the present development and expected potential of this material for infrared detection.

8268-107, Session 24

Structural properties of InAs/InAs1-xSbx type-II superlattices

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Type-II superlattices (SLs) containing III-Sb alloys are becoming recognized as possible alternatives to the HgCdTe material systems for infrared (IR) detectors, and have recently achieved significant success for improved device performance [1]. InAs/ InAs1-xSbx SLs grown on GaSb substrate have been proposed for potential long-wavelength IR applications, where the absence of Ga in the InAs/ InAs1-xSbx SLs may result in longer carrier lifetimes [2]. This paper will describe the structural properties of InAs/InAs1-xSbx SLs with random and modulated InAs1-xSbx alloys grown both by molecular beam epitaxy and metalorganic chemical vapor deposition. The average Sb compositions of the modulated InAs1-xSbx alloys were determined by comparison of simulations with the (004) high resolution XRD measurements. The most intense SL peaks no longer corresponded to the zero-order peak because of the large SL periods, and XRD studies of thick individual InAs1-xSbx and InAs layers showed envelope modulation of the SL peaks on either side of the substrate peak, causing some satellite peaks to be more intense than the zero-order SL peak. From the substrate - zero-order SL peak separation, the average SL strain in the growth direction could be determined. Cross-sectional electron micrographs were used to reveal the entire structure including the GaSb substrate and buffer layer, the SL periods, and the GaSb cap layer. Growth defects were sometimes visible, some starting at the substrate/buffer interface, some starting in the middle of the buffer layer, and some located just within the SL. Higher magnification images of the SL revealed sharp interfaces between the InAs1-xSbx and InAs layers.

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8268-108, Session 24

Quantitative strain analysis of interfaces in InAs/GaSb superlattices by aberration-corrected HAADF-STEM

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Superlattices based on the InAs-GaSb system exhibit interesting optoelectronic properties due to their type II band alignment, wherein the conduction band minimum of InAs is below the valence band maximum of GaS by about 150 meV. However, many studies show that interfaces have significant effects on properties, due to interfacial strain arising from the switching of atomic species in both cation (Ga/In) and anion (Sb/Ga) sublattices across each interface. In this work we apply aberration-corrected transmission electron microscopy, in combination with quantitative image processing techniques for strain analysis, to examine the effects of interface composition control on the strain distribution across interfaces in InAs/GaSb superlattices grown on (100)-GaSb substrates. The structures investigated consisted of superlattices grown with no interface control, and those in which each interface was tailored to be “InSb-like,” with controlled depositions of InSb, ranging from.01 nm - 0.35 nm. The results from samples grown with no interface control revealed that the grading in the interfacial strain profiles was significant, extending about 3-4 monolayers between each layer. Furthermore, the GaSb-on-InAs interface was found to be GaAs-like, exhibiting a tensile strain of about 1.5%, whereas the InAs-on-GaSb was slightly InSb-like, with a compressive strain of about 0.1%. On the other hand, the samples grown with interface control showed distinct differences, with significant reduction in the GaAs-like nature of the GaSb-on-InAs interface, and improved abruptness in the interfacial strain profile. Finally, a comparison of the present approach to other methods used for examining interfaces in this system is also presented.

8268-109, Session 24

MOVPE grown InGaAs/GaAsSb type II quantum well photodiode for SWIR focal plane array

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Low cost, low dark current photodiodes (PDs) in the short wavelength infrared (SWIR) region up to 2.5μm are expected for many applications such as environmental gas detection and bio-diagnostics. HgCdTe (MCT) is predominantly used for infrared imaging applications. However, MCT is expensive and its application has been restricted mainly military and scientific use. Recently, InGaAs/GaAsSb type II quantum well structures are considered as an attractive material system for realizing low dark current PDs owing to lattice-matching to InP substrate. In this report, we describe successful operation of pin-PDs with InGaAs/GaAsSb quantum wells grown by metal-organic vapor phase epitaxy (MOVPE). MOVPE method is well-known to have good uniformity which leads to mass-production of focal plane array.

Planer type pin-PDs with InGaAs/GaAsSb quantum well absorption layer were successfully fabricated for the first time. The p-n junction was formed in the absorption layer by the selective diffusion of zinc. InGaAs layer which was adopted as a layer for adjusting concentration distribution of zinc were grown on quantum wells. Electrical and optical characteristics of PDs such as well number dependence and temperature dependence of dark current and responsivity, were investigated. Dark current of 1.3mA/cm2 at room temperature, which showed good uniformity, and responsivity of 0.8A/W in SWIR region were obtained. The clear image was taken with 320x256 focal plane array at the temperature of 208 K. This result means that planer photodiode using MOVPE grown InGaAs/GaAsSb type II quantum wells is a promising candidate for consumer applications.

8268-110, Session 24

Comparison of the electro-optical performances of symmetrical and asymmetrical MWIR InAs/GaSb superlattice pin photodiodes

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InAs/GaSb superlattice (SL) detectors are a promising technology for high performance infrared (IR) imaging system in the MWIR (3-5μm), as well as in the LWIR (8-12μm) and VLWIR (> 12μm) domains. An alternative period design, named “asymmetrical” since it is based on a different number of monolayers for InAs and GaSb, has been recently proposed to both reduce the dark current and increase the quantum efficiency of MWIR InAs/GaSb superlattice pin photodiodes.

In this paper, we report the full electrooptical characterization of two samples, realized by molecular Beam Epitaxy on p-type GaSb substrate. The first sample is based on a standard, symmetric, 8 InAs monolayers (MLs) / 8 GaSb MLs SL period. The second one uses the alternative, asymmetric design with a 7.5 InAs MLs / 3.5 GaSb MLs SL period. We present dark current, noise under dark conditions, spectral response and quantum efficiency measurements. The comparison of the electro-optical performances of the two samples confirms the predominance of the asymmetrical design.

8268-111, Session 24

Progress in the development of interband cascade infrared photodetectors

R. Q. Yang, The Univ. of Oklahoma (United States)

Progress in the Development of Interband Cascade Infrared Photodetectors (Invited)

Interband cascade (IC) infrared (IR) photodetectors (ICIPs) are a new type of infrared detectors based on quantum-engineered InAs/GaSb/AlSb heterostructures. They combine the features of conventional interband photodiodes with the discrete architecture of quantum-well IR photodetectors. The operation of ICIPs takes advantage of fast intersubband relaxation and interband tunneling for carrier transport, and relatively slow interband transitions for photon generation. As such, ICIPs are sensitive to normal incidence IR radiation and can be optimized for specific application requirements, such as faster response, higher temperature operation or lower noise. Advanced type-II superlattice (SL) detector structures such as unipolar barriers and double-heterostructure are inherent in ICIPs. Our effort has led to the demonstration of ICIPs with low noise and photovoltaic operation in the mid-IR wavelength region. For example, the Johnson-limited detectivity (D*) exceeds 10^13, 10^11, 10^9 Jones at 80, 160, 300K, respectively. We will discuss unique features of ICIPs and report our progress in the development of ICIPs.

8268-112, Session 24

Reduction of noise in very long wave infrared quantum cascade detectors

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In recent years, Quantum Cascade Detectors (QCDs) have been designed as a photovoltaic detector for the Long and Very Long Wave Infrared range (8 to 20 microns). Such devices present no dark current, allowing for longer integration times and higher operating temperatures than the photoconductive Quantum Well Intersubband Photodetectors (QWIPs).

The basic structure of QCDs relies on quantum well engineering with an active doped well where the photon absorption occurs and several wells extracting photoelectrons to the next period. Thus electrons only flow through a cascade of confined quantum levels. This two-dimensional nature of transport allows for a complete theoretical model of transport without any externally adjustable parameter. This feature is to our knowledge unique in detectors physics.

Since the performances of photodetectors are ruled by the signal-to-noise ratio, a precise understanding of the physics of noise in QCDs is needed in order to accurately compare them with QWIPs. In this work, electronic noise in QCDs is investigated for detectors operating at 8 microns and 15 microns. We will explore two different theoretical approaches to model the noise and compare them to experimental measurements. The first approach is based on the Nyquist theorem that identifies interlevel transitions as vacuum diodes and gives a simple and insightful vision of noise in quantum structures. The second one is based on master equation model of transport. It is both a more complex and rigorous model, and sheds a different light on the phenomenon. These two approaches are complementary and grant crucial milestones towards full predictability in quantum design, hence greatly improve QCD structures and performances.

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Part of Proceedings of SPIE Vol. 8269 Photonic and Phononic Properties of Engineered Nanostructures II

8269-01, Session 1

Photonic crystal light trapping for solar energy harvesting

S. John, Univ. of Toronto (Canada)

No abstract available

8269-02, Session 1

Passive and active nanophotonics

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

No abstract available

8269-03, Session 1

Molding light propagation with phase discontinuities

Z. Gaburro, Harvard Univ. (United States) and Univ. degli Studi di Trento (Italy); N. Yu, P. Genevet, M. Kats, F. Aieta, J. Tetienne, F. Capasso, Harvard Univ. (United States)

Conventional optical components rely on gradual phase shifts accumulated during light propagation to shape optical wavefronts. New degrees of freedom in optical design are attained by introducing in the optical path abrupt phase changes over the scale of the wavelength. A two-dimensional array of optical resonators, with spatially varying phase response and sub-wavelength size and separation, can imprint an arbitrary distribution of such phase discontinuities on the propagating wavefront.

For maximal flexibility, resonators with multiple resonances are required. As an example, we propose here V-shaped optical antennas, whose scattering properties can be finely controlled by adjusting the antennas' size and the orientation. We arrange such individually designed antennas in arrays, thus obtaining thin plasmonic interfaces with a phase response that is arbitrarily designed on a point-by-point fashion.

We experimentally report flat interfaces exhibiting phase discontinuities with constant gradients. These interfaces scatter plane waves into plane waves. However, the reflection and refraction obey generalized Snell's laws. In particular, we show cross-polarized anomalously reflected and refracted beams, which exhibit negative refraction and reflection over certain ranges of the angle of incidence, as well as modified critical angles for reflection and critical angles for reflection.

Phase discontinuities enable wavefront engineering with unprecedented flexibility, which is promising for a wide variety of small-footprint planar optical components.

8269-04, Session 1

Applications of the circuit model for plasmonics

E. Yablonovitch, Univ. of California, Berkeley (United States)

No abstract available

8269-05, Session 2

Design and fabrication of HC-PCF for high-power fast laser beam transportation

Y. Wang, M. Alharbi, C. Fourcade-Dutin, T. D. Bradley, F. Benabid, Univ. of Bath (United Kingdom) and Xlim Research institute, CNRS, Univ. of Limoges (France); X. Peng, M. M. Mielke, T. J. Booth, Raydiance, Inc. (United States)

No abstract available

8269-06, Session 2

Design of silica fibers for supercontinuum generation

S. Carneiro, M. M. V. Facão, S. C. Latas, M. F. S. Ferreira, Univ. de Aveiro (Portugal)

Increasing the refractive index difference between the core and cladding materials of an optical fiber has two important effects regarding its nonlinear behaviour. First, it increases the nonlinear parameter of the fiber, since the mode effective area is reduced, as a result of the decreased core size necessary to maintain single-mode operation. Secondly, it modifies the fiber dispersion curve, due to the increased importance of the waveguide dispersion contribution. In such circumstances, the waveguide dispersion can be strong enough to overcome the normal material dispersion and to enable the zero dispersion wavelength to be positioned in the spectral band of 700-1100nm corresponding to the most commonly used short pulse pump sources.

The only way to achieve very high values of index contrast using silica fibers as a basic material is by incorporating air as one component of the fiber cladding. This can be done using a silica tapered fiber, or through the use of various designs of microstructured fiber.

In this paper we look for an optimum design of silica fibers for supercontinuum generation. To achive this goal, we perform an accurate numerical modelling of both tapered and microstructured fibers using a finite element (FE) numerical approach. The dependence of the dispersion parameters on wavelength are calculated by solving the eigenvalue equation for fiber modes and using Sellmeier equation.

Our results show that, when a tapered fiber has a diameter below a certain value, a considerable fraction of the power propagates in the surrounding medium. The electric field at the surface of the fiber shows a maximum for a fiber diameter about 0.7 , below which it sharply decreases. The zero dispersion wavelength (ZDW) can be shifted to the visible range and, in some cases, two ZDWs can be observed, defining a wavelength window with anomalous GVD. The GVD values are quite large in the anomalous dispersion regime, ranging in the order of 200 ps/km/nm; meanwhile, the first zero dispersion points do not exceed a wavelength of 800 nm for a fiber diameter below 3 microns. However, the first zero dispersion point appears around 1 micron and quite small values of the GVD (<40 ps/km/nm) are observed if tapered fibers are immersed in some organic chemical liquids, like acetonitrile, pentane and hexane. This will be important to achieve supercontinuum generation in the infrared and to enlarge the corresponding spectral width.

We have investigated also the dependence of the GVD properties and the nonlinear parameter of a MF with perfect hexagonal symmetry on the air-hole diameter and the hole-to-hole spacing the air-hole diameter and the hole-to-hole spacing. By changing appropriately these parameters, it is possible to shift the zero dispersion wavelength to visible and near-infrared regions, as well as to achieve nearly zero dispersion-flattened behaviour. The design of endlessly single-mode fibers for supercontinuum generation is specially discussed.

8269-07, Session 2

Slow light loss due to roughness in photonic crystal waveguides: insights on loss reduction from an analytic theory

W. Song, R. A. Integlia, W. Jiang, Rutgers, The State Univ. of New Jersey (United States)

We analytically study the general characteristics of roughness-induced scattering loss in a photonic crystal waveguide (PCW). First, a new crosssectional eigenmode orthogonality relation is derived for a general one-dimensional (1D)-periodic system, which allows us to significantly simplify the coupled mode theory in the fixed eigenmode basis. Assisted by this eigenmode orthogonality, analytic loss formulas are obtained with reasonable assumptions despite the complexity of PCW mode fields. We introduce the radiation and backscattering loss factors α1 and α2 such that the loss coefficient α can be written as α =α1*ng+α2*(ng)^2 (ng is the group index). By finding analytic formulas for α1 and α2, we show that these two factors are generally on the same order, which indicates the backscattering loss usually dominates the radiation loss for ng >10. The interplay between certain mode-field characteristics, such as the spatial phase, and structure roughness is found crucial in the loss-generation process. The loss contribution from each row of holes is analyzed. The backscattering loss is primarily contributed by the first row whereas the radiation loss is contributed by both the first and second rows substantially. The theoretical loss results agree well with experiments. The insights gained from this study shows that loss reduction may be achieved by fine tuning the interplay between the spatial phase of the PCW mode and roughness-correlation or modifying the mode polarization characteristics. The cross-sectional eigenmode orthogonality may be applicable to other 1D-periodic systems such as electrons in a polymer chain or a nanowire.

8269-08, Session 2

Broadband optical resonator based on coupled positive and negative-index waveguides

M. Bethune-Waddell, K. J. Chau, The Univ. of British Columbia (Canada)

An optical resonator is a device, typically of dimensions greater than the wavelength, which stores electromagnetic energy by circulating light within a closed path. Energy storage occurs at resonance frequencies where the closed path length of the resonator is equal to an integer multiple of the wavelength of light inside the resonator. When this resonance condition is fulfilled, light circulating in the resonator interferes constructively to form stationary standing wave patterns. Optical resonators are typically constrained to operate over narrow frequency ranges. Frequency-dependent variations in the wavelength of light inside the resonator mean that the resonance condition can only be satisfied at discrete resonance frequencies. Here, we investigate a new type of optical resonator constructed from coupled planar waveguides of two types: one sustaining a positive-index mode having normal dispersion and the other sustaining a negative-index mode having anomalous dispersion. We tailor the geometry of the waveguides so that the modes in the two waveguides possess dispersions of opposing and commensurate slope. When the waveguides are joined into a closed path, a unique resonator is formed where frequency-dependent wavelength increases in one waveguide component of the resonator are compensated by wavelength decreases in the other component. Using the FDFD technique to solve Maxwell's Equations, we show that the resonator sustains a large number of resonances, each satisfying the same resonance condition, when it is illuminated with normally incident light in the visible free-space wavelength range from 350nm to 500nm.

8269-09, Session 3

First steps towards nanophotonic particle accelerators on a chip

I. Staude, Karlsruher Institut für Technologie (Germany); C. McGuinness, SLAC National Accelerator Lab. (United States); A. M. Frölich, Karlsruher Institut für Technologie (Germany); R. L. Byer, Stanford Univ. (United States); E. R. Colby, SLAC National Accelerator Lab. (United States); M. Wegener, Karlsruher Institut für Technologie (Germany)

No abstract available

8269-10, Session 3

Electro-optic lithium niobate photonic crystal nanowire: towards a new generation of lithium niobate integrated optics devices

M. Bernal Artajona, H. Lu, B. Sadani, F. I. Baida, Univ. de Franche-Comté (France)

The optics community has been using lithium niobate (LN)for applications like integrated and nonlinear optics due to its manifold properties like ferroelectricity, piezoelectricity, electrooptics, acoustooptics, nonlinearity etc. Going towards lithium niobate components with small footprints present an enormous interest since all its intrinsic physical properties can be potentially enhanced by the design of suitable geometries based on slow-light propagation. Only recently it has been demonstrated theoretically as well as experimentally that photonic crystal devices realized on LN show numerous interesting effects. However, etching or structuring this material is far from trivial because of the material's high chemical stability.

In this work we will present electro-optically tunable photonic crystal filters fabricated on thin membranes of lithium niobate. Several different configurations such as 200 nm height, 2 microns width ridge waveguides or free standing lithium nibate layers of lithium niobate have been fabricated as the support platform of the photonic crystal devices. We will show that these novel configurations greatly improve the optical performances of the LN nanodevices. Theoretical and experimental results will be presented.

8269-11, Session 3

Nanopatterned metallo-dielectric photonic crystal to enhance nonlinear conversion: theory and experiment

E. Barakat, M. Bernal, R. Salut, F. I. Baida, Univ. de Franche-Comté (France)

Enhanced Second Harmonic Generation was theoretically predicted from a nanopatterned non linear material (LiNbO3) located inside the subwavelength cavities of a metallic Annular Aperture Arrays(AAA). The signal strength is compared to that from a bulk LN. Such a crystal has 2D periodic large second-order susceptibility chi(2). We found an optimal structure design thanks to the relations that link the aperture radii and the metal thickness to the operating point namely the wavelength of the fundamental and SHG signals. Because the patterned LiNbO3 thickness is much shorter than the wavelengths (both fundamental and SH) involved and much shorter than the coherence length, no phase matching is required. A slow light phenomenon, which occurs at the cut-off frequency of the TE11 guided mode through the annular cavities, is at the origin of the SHG signal enhancement. Theoretical results using a homemade NL-FDTD code shows that the conversion of 1550 nm excitation light into 775 nm emission is theoretically enhanced by a factor of 27 with respect to a bulk LiNbO3. The field distribution at the pump and the SH wavelength shows that light is confined inside the cavities and thus it confirms the non-linear enhancement. The benefit of the AAA is demonstrated through a comparison with cylindrical aperture arrays. By referring to the non-linear tensor we choose an X-cut wafer to benefit from the greater non-linear coefficient d33. We used e-beam, ICP-RIE and CMP technologies for the fabrication. Experiments are in progress in order to verify our theoretical results.

8269-12, Session 3

Broadband perfect light absorber using a multiplexed metal-dielectric structure

J. Hendrickson, Air Force Research Lab. (United States); J. Guo, B. Zhang, The Univ. of Alabama in Huntsville (United States); W. Buchwald, R. Soref, Air Force Research Lab. (United States)

Subwavelength structured metal films on dielectric-metal substrates can function as perfect light absorbers at their resonance frequencies. At the resonance frequency, the effective surface impedance of the structured metamaterial matches the impedance of the air, therefore no energy is reflected and all energy is absorbed in the metamaterial. Perfect light absorption usually occurs within a very narrow frequency range. Here we propose and demonstrate a multiplexed metal-dielectric-metal structure metamaterial that gives a significantly broadened near perfect light absorption in the mid-wave infrared range.

8269-13, Session 4

Control of the Purcell effect of quantum dots embedded in photonic crystal nanocavity by manipulating Q-factor

T. Nakamura, T. Asano, K. Kojima, T. Kojima, S. Noda, Kyoto Univ. (Japan)

Cavity quantum electrodynamics (cavity-QED) based on combined systems of semiconductor quantum dots (QDs) and nanocavities are appealing candidates for novel quantum devices. So far, cavity-QED effects in such systems have been mainly studied by observing the transition between non-resonant and resonant conditions via control of the detuning. In this work, we investigate cavity-QED effects by tuning the Q-factor of the nanocavity. This alternate approach is important from the viewpoint of fundamental physics and device applications. We utilized a structure consisting of a point-defect nanocavity and a line-defect waveguide on a GaAs-based 2D photonic crystal slab with embedded InAs QDs, where one side of the waveguide is terminated by a high reflector. A standing wave mode formed between the nanocavity and the reflector superimposes with the nanocavity mode to perturb the Q-factor and the resonant frequency. By independently changing the waveguide propagation constant and the bare nanocavity resonant frequency by using uniform nitrogen adsorption followed by laser-induced, local nitrogen desorption, we can control the Q-factor of the perturbed nanocavity mode while preserving the detuning constant. For example, we observed that the luminescence intensity from a weakly-coupled on-resonant nanocavity-QD system at 4 K increased by a factor of 3.3 by increasing the Q-factor from 4000 to 8000. Numerical simulations determined the modulation of the Purcell enhancement to be ~ 2.0. We believe this approach is important to the development of novel quantum devices such as on-demand single photon sources and photonic quantum memories.

8269-14, Session 4

One-dimensional linear chain photonic crystal laser

S. Kim, S. Ahn, H. Jeon, Seoul National Univ. (Korea, Republic of)

Photonic crystal (PC) lasers, which have a high potential for compact light sources in high-density photonic integrated circuits, have been developed in various device formats, such as single-defect lasers, coupled-cavity lasers, and band-edge lasers. The majority of the PC lasers developed so far employ a two-dimensional (2D) PC slab, in which the in-plane confinement is achieved by PC effects while the conventional index guiding provides the light confinement in the vertical direction. In recent years, however, one-dimensional (1D) PC structures have drawn much attention due to structural simplicity and smaller size compared with their higher dimensional counterparts. In this study, we have investigated a new 1D PC laser structure. The laser structure is basically a linear chain of submicron-sized platelets composed of multiple-quantum-wells (MQWs). Unlike the 2D counterparts, the 1D PC structure provides optical feedback only along the chain axis. To realize the PC laser, an InGaAs etch-stop layer and an InAsP/InP MQW layer were grown sequentially on InP wafer by molecular beam epitaxy. The wafer was then bonded onto a fused silica substrate, with the MQW side facing down against the fused silica substrate. The InP substrate and also the InGaAs etch-stop layer were selectively removed by wet-etching. The 1D PC laser structure was then generated using electron-beam lithography and reactive-ion etching. When pumped optically, the PC laser structure lased at ~1580 nm, with threshold pump power density of about 285 W/cm2. Despite the simplicity, the overall laser performance was comparable (if not better) to the 2D PC lasers reported in the literature.

8269-15, Session 4

Anderson localized modes in random photonic crystal lasers with two-dimensional glassy perturbation

S. Takeda, Keio Univ. (Japan); R. Peretti, P. Viktorovitch, Ecole Centrale de Lyon (France); M. Obara, Keio Univ. (Japan)

The theory of Anderson localization (AL) predicts that all sorts of waves can be localized in random media. Owing to its high Q-factor and small modal volume, AL modes are applicable to new types of optical micro-cavity, capable of opening up a new field of cavity quantum electrodynamics. Despite the strong potential, AL requires a large scattering cross-section combined with minimal absorption loss, hence is difficult to be attained in fully random configurations. It was then predicted that AL is more attainable in a randomized photonic crystal with a wide photonic band gap, where Bloch waves are scattered and become localized. This concept, random photonic crystal, has been studied mainly by perturbing positions or diameters of the air-holes aligned in a photonic crystal. However, the efficient AL formation is hindered by the collapse of the photonic band gap under strong structural perturbations. For the sake of perturbing the crystal structure with keeping its band gap, a new strategy to create a randomized structure is required.

In this paper, we establish a new method to create a random photonic crystal. Based on InP substrate with air holes aligned in a triangular lattice, we displace the holes with keeping their positions correlated each other. The created structure exhibits optically “glassy” refractive index profile, where the periodicity is locally conserved but globally disordered. We characterize the lasing properties of the random photonic crystals by use of FDTD (Finite-Difference Time-Domain) method. Furthermore, the sample will be fabricated and its lasing characteristics are demonstrated.

8269-98, Session 4

fJ/bit integrated nanophotonics toward dense photonic network on chip

M. Notomi, NTT Basic Research Labs. (Japan)

No abstract available

8269-16, Session 5

Recent progresses in optical metamaterials

X. Zhang, Univ. of California, Berkeley (United States)

No abstract available

8269-17, Session 5

Enhanced nonlinear effects in metamaterials and plasmonic materials

A. Alu, The Univ. of Texas at Austin (United States)

No abstract available

8269-18, Session 5

Science meets magic: photonic metamaterials

E. Ozbay, Bilkent Univ. (Turkey)

No abstract available

8269-19, Session 6

Controlling flow of photons with extreme metamaterials

N. Engheta, Univ. of Pennsylvania (United States)

In this talk, I will give an overview of some of our most recent results in my group on exploiting the concept of nonreciprocal metamaterials to control and tame flow of photons. We will discuss the notion of one-way waveguide and one-way terminals, such as one-way cavity and one-way radiators, and how the nonreciprocity plays an important role in such metamaterials. Potential applications of such one-way structures in optical isolation will also be discussed. I will also give a quick overview of our work on non-Foster particle as inclusions for non-Foster metamaterials. Time permitting, I will also discuss the graphene sheets as the one-atom-thick paradigm for controlling the flow of highly-confined surface Plasmon polariton in a predetermined manner, leading to the possibility of several novel optical devices in mid infrared wavelengths. We will present physical insights into our findings, and forecast future directions in these areas.

8269-20, Session 6

Flexible and stretchable plasmonics and metamaterials

H. Altug, Boston Univ. (United States)

No abstract available

8269-21, Session 6

Invisibility cloaking for the light phase at visible frequencies

T. Ergin, J. Fischer, M. Wegener, Karlsruher Institut für Technologie (Germany)

Transformation optics established a new perspective on the relation of the geometry of space-time and the propagation of light. A demanding benchmark example of this field is an invisibility cloak. Recent experiments at optical frequencies have demonstrated cloaking for the light amplitude using the “carpet cloak”, where a bump in a metallic carpet is rendered invisible by adding a nanostructured metamaterial on top. Yet, an object to be made invisible represents a perturbation of the light amplitude and phase. While the reconstruction of the light amplitude can be relatively simple, the reconstruction of the phase is a much more subtle undertaking and thus, a much more demanding test for the cloak’s capabilities. In this contribution, we demonstrate far-field cloaking for the light phase on the previously introduced three-dimensional carpet cloak at 700-nm wavelength and for arbitrary polarization of light. We obtain the phase information by imaging the cloak with an objective onto a camera and letting this image interfere with a known reference image in a Michelson-interferometer like setup. By translating the sample in one of the interferometer arms, a set of arm-length dependent interference images is recorded. The intensity of these interference images oscillates in a cosine-fashion, when a single pixel is considered. The light phase at every pixel can be extracted from this oscillation, yielding a complete phase image of the cloak. Numerical modeling of the cloak via ray-tracing is also presented.

8269-22, Session 6

Microscroll invisibility cloak

P. A. Munoz, Harvard Univ. (United States); R. Iutzi, Massachusetts Institute of Technology (United States); E. Mazur, Harvard Univ. (United States)

We present a design for a self-assembled cylindrical invisibility cloak, based on strained-induced rolling. Here, a 2D slab metamaterial is patterned by electron beam lithography on a compressively strained InGaAs thin film. The metamaterial is composed of an array of periodically spaced silver nanorods embedded in a polymer background. The anisotropic effective permittivity of the slab is defined by on the aspect ratio and pitch of the nanorods, and is modeled by Effective Medium Theory and the Finite Differnce Time Domain method (FDTD). The stained film is released from the substrate by wet etching, and the film strain relaxes, causing the combined metamaterial/thin-film to curl into a tight roll. The rolling radius is modeled by continuum strain theory and confirmed by experiment. Resulting microscroll has an anisotropic and radially-dependent effective permittivity, which is inherited from the original slab metamaterial. Depending on the nanorod spacing in the metamaterial layer, we can tune the radial dependence of the permittivity. This design can be used to realize a variety of transformation optical devices with cylindrical symmetry. In particular, we analyze the case of a TE cylindrical invisibility cloak with reduced parameters using FDTD.

8269-23, Session 6

Design of metamaterials with predetermined optical properties for broadband applications

K. Chen, A. V. Goncharenko, National Cheng Kung Univ. (Taiwan); V. U. Nazarov, Research Ctr. for Applied Sciences (Taiwan)

We show that combining dielectric and metallic materials it is possible to produce a composite metamaterial with a desired value of the permittivity εd or refractive index over a frequency band. The composite has the gradient of the local permittivity within the unit cell. Mathematically, for the case of the permittivity the problem reduces to minimizing a functional which is a norm of some

function on the [$\omega 1$, $\omega 2$] frequency band. The function depends on the effective permittivity and the metal phase distribution to be determined using a proper minimization procedure.

As conceptual examples, we consider the design of refractive-index-near-unity (RINU) and epsilon-near-zero (ENZ) metamaterials. While there is a lot of work on realization of the broadband RINU metamaterials (see, e.g., [1] and references therein), much less research has been done on the design of the broadband ENZ metamaterials (one exception is our previous work [2], where we have used another approach, which is, however, feasible for ENZ metamaterials only).

We provide a means to specify materials' architecture to obtain the predetermined optical properties. The range of applicability of our technique and its limitations are discussed. The results of semi-analytical calculations are validated by ab initio FDTD simulations.

8269-24, Session 7

Dynamic and aperiodic nanophotonic structures

S. Fan, Stanford Univ. (United States)

No abstract available

8269-25, Session 7

Photon localization in randomly mixed photonic crystals

J. Lee, Seoul National Univ. (Korea, Republic of); S. Kim, Tufts Univ. (United States); H. Jeon, Seoul National Univ. (Korea, Republic of)

We have investigated the localization of photons in mixed photonic crystals (PCs), which were patterned into a triangular-lattice structure on a wafer-bonded InAsP/InP quantum well slab. Four kinds of air-holes with different radii, which represent different photonic atoms, were randomly distributed to form mixed PCs; the air-hole radius was varied within the range of $\Delta r = 0.01a$ for a weakly disordered system and of 0.03a for a strongly disordered system. The air-hole radii in each mixed PC were chosen such that the overall air-hole filling factors remain the same as that of the reference PC composed of an identical air-hole size of $r = 0.25a$. In addition, the composition ratios for the four kinds of air-holes were kept the same to be 1/4. The mixed PCs were optically pumped to lase. The homogeneous reference PC exhibited two lasing peaks at the spectral positions of both edges of photonic band-gap (PBG), indicative of lasing in extended band-edge modes. The weakly disordered mixed PC also exhibited two lasing peaks at very similar spectral positions, which implies that the PBG and band-edges retain their properties in disordered systems as well. Laser spectra measured from some of the strongly disordered mixed PCs, on the other hand, showed an extra lasing peak inside the PBG. We attribute this to a localized photonic mode developed deep inside the PBG as a result of complex photon scatterings in the highly disordered PC. We performed finite-difference time-domain simulations on the mixed PCs, which suggest that this mode is clearly not a (spatially extended) band-edge mode but a localized one.

8269-26, Session 7

Fourier-Bessel expansions of localized light in disorder dielectric lattices

S. R. Newman, R. C. Gauthier, Carleton Univ. (Canada)

It has been shown that light localization can occur within disordered and random dielectric lattices. A translational symmetric optical lattice containing a lattice defect is not the sole scenario in which light localization takes place. The presence and nature of the localized light within disordered and random dielectric layouts is examined in the context of the rotational symmetry present within the localized light's field profile and the local dielectric. The level of rotational symmetry is determined through the use of Fourier-Bessel expansions where the radial and angular components are represented by linear combinations of exponential and Bessel basis functions respectively. The expansion origin is selected to coincide with the localized light's field center allowing the rotational symmetry of the local dielectric to be extracted. The Fourier-Bessel decomposition demonstrates a strong link between the rotational order, the order of the exponential expansion, of the localized state and the dielectric local to that state. This relationship is present in both translational symmetric photonic crystals containing lattice defects and quasi-periodic photonic crystals. The observed interaction of the order of the local dielectric and that of the mode is also seen in the localized states that are present within disordered optical structures, demonstrating the significance of rotational order in the manifestation of localized states.

8269-27, Session 7

Titanium dioxide square spiral photonic crystals: numerical analysis and experimental realization

J. D. Krabbe, V. A. Leontyev, M. T. Taschuk, Univ. of Alberta (Canada); A. Kovalenko, National Research Council Canada (Canada); M. Brett, Univ. of Alberta (Canada)

Titanium dioxide square spiral photonic crystals with a band gap in the visible spectrum have been analyzed with finite-difference time-domain (FDTD) and frequency-domain methods, and fabricated by the glancing angle deposition (GLAD) technique. The square spiral structure is a polygonal spiral formed of straight columns connecting adjacent nodes of a diamond lattice geometry.

Simulations have shown that the 3D band gap is strongly influenced by the column's cross-section in the substrate plane. In the model this cross-section has been approximated as elliptical, with one axis oriented parallel to the plane of the column tilt, and the other one perpendicular. With elliptical cross-sections a 3D band gap is easily obtained if the column cross-section in the plane of column tilt is at least twice as wide as perpendicular to it. The gap disappears as the cross-section becomes close to circular and further elongated normally to the column tilt plane.

Square spirals were fabricated using nanoimprint lithography to define an array of seeds on the substrate, followed by TiO2 deposition using the GLAD process. SEM analysis showed a column cross-section close to circular, thus both theoretical and measured reflectance spectra for the fabricated structure did not show the evidence of a full 3D band gap. Simulations predict that the inverse structure (square spiral air columns in a TiO2 matrix) can have a full 3D band gap with column cross-sections close to circular. Such a geometry should be achievable experimentally using templating process.

8269-28, Session 7

A parametric study of extraordinary transmission through metallic photonic crystals targeting infrared photodetectors

R. Soltanmoradi, Royal Institute of Technology (Sweden); Q. Wang, J. Y. Andersson, Acreo AB (Sweden); M. Qiu, Royal Institute of Technology (Sweden)

In order to improve the performance of optoelectronic components, such as photodetectors and emitters, one can integrate a metallic subwavelength photonic crystal (PhC) structure onto the devices to enhance the optical field using plasmonics. Light interaction with a subwavelength hole array created in a metal film excites a surface plasmon resonance (SPR) wave in the metal-dielectric interface and thus enhancing the light transmission at specified wavelengths.

In this work we focus on the design and fabrication of the metallic PhC structures targetting enhanced responsivity of quantum dot infrared photodetectors using an integration approach. To observe the different parameters affecting the transmission spectra of the PhC structure, subwavelength square array with various periodicities - 4um, 3.5um, 2.4um, 1.8um- and a range of area filling factors were fabricated on Au films with different thicknesses -50nm, 100nm, 200nm- on Si substrate. The transmission spectra of the samples were measured by Fourier transform infrared spectroscopy.

It is experimentally demonstrated that the SPR wavelength is independent of the filling factor but changes linearly with the periodicity of the hole array. Experimentally, we verify that there is an optimal filling factor to achieve the maximum transmission peak.

Our results confirm that while a thicker metal layer decreases the transmission; the deeper holes of thick layers make the SPR peak narrower, subsequently leading to higher wavelength selectivity and increased Q factor. An optimum thickness must be selected to satisfy the required selectivity and maximum amplitude transmission peak.

8269-29, Session 7

Photonic band gaps of increasingly isotropic crystals at low dielectric contrasts

M. Pollard, G. Parker, M. Charlton, Univ. of Southampton (United Kingdom)

Photonic band gaps (PBGs) are highly sensitive to lattice geometry and dielectric contrast. Here, we report theoretical and experimental confirmation of PBGs in photonic crystals (PhCs) with increasing levels of structural isotropy. These structures are: a standard 6-fold hexagonal lattice, a locally 12-fold Archimedean-like crystal, a true quasicrystal generated by non-random Stampfli inflation, and a novel biomimetic crystal based on Fibonacci phyllotaxis. Experimental transmission spectra were obtained at microwave frequencies using both high-index alumina (ε=9.61) and low-index PMMA (ε=2.6) rods. The results were compared to FDTD-calculated transmission spectra and PWE-calculated band diagrams. Wide and deep (>60dB) primary TM gaps present in all high-index samples are related to reciprocal lattice vectors with the strongest Fourier coefficients. Their mid-gap frequencies are largely independent of the lattice geometry for comparable fill factors, whereas the gap ratios shrink monotonically as structural isotropy increases. Conversely, the primary TM gaps (>30dB) in low-index samples become wider in more isotropic crystals. In particular, we note that higher isotropy leads to both a complete TM/TE gap in the Stampfli quasicrystal, and a greater than 23% TM gap in the biomimetic crystal. This represents, to date, the widest omnidirectional PBG reported for a dielectric contrast of 2.6:1, and highlights the importance of long-range interaction with the weaker Fourier components of isotropic crystals.

8269-30, Session 7

From electromagnetically induced transparency to superscattering with a single structure: a coupled-mode theory for doubly resonant objects

L. Verslegers, Z. Yu, Z. Ruan, P. B. Catrysse, S. Fan, Stanford Univ. (United States)

The concept of cross section is commonly used to describe how large an object appears to incident external radiation. The deviation of the electromagnetic cross-section with respect to the geometrical cross section is well documented for nano-scale objects. We study the electromagnetic cross-section of two nano-scale objects in close proximity to each other. It is known that when both objects support resonances in close proximity, this may lead to an optical analogue of electromagnetically induced transparency (EIT). On the other hand, one may also expect that there exists a case of superscattering. A formalism that elucidates the occurring of both cases has not been proposed before.

We find from simulations of a double slit, that one structure can exhibit both EIT and SS behavior, depending on the excitation. We develop a coupled-mode theory that identifies the relevant pathways for resonant transmission as well as how these interact and explains this behavior in terms of the orthogonality of the radiation patterns of the subradiant and superradiant eigenmodes. In particular, we demonstrate that the perfect EIT analogue shows up as an extreme case where the radiation patterns of the eigenmodes are identical. Transmission beyond the single channel limit, on the other hand, becomes more likely when the radiation patterns are less correlated and is guaranteed when the radiation patterns of the eigenmodes are orthogonal.

This theory provides insights in the general spectral behavior for metamaterials, as well as optical antennas and nanoparticles.

8269-31, Session 8

Homogenized dynamic constitutive relation for Bloch-wave propagation in periodic composites: structure and symmetries

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Following the birth of quantum mechanics in the early part of the 20th century, Nobel laureate Felix Bloch formulated the concept of electron bands in crystals, which provided a basis for the study of the optical, thermal, and magnetic properties of crystals. Another type of periodic system at the macro-scale emerged during the latter half of the 20th century, further igniting research in Bloch wave propagation. Independent to this research, Victor Veselago, in his seminal paper in 1968, theorized upon the physical implications of discovering electromagnetic materials with simultaneously negative electrical permittivity and magnetic permeability. Such materials, termed metamaterials, were experimentally realized in the last decade by the use of periodic composites.

Central to the idea of metamaterials is the concept of dynamic homogenization, which seeks to define frequency dependent effective properties for Bloch wave propagation. While the theory of static effective property calculations goes back about 60 years, progress in the actual calculation of dynamic effective properties for periodic composites has been made only very recently. Here we discuss the explicit form of the effective dynamic constitutive equations, beginning with simple physical systems where the coupled form of the effective relation emerges naturally from the fundamental act of subsuming microstructural effects into an overall description of motion. We elaborate upon the existence and emergence of coupling in the dynamic constitutive relation and its dependence upon the architectural symmetries of the unit cell. Further symmetries of the effective tensors are discussed in the light of the fundamental symmetries inherent in the Green's function. Finally we discuss concerns about the uniqueness of the constitutive relation and present explicit results for effective dynamic property calculations for a 3-D periodic unit cell further clarifying the nuances of the dynamic constitutive relation.

8269-32, Session 8

Nanostructured phononic materials for thermal management

K. Muralidharan, P. A. Deymier, The Univ. of Arizona (United States)

Developing the ability to control the propagation of phonons in solid-state systems, opens up the possibility of realizing materials with tunable thermal properties. Towards this end, using atomistic computational techniques, we examine two-dimensional materials with high Debye temperatures such as graphene and boron nitride. Both systems, when appropriately nanostructured, exhibit interesting phononic properties. In particular, for certain filling-fractions, the phonon life-times in graphene nano-antidot lattices do not change significantly over a range of temperatures, indicating that graphene can be tuned to exhibit thermal properties that are independent of temperature. Recently, boron nitride sheets containing a distribution of triangular nanometric holes have been experimentally synthesized. Simulations clearly demonstrate that such systems exhibit spatially varying as well as temperature dependent thermal conductivity, implying that boron nitride sheets can be designed to function as thermal rectifiers. The above results have enormous technological relevance and can lead to the development of high-efficiency thermoelectric and thermal interface materials.

8269-33, Session 8

Microfabricated GHz phononic crystals

G. Piazza, Univ. of Pennsylvania (United States)

No abstract available

8269-34, Session 8

Topologically evolved phononic materials: breaking the world record in band gap size

O. R. Bilal, M. I. Hussein, Univ. of Colorado at Boulder (United States)

No abstract available

8269-35, Session 9

Phononic crystal strips for engineering micromechanical resonators

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In micromechanical resonators, energy loss via their anchors into the substrates reduces the quality factor. To eliminate the anchor loss, in this paper a phononic band-gap structure is employed. We demonstrate a design of lossless anchor based on phononic-crystal (PnC) strips to support the micromechanical resonators. The PnC strips are introduced to stop elastic-wave propagation by the band-gap and deaf-band effects so that the energy is effectively isolated within the resonators. Numerical analyses of resonant characteristics of the resonators and the dispersion relations, eigenmodes, and transmission properties of the PnC strips are presented. With the proposed resonator architecture, finite-element simulation results show that the leaky power is significantly reduced and the stored energy inside the resonators is enhanced simultaneously as the operating frequencies of the resonators are within the band gaps or deaf bands. Realization of a high quality factor micromechanical resonator with minimized anchor loss is expected.

8269-36, Session 9

Bending and directing of lamb waves using phononic crystal slabs

S. Mohammadi, A. Adibi, Georgia Institute of Technology (United States)

No abstract available

8269-37, Session 9

Effect of Bragg and local resonance on the formation of phononic band gaps in a silicon plate with metallic pillars

R. Pourabolghasem, Georgia Institute of Technology (United States); A. Khelif, Georgia Tech-Lorraine (France); A. Adibi, Georgia Institute of Technology (United States)

No abstract available

8269-38, Session 9

Anisotropic acoustic metamaterials: from transmission lines to pentamodes

G. Orris, U.S. Naval Research Lab. (United States)

No abstract available

8269-39, Session 10

Classical and quantum applications of optomechanical crystals

O. J. Painter, California Institute of Technology (United States)

No abstract available

8269-40, Session 10

Optomechanical cooling, amplification, and bistability in coupled-mode suspended waveguide geometries

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Opto-mechanical cooling and amplification have been extensively studied recently in both the sideband-resolved and the sideband-unresolved limits in a wide array of geometries, including whispering gallery mode resonators and micromirrors. Optically-induced mechanical bistability has also been studied, but the effect has often been obscured by large thermal effects caused simultaneously by small mode volumes and large optical Qs. Here, we present a geometry consisting of a silicon photonic crystal slab waveguide suspended by a few hundred nanometers over a silicon-on-insulator substrate waveguide whose modes interact with each other through their evanescent fields. The photonic crystal slab acts as a second order grating on the suspended silicon waveguide and allows vertical coupling at the Gamma point into low-group velocity bonding and antibonding-like states. By sweeping a tunable laser across the optical resonance, we can take advantage of the opto-mechanical bistability and adiabatically tune the static displacement of the membrane. Large optical mode volumes combined with optical Qs around 5000 generate opto-mechanical cooling and amplification in the sideband-unresolved limit free from thermal contributions. We can obtain static displacements and mechanical oscillation amplitudes on the order of a nanometer for sub-milliwatt input powers due to the low mechanical stiffness of our structures. We obtain opto-mechanical coupling parameters as high as 8 GHz/nm. These structures show potential applications in sensitive on-chip mass and force detection.

8269-41, Session 10

Photonic and phononic properties of engineered nanostructures

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No abstract available

8269-42, Session 10

Multiphonon acousto-optic interactions in normal and oblique incidence inside a 1D phoxonic cavity

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We study the coupling between an acoustic and an optical wave, inside unidimensional periodical multilayer structures. The basic idea is to create a localized defect inside a phononic and photonic (phoxonic) structure, where both sound and light can be simultaneously localized. That way it is possible to enhance their interaction through acousto-optic and opto-mechanical processes, then allowing mechanical control of light at the nanoscale. If a lot of both numerical and experimental work has already been realized in the Born approximation regime, few studies exist for multiphonon interactions. In this work, we developed a method based on Green's function formalism in the frequency domain. We applied it to both normal and oblique incidence and extend the results already obtained by Psarobas et al. [1] with their time-domain approach. We show in particular that for a frequency near the localized optical mode resonance, the phonon frequency cannot be neglected compared to the optical frequency in the simulation despite its small relative value, because the width of the optical mode starts to be comparable to the phonon frequency. This is illustrated in this work by some noticeable features on the scattering spectrum. Moreover, our first results on oblique incidence are as well presented. More specifically we explore the coupling between in- and out-of-plane polarized waves depending on the acoustic wave characteristics.

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[1] I.E. Psarobas, N. Papanikolaou, N. Stefanou, B. Djafari-Rouhani, B. Bonello, V. Laude, Enhanced acousto-optic interactions in a one-dimensional phoxonic cavity, Phys. Rev. B 82, 174303 (2010).

8269-43, Session 11

Orienting emission: quantifying and controlling excitons in layered materials

R. Zia, Brown Univ. (United States)

No abstract available

8269-44, Session 11

Multipolar effects and strong coupling in hybrid plasmonic metamaterials

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Metamaterials composed of subwavelength structures are of great interest since they can be tuned to exhibit normally unattainable electromagnetic properties. In the optical regime, such artificial structures as periodic metallic gratings, nanodots, and splitring resonators have been investigated. In addition, stacked composites of such structures have also been proposed and investigated for additional tunability of the spectral properties, and even more recently stacked metamaterial structures coupled to a conductive plane have been investigated and have been shown to exhibit the same properties as stacked structures with double the layers, due to dipole mirror coupling. In the case of optical metamaterials, the metallic nanostructures support localized plasmon resonances while a conductive plane such as a metal film supports propagating plasmon resonances. The coupling of the two, i.e. a plasmon hybridization, results in not only the localized modes of a doubly layered structure, but also, for non-normal incidence, modes that exhibit a clear propagation and a higher order localization of the electromagnetic field in the region between the metal film and the periodic layer. This strongly hybridized mode excited for any N number of periodic layers is further influenced by coupling with the highest energy bonding mode of the periodic stack and metal film. Additional insight into the behavior of such systems is obtained by observing the effect of changes in parameters such as increased coupling via reduced spacing between the periodic layers and the metal film.

8269-45, Session 11

Plasmonic nanoparticles for a bottom-up approach to fabricate optical metamaterials

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We investigate experimentally and theoretically metallic nanoparticle (NP) composites fabricated by bottom-up techniques as potential candidates for optical metamaterials. Depending on the plasmonic resonances (LSP) sustained by individual NPs and their nanoscale organization into larger meta-atoms, various properties emerge, i.e. a very high or very low permittivity, or even a negative permeability. Here, the focus of our contribution is on the fabrication and optical characterization of silver NP clusters with a spherical shape.

As a first step, the “bulk” dielectric constants of our starting material, i.e concentrated silver NP inks, are measured by spectroscopic ellipsometry. The results show a wide spectral tunability and large permittivity values depending on the NP densities (i.e from strongly diluted dispersions to solid randomly packed films). The NP clusters with a spherical shape are prepared by an oil-in-water emulsion technique using NP inks as the dispersed material and polyvinylalcohol (PVA) as a polymeric surfactant. The NP self assembly is induced by the addition of a dithiol linker after the formation of PVA-coated ink nanodroplets by sonication. Following size fractionation, the plasmonic response of the dilute emulsions is monitored by optical spectroscopy. The absorption peak of the clusters shows a steady red-shift as the cluster size increases, suggesting the presence of shape (or Mie) resonances rather than the LSP of isolated NPs. Calculations provide evidence that such clusters act as Mie scatterers supporting magnetic resonances; and could be hence used as building blocks to obtain a material with an effective negative permeability.

8269-46, Session 11

Optimal arrangement of meta-atoms composing metamaterials

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In this study, the relative location of meta-atoms with respect to one another is numerically investigated based on their individual three-dimensional (3D) scattering patterns. This is in order to better understand how to improve the performance of a superlens. Each meta-atom (i.e. the unit element composing a metamaterial) in our study is an asymmetric 3D “S”-shaped resonator. This structure radiates an enhanced scattered field at several possible resonant frequencies, some of which are out of phase with the incident wave. We investigate the relationship between the structure of the 3D scattering pattern and the spatial frequency of an incident wave (including evanescent components). By viewing the pattern of the scattered field from a single S element, one can better understand the coupling between elements in an assembled metamaterial, in order to facilitate backward waves associated with negative index phenomena. The 3D structure of the scattered field suggests new lattices on which to place each meta-atom, other than cubic. We discuss the role of meta-atom symmetries and dimensions with the transfer of spatial information at the subwavelength scale from an object to an image domain. Relative locations and orientations of individual meta-atoms are investigated to optimize this information transfer in a bulk metamaterial despite some inherent losses and the finite size of each meta-atom. Scattered fields from differently sized “S” arrays are also evaluated and compared. The results presented provide insights for designing superlenses, resonant antennas, and other potential applications.

8269-47, Session 11

Loss-compensation in metamaterials based on plasmonic nanoparticles

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Composite materials based on plasmonic nanoparticles allow building metamaterials with very large effective permittivity (positive or negative) or epsilon-near-zero; moreover, if clustered or combined with other nanoparticles, it is possible to generate also effective magnetic permeability (positive or negative), and an ad-hoc design would result in the generation of double negative materials, and therefore backward wave propagation. However, losses are usually significant and affect the metamaterial performance. In this work, we report on the possibility of adopting fluorescent dye molecules or semiconductor materials, optically pumped, into the dielectric regions, and provide loss compensation at optical frequencies of ordered periodic arrays of dielectric/metallic nanospheres and/or dielectric core-metallic shell nanospheres.
Each spherical nanoparticle is modeled as an electric dipole through single dipole approximation, and the metal permittivity is modeled by using the Drude model. We then find the modes with complex wavenumber (computed by means of the periodic dispersion relation) in the metamaterial, and describe the composite material in terms of homogenized effective electric and magnetic material parameters. Furthermore, we compare the results obtained from modal analysis with the ones computed by using two different methods: (i) Maxwell Garnett homogenization theory and (ii) Nicholson-Ross-Weir retrieval method. For example, by using fluorescent dyes, we have been able to reduce the extinction coefficient from 0.37 to 0.0007 in an epsilon-near-zero frequency band in a 3D periodic array of dielectric core-gold shell nanospheres and from 0.16 to 0.01 in an epsilon-near-zero frequency band in a 3D periodic array of dielectric core-silver shell nanospheres, by using realistic parameters to model the emission of the dye molecules.

8269-48, Session 11

Infrared plasmonic metamaterials for energy and life sciences applications

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No abstract available

8269-70, Poster Session

Resonant mode mapping in photonic crystal nanocavity by atomic force microscope nano-oxidation

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Photonic crystal nanocavity (PCN) with embedded quantum dots (QDs) is an excellent optical system for the investigation of the solid-state cavity quantum electrodynamics effects. To identify the resonant modes of a PCN, micro-photoluminescence measurements are made at the far field and compared with the results of computer simulations. The measurements yield the resonant wavelength, the Q factor and the polarization of resonant modes. However, the information on the field distribution of resonant modes is missing. Various near-field approaches have been developed to visualize the PCN resonant mode patterns. One straightforward method for obtaining a resonant mode pattern is scanning near-field optical microscopy (SNOM). In this method, a taped optical fiber tip is used to collect the near-field luminescence intensity distribution on the cavity. Besides, the presence of the fiber tip in the near-field region of the cavity also induces a spectral shift in the resonant wavelength. This spectral shift provides another method for probing the PCN resonant mode patterns. Recently, a new approach for tuning the resonant wavelength of PCN by introducing oxide patterns on cavity using atomic force microscope (AFM) nano-oxidation was demonstrated. The same principle can be used as a powerful method for imaging the electric field distribution of PCN. In this work, this AFM nano-oxidation technique was extended to image the resonant mode of PCN by introducing nano-size oxides on the cavity surface. Experimental results were compared with finite-difference time-domain calculations. The spatial distribution of the electric field was obtained with high resolution and high image contrast.

8269-71, Poster Session

Reflection of the circular polarizer with metallic helical metamaterials

Y. Yang, Z. Yang, M. Zhao, Huazhong Univ. of Science and Technology (China)

Recently, it was reported that Gansel succeeded in developing a broadband circular polarizer by using gold helical metamaterials. However, as far as we know, most of the studies just focused on the transmitted light through the polarizer, and little research mentioned the reflected light.

In our work, the circular polarizers consisting of metamaterials with single-, double-, three-, four-, and five-helical nanowires were simulated using FDTD method. The optical performances of the reflected light, such as intensity, polarization and signal-to-noise ratio, were studied, respectively. The simulation results demonstrated that the reflection of the single- and double-helical circular polarizers was very different from that of the three-, four-, and five-helical ones. For the single- and double-helixes, most of the un-transmitted light was reflected, and the polarization of the reflected light only depends on the spiral direction of the helical wires. However, for the three-, four-, and five ones, most of the un-transmitted light was absorbed due to the split ring resonance.

8269-72, Poster Session

Surface plasmon propagation in novel multilayered metallic thin films

F. A. Ferri, V. A. G. Rivera, S. P. A. Osorio, O. B. Silva, A. R. Zanatta, B. V. Borges, J. Weiner, E. Marega, Univ. de São Paulo (Brazil)

Multilayered Ag/Au/Ag/Au and Au/Ag/Au/Ag films with 200 nm of thickness (50 nm for each layer) were evaporated onto BK7 glass substrates. Sequences of slits (with 50, 100 and 150 nm nominal widths) were milled with a FEI focused-ion beam (Ga+ ions, 30 keV) in the films. The lateral dimension of the slits with 100 nm of width was varied in the range of 5–20 µm. We have undertaken a series of high-resolution measurements of the optical transmission through the series of slit arrays. The transmission measurement setup consists of a 488.0 nm (for the Ag/Au/Ag/Au film) and a 632.8 nm (for the Au/Ag/Au/Ag sample) wavelength light beam from an Ar ion and a HeNe laser, respectively, aligned to the optical axis of a microscope. The beam is focused onto the sample surface by a microscope objective in TM polarization (magnetic H-field component parallel to the long axis of the slits). The origin of the slits transmission is attributed to collective conduction band electron oscillations in response to the electrical field of the electromagnetic radiation of light. The optical absorption of the metallic film creates a localized surface plasmon (LSP) that can propagate through the slits (resonance cavities) and eventually enhance their transmission, depending on the geometry of the slit and film structure. As well, we have performed computer simulations carried out with COMSOL Multiphysics® investigating the slits optical transmission and comparing to experiment. It is valuable to notice that a very good correspondence between theory and experiment was observed.

8269-73, Poster Session

Theoretical analysis of the modal behavior of 2D random photonic crystals

S. Hamada, S. Takeda, Keio Univ. (Japan); P. Viktorovitch, Ecole Centrale de Lyon (France); M. Obara, Keio Univ. (Japan)

We present the effect of structural randomness on the formation of Anderson localization (AL) in photonic crystals. In order to induce strong localization of optical waves in nanostructures, there are two kinds of schemes: the band-edge modes in photonic crystals and AL modes in random structures. Recently, the intermediate state between them, random photonic crystal (RPC) has been remarkably paid attention. In a photonic crystal with a wide bandgap, the introduction of structural perturbation can get the periodically extended band-edge Bloch modes to be Anderson localized. RPCs have been realized by dislocating the positions of air holes of photonic crystals. Introducing randomness exceedingly, however, the bandgap is collapsed and the AL disappears. Here, we control the number of dislocated air holes to optimize the structural randomness for the high photon confinement efficiency.

We investigate an impulse response of the RPCs by using two-dimensional FDTD (Finite-Difference Time-Domain) algorithm. We array air holes with triangular lattice shape in silicon material, and place a defect area in the center. The randomness is introduced by randomly dislocating the positions of air holes. After the impulse irradiation, we acquire the temporal evolution of the electric amplitudes over the system. By Fourier transforming the sampled signals, we obtain the frequency spectrum and Q-factors of the modes. We will study the modal characteristics of AL as a function of structural randomness in RPCs and optimize the structure to achieve the high photon confinement efficiency.

8269-74, Poster Session

Economic fabrication of photonic crystal nanostructure at selected area using nanospherical-lens lithography

J. Huang, H. Chung, Y. Chang, National Cheng Kung Univ. (Taiwan)

Photonic-crystal is a very important nanostructure and exhibit very interesting optical properties, which has been studied for decades. The most important aspect for a photonic crystal is the ability to modify the propagation behavior of the incident light and has potentials to create novel optoelectronic devices. However, the high fabrication cost has severely hindered the further developments of photonic-crystal-based optoelectronic devices.

In this study, photonic-crystal nanostructures were proposed to be fabricated using the Nanospherical-Lens Lithography (NLL). Sub-micron silica nanospheres were first assembled into a close-packed single-layered array on top of a transparent quartz substrate. Subsequent high-temperature anneal fixed the silica nanospheres on top of the substrate. The silica nanospheres were used as nanoscale spherical lens to focus the incident UV light. Pre-patterned substrates were prepared using regular photolithography process and subsequently covered with unexposed photoresist film. Due to the short depth-of-focus of the nanosphere, the focus UV light only exposed the selected parts of the photoresist film that was in direct contact with the silica nanospheres. Periodicity hole arrays revealed after subsequent photoresist develop. After the UV exposure process, the silica nanosphere array can be easily cleaned by oxygen plasma and used again. The re-usable nanosphere mask is a very important advantage of the proposed NLL compare to those that were proposed before, which saves the cost of the nanospheres and the efforts to assemble them into well-defined single layer. Further development of this method should help the implementation of photonic crystals into real optoelectronic devices.

8269-75, Poster Session

Investigation of two-dimensional photonic crystal properties using approximate analytical methods

I. Nusinsky, A. A. Hardy, Tel Aviv Univ. (Israel)

We analyze physical properties of various two-dimensional photonic crystals using approximate, perturbation based analytical approach. Both E- and H-polarizations are treated. First, photonic crystals structures with rectangular geometry are analyzed. Next, the approach is extended also for complex-shaped structures. Using derived analytical expressions we investigate symmetry properties of photonic bands and the anticrossing effect. Moreover, we derive simple and useful expressions for the first band gap edges. The conditions for the creation of the first lower photonic band gap for various two dimensional photonic crystals are also presented.

The accuracy of the approximations is tested against accurate numerical calculations, and quite a good agreement is found for a wide range of photonic crystal parameters.

The present approach and the derived expressions not only provide fast method for calculating photonic band structures but also yield a physical insight into the problem.

8269-76, Poster Session

Fractal complementary bowtie aperture for confining and enhancing optical magnetic field

Y. Yang, H. Dai, Tianjin Univ. (China)

Due to their capability of dramatically enhancing electric field, plasmonics antennas, such as bowtie and bowtie aperture, have attracted much attention for near-field applications in biosensing, near-field scanning optical microscopy, etc. Recently, based on Babinet's principle, the complementary structures of these antennas were designed to confine and enhance magnetic field effectively, e.g. Diabolo antenna (DA) and Complementary Bowtie Aperture (CBA). Fractal structures were also used to achieve higher electric field enhancement, i.e. Sierpiński Fractal Plasmonic Antenna (SFPA), which is a kind of a modified bowtie antenna designed by placing two Sierpiński triangles together. In this letter, we introduce fractal structures into CBA and construct Fractal Complementary Bowtie Aperture (FCBA) to achieve the better confinement and enhancement of magnetic field. The magnetic enhancement factors of CBA and FCBA, which is defined as the ratio of the magnetic intensity at one point 10 nm above the center of the metal gap with and without the metal structure, is calculated in terms of finite difference time domain (FDTD) method. Simulation results show that the magnetic enhancement factors will be increased remarkably by replacing CBA with FCBA. The resonance wavelength of FCBA and CBA are also compared in near visible region. The parameters of FCBA, such as the metal gap and the thicknesses, are engineered carefully to obtain a higher magnetic enhancement factor. At last, we compare the enhancing effect of various FCBA, which created by different generating rule to facilitate the practical fabricated process for such structures.

8269-77, Poster Session

Integrated plasmonic Moiré cavity in photonic crystal cavity for luminescence enhancement

S. P. A. Osório, O. B. Silva, F. A. Ferri, V. A. G. Rivera, A. R. Zanatta, E. Marega, Jr., Univ. de São Paulo (Brazil)

Luminescence enhancement and surface enhancement Raman scattering (SERS) spectroscopy has been among the principal applications in plasmonic. This work reports on the fabrication and characterization of a disk-shaped plasmonic Moiré-type cavity inside a photonic crystal cavity, in an attempt to enhance the luminescence by increasing the photonic cavity's Purcell factor. Near plasmon resonance, the charges accumulates on the various concentric sharp edges of the Moiré cavity producing a high electric field intensity in the region immediately above the cavity, that is suitable for exciting the fluorescence of molecules in this high field region. The device fabrication begins with deposition of a thin film of gold over a silicon oxide film deposited on a silicon substrate. By the lift-off process, gold patterns for the Moirè cavity and electric contacts are defined. The electric contacts were devised to polarize the Moirè cavity in an attempt to adjust its resonance frequency to some extent. Then, a silicon nitride film of 300 nm thickness is deposited by a magnetron sputtering equipment. The light from an optical fiber couples to the device by a grating region conjugated with waveguides to the photonic crystal. The coupling region and the waveguides are defined by lithography in the silicon nitride film, and finally, both the photonic crystal cavity and the Moiré cavity are made by Focus Ion Beam (FIB). The substances, or analytes, tested were porphyrins and methil-benzenethiol molecules, whose spectrum was obtained with excitation at 532 nm and 633 nm.

8269-78, Poster Session

Polarization splitter based on a porous silicon waveguide

Y. Liu, Z. Jia, Xinjiang Univ. (China)

Optical communication systems employ polarization splitters in many applications, such as coherent and polarization diversity optical detection.

A prism coupled porous silicon(PS) waveguide has similarity with the surface plasmon resonance(SPR),however PSi is easy fabricate for its advantage of nonpoisonous, label free and so on. In this work, the polarization splitter is based on the phenomenon of resonant waveguide. Two pores density PS layer act as waveguide core and cladding. When the component of the incident field wave vector parallel to the surface matches the mode of the PS waveguide core, the resonant happens, the reflectance reached the minimum at the same time. Conclusion is drawn, in fixed incident angle of 47.9 degree, s polarization beam has almost zero reflectance, while p-polarization has nearly 100% reflectance at the same wavelength 1.55μm.

8269-79, Poster Session

Fabrication of nano-sized metamaterial by focused-ion-beam milling process and its optical characteristics

J. Kim, Y. Lee, B. Kang, J. H. Woo, E. Y. Choi, E. S. Kim, M. Gwon, D. Kim, J. Wu, Ewha Womans Univ. (Korea, Republic of)

Nano-sized meta-structures are fabricated by the focused ion beam milling process. We use 1mm-thick fused silica substrate and thin metalic layers are formed by a conventional e-beam evaporation process. On the 30nm-thick Au layer, 200nm x 200nm sized double-split rings are arrayed with 300nm lattice constant. The patterns are engraved with 30nm line-width, and the gap-size of double-split ring is 30nm. Total size of the array is 100μm x 100μm and the number of double-split-rings is 110,889. Using the halogen lamp of 20W through the optical fiber, the optical characteristics are measured in the visible and near-infrared regime. When a linearly polarized light is normally incident on the meta-structures, the intensity of reflection shows the polarization-angle dependence. Particularly, in the near-infrared regime, the polarization dependence of reflection is striking. When the polarization direction of the source is normal to the gap-baring arm, there occurs the minimum reflection at around 1000nm. On the other hand, there is no such dependence in the uv-visible regime. For the transmission property of this structure, we can see two characteristic peaks around 500nm and 1000nm and they show no polarization dependency. We interpret this property in terms of Babinet principle.

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8269-80, Poster Session

Demonstration of self-imaging effect without paraxial approximation

W. Zhao, Rochester Institute of Technology (United States); X. Huang, Michigan Technological Univ. (United States); Z. Lu, Rochester Institute of Technology (United States)

In a conventional homogeneous medium, a periodic electromagnetic wave distribution from a grating can be repeated at regular distances away from the input plane. However, this phenomenon, which is named as Talbot effect, is only observed when the period is larger than the diffraction limit. Information of the subwavelength features of the input grating carried by evanescent waves will decay exponentially. Hence, there will be no Talbot effect seen in conventional material, as the period of the grating is much smaller than the wavelength. By contrast, the self-imaging effect can be achieved in an indefinite anisotropic metamaterial, where the evanescent waves are converted into propagating waves and thus conveyed far away.

The indefinite anisotropic metamaterial can be approximated by a system of thin, alternating multilayer metal-insulator (MMI) stack. As long as the thickness of each layer is sufficiently thin, the effective medium theory (EMT) can be applied to describe the MMI stack by a macroscopic parameter, the permittivity tensor. By properly choosing two suitable materials and thickness ratio, the permittivity components along the propagation direction and the transverse direction could have opposite signs. Considering a MMI stack composed by Ag/SiO2 alternating layers, even material loss is included, deep subwavelength image size in terms of wavelength as $0.087\lambda 0$ can be obtained with a distance of 642 nm away from the input.

The super Talbot effect may find a variety of applications in the fields as nanolithography and optical storage.

8269-81, Poster Session

The surface plasmon resonance sensor with the metallic nanostructure for biosensing

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Surface plasmon is the collective charge density oscillation on a nano-metallic structure excited by incident light. When in a resonant condition, the incident light is highly absorbed and loses a fair amount of its energy, resulting in a dip in the intensity profile of the reflected light. This phenomenon is called the surface plasmon resonance (SPR). The SPR has been an essential technology in chemical and bio-chemical sensing, pharmaceutical research, and environmental monitoring area. It has many major features, such as high sensitivity, real time detection, and non-labeling. More development of different types of SPR sensors have been done recently, which are comparable to or better than the conventional SPR sensors in terms of sensitivity and compactness.

In this paper, we demonstrate the SPR sensor for an improvement in biosensing sensitivity using a metallic nano-structure. We have fabricated the random metallic nano-structures on the metal thin film using the etching process. Moreover, we have analyzed the structure using the finite-difference time-domain method for the analysis of exact characteristic. More detailed results will be presented.

8269-82, Poster Session

Dispersion engineering for surface waves on multilayer metal-insulator stacks

R. Yang, Z. Lu, Rochester Institute of Technology (United States)

The multilayer metal-insulator (MMI) stack system has been widely used as a 2-dimensional anisotropic metamaterial, and has been further utilized to super-resolution imaging, optical lithography and subwavelength sensing/detecting. The most attractive feature of this stratified configuration is its ability to engineer the dispersion of engaged electromagnetic waves, and to tune the frequency range where extraordinary optical phenomena could occur. On the other hand, plasmonic materials are scarce in variety plus the working frequency is limited because of the preset plasma frequency. This problem is worse off in optical frequency. In this report, we have investigated the MMI stack as a plasmonic metametal and studied its capability of supporting surface waves and engineering surface plasmon frequency. The analysis proposes a useful concept of effective surface plasma frequency that can be effectively controlled by not only the filling ratio, but also the coating material, which is largely neglected in prior arts. The analytical conclusions are then verified by electromagnetic modeling for beam size control and optical sensing applications. The results provide new insight into using MMI stacks as a type of metametal to accomplish artificial dispersion, and the outlined design rules would empower researchers to excite confined surface waves more freely from a limited pool of plasmonic materials for optical lithography and subwavelength imaging, and to envision and demonstrate novel detecting/sensing.

8269-84, Poster Session

Negative refraction in the third photonic band of a two-dimensional elliptical rod photonic crystal in a centered rectangular lattice

J. R. Lutkenhaus, K. Ohlinger, H. Zhang, Y. Lin, Univ. of North Texas (United States)

Study of structures that demonstrate negative refraction is important in the search for materials suitable for imaging capabilities below the diffraction limit. In this work, we study negative refraction behavior for the third photonic band of two dimensional elliptical rod photonic crystals in a centered rectangular lattice in air background using analysis of the equifrequency contours of this band combined with FDTD simulations. Hyperbolic equifrequency contours on the third photonic band indicate both negative and positive refraction at different angles. FDTD simulations will be used to verify negative and positive refraction in the third band and search for potential imaging capabilities. If these behaviors are found, this photonic crystal design could potentially find use in sub-diffraction limit imaging applications.

8269-85, Poster Session

Optimization of a localized surface plasmon resonance biosensor for heat shock protein 70

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Localized surface plasmon resonance (LSPR) of metal nanoparticles is a promising technique for label-free bioanalysis. Optimizing the performance of LSPR sensors is required for practical applications, as current limits of detection are inadequate for direct detection of most analytes of interest. One aspect that is often overlooked when designing LSPR sensors is the optimization of the electromagnetic field decay length, ld, which is the distance over which the electric field outside of the nanoparticle approaches zero. Due to differences in the thickness of the functionalization layer and size of the target analyte there is an optimal ld for each sensor system. If the ld is less than the thickness of the functionalization layer, the analyte cannot be detected. If the ld is much larger than the thickness of the functionalization layer and analyte, the sensitivity to analyte binding is reduced with an unwanted increase in sensitivity to fluctuations in bulk solution properties.

The effects of nanoparticle material, size and shape on the ld has been studied in the past, but the optimization of the decay length for specific analyte detection systems has yet to be investigated. Here, a numerical modeling technique that we have recently developed is used to optimize the decay length of an LSPR sensor used for the detection of Heat Shock Protein 70 (HSP70), an important biomarker in environmental monitoring and health care. This work is a step forward to enabling LSPR sensors with practical detection limits.

8269-87, Poster Session

Luminescence enhancement of Er3+ ions from electric multipole nanostructure arrays

V. A. G. Rivera, F. A. Ferri, S. P. Osorio, L. A. Nunez, E. Marega, Jr., Univ. de São Paulo (Brazil)

The most fascinating aspects of metallic nanostructures for plasmonics are their linear and nonlinear optical properties. In this sense, periodic nanostructure arrays forming electric dipoles or quadrupoles were fabricated with a Focused Gallium Ion Beam on Silver and Gold thin films deposited onto an Er3+-doped tellurite glass. The nanostructures were vertically illuminated with an Argon Ion laser (488 nm) for the Silver film and with a HeNe laser (632 nm) for the Gold film. The laser light sources were highly focused by means of a 20x objective lens. The Er3+ luminescence spectrum was then measured in the far-field. The observed luminescence is elucidated considering the following effects: (i) excitation of the Er3+ ions by means of the localized surface plasmon resonance from the electric dipole/quadrupole nanostructures, that produce an improvement of the local field, resulting in an enhanced luminescence, and (ii) the Er3+ luminescence spectrum depends on the albedo of the system (electric dipole/quadrupole arrays), for which its resonant properties is strongly affected. In this way, the emission of the Er3+ is achieved through the metallic nanostructures. Additional contributions for the observed emission spectrum regarding the influence of physical and geometrical parameters (such as metallic film type, period of the electric multipole and lattice symmetry) have been investigated. The variation of these parameters resulted in a significantly change of the luminescence spectrum.

8269-88, Poster Session

Focusing surface plasmons on Er3+ ions with convex/concave plasmonic lenses

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Surface plasmons enable the localization of light in nanoscale and provide an effective way to control the excitation and emission properties of quantum systems. The confinement of electromagnetic fields in regions as small as possible is important for technological applications such as sub-waveguides and nano-lasers. Plasmonic lenses consisting of convex/concave concentric rings with different periods were milled with a Focused Gallium Ion Beam on a Silver thin film deposited onto an Er3+-doped tellurite glass. The plasmonic lenses were vertically illuminated with an Argon Ion laser (488 nm) highly focused by means of a 20x objective lens. The focusing mechanism of the plasmonic lenses is explained by using a simple coherent interference model of surface plasmon-polariton (SPP) generation on the circular grating as a result of the incident field. Particularly, this beam focusing structure has a modulated groove depth (concave/convex). As a result, phase modulation can be accomplished by the groove depth profile, similar to a nano-slit array with different widths. This focusing allows a high confinement of SPPs which excited the Er3+ ions of the substrate. The luminescence spectrum of Er3+ ions was then measured in the far-field, where we could verify the yield of excitation of the plasmonic lens on the Er3+ ions. We analyze the influence of physical and geometrical parameters on the emission spectrum, such as the periodicity and depth profile of the rings. The variation of these parameters resulted in considerable changes of the luminescence spectrum.

8269-89, Poster Session

Enhancement of black silicon beyond band edge Eg into NIR due to optical antenna 2D cone grating structure

H. E. Ahmar, The City College of New York (United States); M. Sher, E. Mazur, Harvard Univ. (United States); R. Alfano, The City College of New York (United States)

This presentation will discuss the micron cone 2D array structure of Black Silicon (BSi) altering the absorption and reducing the reflectance over planar silicon for solar cell use. The 2D cone grating increases the number of available photon modes (or states) which can enhance the overall absorption by trapping by the micron structures. In this trapping model the number of photon modes will cause the absorption to be enhanced in 1D-grating structure by a factor (F) = 3.14n and in 2D-structure by a factor of F = 8n2 over planar silicon, where n is the index of refraction of the microstructure layer. For n=3.42, the enhancement of BSi would be F =93x over planar silicon structure. This results in weaker absorption to become larger, in this case beyond 1100-nm region for BSi over Si layer by 90 folds. Biological inspired structures such as insects' eyes, (flies) have micron-sized structures modulated by nano-structures that enhance their light collection capabilities by reducing the reflection by seven folds. The photocurrent in BSi will be fitted by the enhanced function, (F), beyond Eg=1100nm into 1500nm by band tailing and the reflection reduction.

The 2D micron cones act as optical antenna to improve the operation of silicon as solar cells in NIR to 1500nm.

8269-90, Poster Session

Subwavelength imaging achieved by indefinite metamaterial

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The image size achieved in a conventional material is restricted by the diffraction limit. Recent research show that an anisotropic metamaterial, in which one of the components of the permittivity tensor has a different sign to the others, can support the modes which are originally evanescent in the conventional medium. In this paper, we take the concept and build an anisotropic metamaterial based on wire medium and experimentally demonstrate that subwavelength image can be achieved by the metamaterial.

The anisotropic metamaterial is built of aligned printed circuit boards (PCB) with thin copper wires on the each top surface. The period of the copper wires is 5 mm, which is identical as the thickness of each single board. Keeping the diameter of the copper wires as 0.2 mm, the plasma frequency is approximated as 12 GHz. The measurements are carried out on a microwave near-field imaging system based on a vector network analyzer (VNA). Preliminary result shows that as a TM-polarized point source placed in front of the metamaterial, an image with the size of 10.5mm-by-8mm, which in terms of wavelength as 0.256 0-by-0.195 0, has been obtained at the other interface.

8269-91, Poster Session

Optical funneling and enhanced absorption in plasmonic nanogrooves

H. Shi, L. J. Guo, Univ. of Michigan (United States)

Recently, funneling of light into periodic plasmonic structures and the resulting total energy absorption has attracted increasing research interest for its potential applications in photo-detectors and solar cells. Theoretical and experimental studies showed that such phenomenon could be attributed to the magneto-electric interference of the incident wave with the evanescent field. However, previous studies were mostly focused on periodic structures and the following two basic questions remain unclear: (1) Is periodic structure necessary for this effect? Can funneling and enhanced absorption occur for a few or a single nanogroove? (2) Is there any coupling between the grooves, and if so how does it influence the funneling and absorption properties? Here, we experimentally study the funneling and enhanced absorption in single, double, and periodic plasmonic indentations to systematically understand the underlying physical principle.

There are three sets of structures in our experiments: (I) single groove with vary depths from 350 nm to 650 nm, (II) double indentations with vary distance from 0.6 um to 6.2 um, and (III) periodic indentations. All the structures were made on 700nm thick gold film by Focused Ion Beam (FIB) drilling, and then characterized by Fourier Transform Infrared Spectroscopy (FTIR) microscope.

Experimental results show that the single groove with width of 150 nm can absorb 16 times wide light beam than its width, and gives absorption of 12% when illuminated by wavelength of 2.6um with beam width of 20 um. Such high absorption is due to funneling of light, and the effect can be explained quantitatively based on an electrostatic approximation. Experimentally we found the effective funneling length increase linearly with the resonance wavelength.

In a double grooves experiments we observed periodic oscillations in resonance wavelength and reflection minimum when increasing the distance between the grooves. We propose a quantitative analytical model to explain this effect, which reveals that the optical properties of double indentations system are the superposition of two individual physical processes: funneling into each groove due to evanescent wave around indentations and coupling between two indentations due to cylindrical wave scattered at the indentations edges. The model was further extended to periodic structures and the results agree well with experiments.

8269-92, Poster Session

GaAs nanostructure arrays for III-V solar cell applications

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State of art III-V multijunction solar cells have demonstrated a record high efficiency of 43.5%. These cells are only applicable to high concentration systems due to their high costs of the substrates, expitaxial growth material and installations. We propose a flexible nanostructured thin film III-V solar cell which allows substrate recycling and much thinner epitaxial layer, produces higher energy conversion efficiency and reduces the installation and system assembly cost.

We fabricated the GaAs hollow nano-pyramids using a combination of various nano-fabrication methods such as a nanosphere-based lithography, nanopyrmids MOCVD growth technique and a gas phase lift-off approach. We demonstrate the excellent optical absorption of a 160nm-thick film of GaAs hollow nano-pyramids over a broad range of wavelengths, incidence angles and bent curvatures. Compared to a similarly thick planar control device, the absorption enhancement is about 300% at long wavelengths due to significant light trapping effect and about 30% at short wavelengths due to antireflection effect of the gradient change of refractive index. The overall number of photons absorbed is increased by 100%. Thus a doubling of the short circuit current and the overall energy conversion efficiency can be expected. The 160nm thick of the hollow nanopyramid film is optically equivalent to a micron thick planar thin film. With this proposed hollow nanopyramids for lift off III-V thin film solar cells, the solar system cost after installation can be greatly reduced, leading toward the next generation of low $/W and high kW/kg flexible solar systems.

8269-93, Poster Session

Numerical study of helix photonic metamaterial

Y. Li, H. Huang, Y. Ling, Y. Hung, National Tsing Hua Univ. (Taiwan)

Helix photonic metamaterials are attractive to many applications due to the unique properties of strong circular dichroism and gyrotropy. In this study, the optical properties of metallic helix metamaterial were systematically investigated. Such metamaterial is composed of three-dimensional metallic helical nanowires arranged in a two-dimensional array. 3D finite-difference time-domain (FDTD) method was adopted for simulating the spectral response under the excitation of circularly polarized light. We show that the spectral responses were correlated to the dimensions of the helix structures. Generally, the resonance wavelengths as well as optical properties were determined by the geometrical parameters and the composed materials of the structures. When the dimension scaled down, electromagnetic interactions between helices are pronounced, which consequently affect the optical responses of the structures. The dependency between structure dimension and the corresponding optical properties were discussed and presented in this report.

8269-94, Poster Session

Characterization of guiding properties of metallic nanorod metamaterials

Y. Ling, L. Chang Chien, Y. Hung, National Tsing Hua Univ. (Taiwan)

Metallic nanorod array metamaterials, consisting of nanowires arranged in a two-dimensional array, have exhibited many unique features and attracted much attention recently. Owing to the sensitive nature of the plasmon resonances to changes in geometrical parameters of nanorod arrays, significant shift in resonance wavelengths along with variances in field distribution have been observed. In this study, we characterize the distribution of electric fields and the energy flow in the metallic nanorod metamaterial by finite-difference time-domain (FDTD) method. We show that the direction of energy flow is strongly correlated to the geometrical parameters of nanorod arrays and the wavelength. We estimated the energy flow along a plasmonic waveguide and analyzed the field distribution in a unit cell corresponding to different geometrical parameters and excitation wavelength. The results show that the dominant direction of energy flow is related to the geometrical parameters and the excitation conditions. The reported phenomena for metallic nanorod metamaterials may find numerous applications for guiding structures and sensors.

8269-95, Poster Session

Phase measurement interferometric microscopy of stacked fishnet metamaterials

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Alternating stacks of metal and SiO_2 with nano-hole arrays, called fishnet structures, allow control over the propagation of electromagnetic waves. In such a structure, changing a dimension or a shape, especially the change in shape of nano-holes, give rise to a change of propagation constants. In this study, we report the dispersivity of fishnet structures is controllable with different hole shapes, by measuring the interferometric fringe in various wavelengths. Two structures were fabricated by electron-beam lithography and reactive ion etching. Both consist of five alternating stacks of Al (20nm) and SiO_2 (80nm) with nano-hole arrays. The holes in one of the structures are circular with diameters of 500nm, and the other are square with 500nm sides. The lattice constant in each case is 1,000nm. Since fishnet structures are wavelength-dependent structures, an original interferometric microscope system was set up. This microscope system was built with a Mach-Zehnder type interferometer, a microscope, and a variable-wavelength laser (lambda=1470-1545nm). Interferometric microscope directly reveals the phase difference between two adjacent regions. The phase difference between the fishnet and the free-space was measured. From this measurement, the phase shift of the circular hole and the square hole fishnet were about 110 degrees and 85 degrees, respectively, within a tunable wavelength from 1,470nm to 1.545nm. These values were equivalent to a refractive-index-change of 0.8 and 0.6, respectively. From these results, it can be said that high dispersivity can be obtained from fishnet structures. The value of the dispersivity can be controlled by the shape of the hole.

8269-96, Poster Session

Dual phononic and photonic strip waveguides

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Many studies have been devoted to the search of photonic and phononic band gaps, but relatively few works are dealing with the simultaneous control of phonons and photons. Phoxonic structures hold promises for the simultaneous confinement and tailoring of sound and light waves with potential applications to acousto-optical devices and highly controllable photon-phonon interactions. The aim of this presentation is to investigate both the photonic and photonic band structures, and in particular dual photonic-photonic band gaps, in a model of silicon strip waveguide in which each unit cell contains one hole in the middle and two symmetric stubs on the side of the waveguide. We use the finite-element (FE) methods to calculate the dispersion curves and the finite difference time domain (FDTD) to obtain the transmission spectra.

Appropriate choices of the geometrical parameters allows us to obtain a complete phononic gap together with a photonic band gap of a given polarization and symmetry. Then, we investigate the possibility of confined modes inside cavities inserted in the phoxonic strip waveguide, which lead to an overlap of both elastic and electromagnetic fields. We also propose structures that can support simultaneously slow photonic and photonic branches. Both situations are suitable to enhance the photon-phonon interaction.

Finally, we discuss the actual values of the geometrical parameters, compatible with the technological fabrication constraints, in order to find the photonic features in the range of the telecommunication wavelengths, with the acoustic frequencies falling in the gigahertz regime.

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8269-97, Poster Session

Colorimetric polarization sensing with single plasmonic gold nanorods

S. Biswas, D. Nepal, K. Park, R. Vaia, Air Force Research Lab. (United States)

The color of scattered light from longitudinal and transverse surface plasmon resonances of individual gold nanorods is used to detect the polarization direction of incident light at the nanoscale. The transverse and longitudinal bands of metallic nanorods arise from the anisotropy in the shape of the nanoparticle. These bands show different sensitivities to the polarization of incident light with the longitudinal being more sensitive due to its larger dipole moment.

Colorimetric polarization sensing using plasmonic gold nanorods is performed in a darkfield microscope with a high numerical aperture (1.3) oil immersion objective lens and a dark field condenser. Since the longitudinal and the transverse resonances occur at different energies, the scattered light from each resonance is spectrally unique. The relative intensity of the scattered light determines the observed color of the particle. The amount of light coupling to the two modes is determined by the relative orientation of the incident light and the particle and can be tuned by rotating the direction of polarization of the incident polarized broadband light. This generates different colors at different polarization directions. With this construct, nanorods (diameter ~ 20 nm) with aspect ratio between 2 and 5 have been used to perform colorimetric polarization sensing in the visible to near infrared.

The ability to determine the polarization of light visually at the nanoscale provides an important tool in material science and molecular biology for probing anisotropic material properties at the nanoscale using single nanorods. In contrast to photothermal imaging where laser induced deformation of nanoparticles occur, this bimodal darkfield scattering is non-destructive and internally calibrated. The tunability of the plasmonic bands by varying the aspect ratio is beneficial for the usage of this method over a broad spectral range.

8269-49, Session 12

Plasmonic interferometry: a versatile tool for high-throughput biochemical sensors and energy-efficient thin-film solar cells

D. Pacifici, Brown Univ. (United States)

No abstract available

8269-50, Session 12

Engineering photonic-plasmonic coupled resonances for optoelectronic device applications

L. Dal Negro, Boston Univ. (United States)

No abstract available

8269-51, Session 12

Highly efficient photon coupling into a plasmonic nanostructure using a fiber-coupled microspherical cavity

K. Sasaki, H. Takashima, Y. Tanaka, H. Fujiwara, Hokkaido Univ. (Japan)

Localized surface plasmons (LSPs) of metal nanoparticles and nanogap structures have the ability to confine photons into the single-nanometer areas, so called optical antenna effect. Such intense LSP fields strongly enhance the interactions between photons and matters, such as surface-enhanced Raman scattering, nonlinear photochemical reactions with weak excitation. However, the LSP antenna size, that is the extinction cross-section of a single metal nanostructure, is limited to the square of tens nanometer for visible light, that is much smaller than the mode area of photons. Therefore, the efficiency of propagating photon coupling into the LSP antenna is extremely low level (typically $<1\%$). In this paper, we report the highly efficient photon coupling system using a tapered-fiber coupled microsphere. In this system, photons introduced in the fiber are trapped into the microspherical cavity through the evanescent field. By approaching an Au-coated atomic force microscope (AFM) probe to the sphere, the slow photons on the cavity surface are strongly coupled into the metal tip. The control of the distance between the AFM tip and the sphere achieves the critical coupling condition, on which the propagating photon can couple with the LSP with high efficiency up to 100%. The experimental results demonstrated the 93% photon coupling into the Au tip with the cross-section of 40 x 40 nm2.

8269-52, Session 12

Multispectral plasmonic absorbers for broadband and multispectral absorbtion

S. Ayas, H. Guner, B. Turker, O. O. Ekiz, A. Dana, Bilkent Univ. (Turkey)

Efficient omni-directional absorption over a wide spectral band is very important for efficient enhancement in real-world applications. Using numerical simulations we have show that, wide angle and over 40nm absorption bandwidth can be obtained by using one dimensional metamaterial absorbers(MA).We also verify broadband and multispectral MAs using two dimensional structures experimentally.MA structures are made of metallic nanostructures separated from a ground plane by a thin dielectric layer.In our case the thickness of dielectric layer is about 10nm SiOx and the top nanostructured layer is one and two dimensional silver gratings with 50nm thickness and 250nm periods. We also used 2nm Germanium wetting layer to smothen the roughness of silver layer which degreases from 6-7nm to 1-2nm with germanium layer. Without the germanium layer, The roughness of silver film on glass results in unexpected spectral response, since the thickness of dielectric layer is comparable with the surface roughness. From FDTD simulations with surface roughness, spectral response of structures shows a redshifted random behaviour. The structures are defined with e-beam lithography and lift-off of a 50nm thick silver film. The pitch is tuned from 100nm to 210nm.Spectral characterization is performed with a reflection mode experimental setup.We observe only one mode for pitch lengths smaller than 100 nm and that this mode splits into multiple modes as the pitch length is increased. Such multiply split modes form a band-like absorption spectrum. We show using RCWA simulations that the absorbance is omnidirectional,with acceptance up to 80 degrees of angle of incidence. Such structures with extended angular acceptance are very suitable to be used with high numerical aperture objectives, as well as in solar energy conversion applications. Through optimization, we obtain doubly and multiply-resonant omnidirectional structures for simultaneous excitation and emission enhancement.We employ the absorber structures as SERS substrates. Peak and average Raman enhancement factors are investigated

8269-53, Session 12

Control of the local SPP excitation with a magneto-optical nanoparticle

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Surface plasmon polaritons are surface electromagnetic modes propagating along metal-dielectric interfaces. This last decade, renewed interest in surface plasmon polaritons (SPP) arises from advances in nanotechnology allowing to structure surfaces at an optical subwavelength scale. Nowadays, the search for active plasmonics components has become a central issue. Active plasmonics can be achieved, for instance, by the uses of ferromagnetic materials [1]. These materials exhibit magneto-optical response, i.e., an anisotropic dielectric response controlled by a static external magnetic field. For example we have shown recently the possibility of controlling fluorescence resonance energy transfer (FRET) using a magneto-optical nanoparticle to tune the donor-acceptor interaction with the external magnetic field as an external control parameter [2].

In the present work, we study the excitation of surface plasmon polaritons on a flat metallic surface by a magneto-optical nanoparticle placed at subwavelength distance from the surface, and illuminated by a linearly polarized plane wave. We show that the directivity of plasmon excitation can be controlled with the external magnetic field. Furthermore considering the well-known LMOKE signal, for subwavelength distance above the interface, we predict an unseen intensity for this signal.

Our study is based on exact numerical simulations, using an extended coupled-dipole and Green function method that we used previously for the study of purely metallic structures [3, 4]. The numerical results are analyzed qualitatively using a perturbative approach that provides physical insight and simple rules for the design of magnetoplasmonic components.

8269-54, Session 13

Widely tunable V-shaped plasmonic antennas for planar optics

M. A. Kats, P. Genevet, N. Yu, G. Aoust, R. Blanchard, Z. Gaburro, F. Capasso, Harvard Univ. (United States)

V-shaped plasmonic antennas can serve as passive subwavelength optical elements which can locally tailor the amplitude, phase, and polarization of light and can serve as building blocks for planar optical devices.

In this work, we present a detailed experimental and theoretical study of the unique properties of V-shaped plasmonic antenna arrays. Fourier transform infrared (FTIR) spectroscopy is used to obtain experimental polarization-sensitive scattering and absorption spectra of lithographically-defined nanoscale V-shaped antennas over the mid infrared spectral range. Fully-vectorial 3D finite difference time domain (FDTD) simulations are used to confirm the experimental spectra as well as to study the near-field properties of V-shaped antennas and the effect of the underlying substrate, including the native oxide layer on silicon.

We found that the overall behavior of V-shaped antennas with one axis of symmetry can be understood as the linear superposition of two independent plasmonic modes with opposite charge symmetries. These modes can be tuned by varying the antenna geometry which, in turn, allows for tunability of the phase, amplitude, and polarization of the light scattered by the antennas. We devised two-oscillator model to heuristically describe this behavior.

Finally we also investigated theoretically and experimentally the near-field coupling between nearby V-shaped antennas and showed that these near-field interactions provide yet another route to engineering the antenna scattering properties.

8269-55, Session 13

Characterization of high order modes of plasmonic antenna formed by nanoparticle/ thin film hybrid structures

S. Chen, Y. Urzhumov, D. R. Smith, A. A. Lazarides, Duke Univ. (United States)

The plasmonic modes of a nano-antenna formed by a nanoparticle/ thin film hybrid system are investigated. Plasmonic nano-antennas are well-known for their capabilities to concentrate electromagnetic wave into extreme small region and couple the emission from active materials in proximity to the antennas into far-field region. Previously, we have shown through direct measurement of emission profile images that the nano-antennas not only enhance Raman emission but also systematically direct inelastic emission to the far-field through the dipole mode. We also showed that high order modes of the hybrid structure can be detected. Here, the higher order plasmonic modes are characterized through imaging, variable angle linearly polarized excitation, and simulation. Through spectral simulation with improved resolution, two distinct modes are found to contribute to the broad band high order mode. One has dipole-like behavior and the other has quadrupole-like behavior. The modes are characterized both through near-field distribution and far-field scattering profiles. The quadrupole-like mode can be excited by both p- and s-polarized light whereas the dipole-like mode is only excited by p-polarized light. These high order modes are not as bright as the dipole mode in the far-field spectrum but have substantial near field enhancement which can be utilized for surface-enhancing spectroscopy and sensing. In addition, characterization of high order modes may serve to clarify the interaction between nano-antenna and active materials and will lead to design rules for applications of active plasmonic structures in integrated optical circuits.

8269-56, Session 13

Fabrication of arbitrary small conical shape metal nano-apertures on optical fiber facets

J. Guo, H. Leong, B. Zhang, R. G. Lindquist, The Univ. of Alabama in Huntsville (United States)

Using rotational oblique angle metal deposition, we have demonstrated that we can fabricate arbitrary small nano-apertures in metal film on optical fiber facets with arbitrary small aperture size down to 10s nanometers. The metal nano-apertures have a conical shape in the direction of light propagation. Surface plasmon resonances of these conical shape nano-aperture arrays on optical fiber facets with various aperture sizes have been measured for refractive index sensing application.

8269-57, Session 13

Cavity resonances of plasmonic patch nanoantennas

F. Wang, A. Chakrabarty, F. Minkowski, Q. Wei, Kent State Univ. (United States)

Focusing and confining light at nanometer scales is important to various applications, ranging from ultrasensitive photo-detection to ultra-sensitive bio/chemical sensing. Here we propose and demonstrate high power of confining light in ultra-small mode volume through cavity resonances in plasmonic patch nanoantennas. The plasmonic patch antennas are composed of metal disk arrays on metal films with dielectric spacers. Since the dielectric layer can be fabricated through thin-film deposition techniques, its thickness can be well controlled with down to sub-nanometer accuracy. In this paper, we will present our experimental and numerical results on the cavity modes and their excitation conditions. Especially, some cavity modes can be excited with normal or tilted illumination, while others can only be excited with tiled illumination under certain polarization condition. We will show one unique application of such anisotropic plasmonic nanocavities in manipulating the polarization of reflected light at those resonant frequencies. The optical patch antennas with ultra-small mode volumes may find additional applications in enhanced light-matter interactions, controlling light emission and single-molecule surface-enhanced Raman spectroscopy.

8269-58, Session 13

Near-field optical study of strong coupling effects in a chain of gold nanorods integrated on silicon waveguides

A. Apuzzo, Univ. de Technologie Troyes (France)

Conventional dielectric waveguides do not offer the possibility of highly miniaturized integrated circuits because the minimum beam diameter is determined by the effective wavelength in the core material [1]. This has motivated the study of alternative approaches based on chains of closely-spaced metal nanoparticles [2].

On the other hand, optical far field tests cannot resolve subwavelength-scaled dimensions, so complementary characterization techniques are needed such as the scattering near field microscope (SNOM). In this work, we report on the experimental study of a chain of gold nanoparticles (MNPs) on a Si waveguide by using a heterodyne scattering-SNOM (s-SNOM). We have measured giant coupling between MNPs and silicon waveguide with a periodic transfer of energy from one guide to the other. Finally we have performed FDTD [3] simulations of optical amplitude and phase profiles along the MNPs waveguide and compared them successfully to experimental results.

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8269-59, Session 14

Optical properties of plasmonic structures based on biological and synthetically fabricated templates

J. W. Perry, Georgia Institute of Technology (United States)

No abstract available

8269-60, Session 14

Holographic plasmonic quasi-crystal

W. Mao, M. R. Wang, Univ. of Miami (United States)

Plasmonic crystals, to which a number of works have been devoted, have received growing interests due to plasmons created at the surface enabling localization of electromagnetic energy below the diffraction limit. The light-matter interaction can be surprisingly enhanced by the localized surface plasmon resonances that have wide applications in such as ultrasensitive chemical and biological sensing. Electron beam lithography, soft lithography, and focused ion beam milling have been used to produce metallic gaps for greatly enhancing the effect of localized surface plasmons, furthermore for the preparation of plasmonic devices. Holographic lithography (HL), including Lloyd's Mirror interferometer, two-beam interferometer, dual beam multiple exposure and multiple beam single-exposure HL, provides a much feasible and convenient way for fabrication of various simple or complicated micro- and nanostructures, which can possess compound lattices, chiral construction, or quasi-periods. However, how to design and fabricate plasmonic quasi-crystals with high-order symmetries is a challenging issue. Here, we present eight-fold symmetric plasmonic quasi-crystals created by five-beam single-exposure laser interference lithography combined with advanced techniques such as metal deposit. Metallic nanogaps are distributed with eight-fold symmetry, being accompanied by the same symmetrically distributed sub-micron metallic islands to form double rings. Polarization changes are tested for revealing the unique character of the eight-fold plasmonic quasi-crystals. This work will extend the HL method to combining photonic and plasmonic features in the same nanostructure.

8269-61, Session 14

Self-assembled plasmonic nanoclusters

J. Fan, Y. He, Harvard Univ. (United States); K. Bao, Rice Univ. (United States); C. Wu, The Univ. of Texas at Austin (United States); J. Bao, Univ. of Houston (United States); V. N. Manoharan, Harvard Univ. (United States); G. B. Shvets, The Univ. of Texas at Austin (United States); P. J. Nordlander, Rice Univ. (United States); D. Liu, F. Capasso, Harvard Univ. (United States)

The self assembly of colloids is an alternative to top-down processing that enables the fabrication of a new class of nanophotonic structures. Their applications include chemical sensors, plasmonic rulers, optical nanocircuits, and new types of metamaterials. We show that by tailoring the number and position of metallic spheres in clusters, plasmon modes exhibiting strong magnetic and Fano-like resonances emerge. Nanoshells, which are silica-core gold-shell particles, are used as building blocks for these clusters, and their highly spherical geometry supports orientation-independent optical coupling. Dielectric spacers are used to tailor the interparticle spacing in these clusters to be approximately 2nm, which exceeds the spatial resolution of traditional lithographic processes. Scattering spectra are measured from individual clusters to eliminate inhomogeneous broadening effects.

Two assembly routes are explored: the capillary assembly of particles from droplets and cluster assembly via smart polymers. In the former, capillary forces from drying droplets of nanoparticles are used to pack the particles into close-packed geometries. Its simplest conception involves the drying of particles on a hydrophobic substrate; this is sufficient for the assembly of a broad range of packed two-dimensional clusters, but with low yields. Polymers provide a flexible platform for tailoring the interaction between particles and even programming the assembly of clusters to well-defined geometries. We show that this route allows particles of different sizes and types to be assembled in a highly controlled fashion, and that it provides the potential for the assembly of three dimensional nanostructures.

8269-62, Session 14

Polarization controlled dipolar plasmon resonances in lithographically defined metal nanoparticle arrays

M. Kaniber, B. Mayer, S. Dietl, J. J. Finley, G. Bracher, Technische Univ. München (Germany)

Metallic nano-particle arrays provide strong potential for plasmonic enhanced fluorescence [1] and photovoltaic devices [2]. We report on the fabrication and optical investigation of lithographically defined gold nano-triangle arrays on glass and their influence on the optical properties of proximal CdSe nanocrystals. Our results demonstrate that the spectral and polarization response of the system can be precisely tuned by varying both the lattice constant of the array (a) and the size (a,´b') of the isosceles nanotriangles.

Structures were fabricated using electron beam lithography on glass and consisted of a square lattice of nanotriangles. For a'=b'=150nm equilateral triangles with a Au-film thickness h=40nm (roughness <5nm), a lattice periodicity a=300nm the optical extinction spectrum is unpolarized and exhibits a pronounced dipolar plasmon resonance at 695±5nm. In strong contrast, as the aspect ratio is systematically varied from a'/b'=1.0 to 1.8, two linearly polarized dipolar modes emerge with a splitting that increases systematically. For a'/b'=1.8 we measure two strongly linearly polarized modes at 650nm and 800nm splitting of 150±10nm. First studies will be presented of the influence of such nanotriangle arrays on the optical properties of proximal CdSe nanocrystals created in the glass substrate via ion implantation. In combination with the polarization dependence of the metal nanoparticle arrays such hybrid systems could provide a way for optical switching in optically active semiconductor-metal hybrid systems.

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8269-63, Session 14

Nanoptical characterization of plasmonic nanostructures and devices with single and multiprobe NSOM and apertureless NSOM

A. Lewis, Hebrew Univ. of Jerusalem (Israel)

More than two decades ago our group investigated plane wave light transmission and the transmission of fluorescence through nano aperture arrays in gold palladium films [1-2]. In our earliest report [1] we reported that "Although the transmission through 1 µm apertures appears consistent with exact electromagnetic field calculations there appears to be more transmission through the smallest apertures than theoretical prediction." About a decade and a half after our investigations Ebbesen and coworkers verified our observations and explained the large transmission property of such nano-hole arrays as an effect involving surface plasmons (SPs) [3,4]. Since Ebbesen's paper in 1998, nano-holes arrays have generated both theoretical and experimental interest in order to understand the physics involved in the Extraordinary Optical Transmission (EOT) through such arrays [5-8]. Both our earlier experimental investigations and those of others have generally focused on far-field optics. Nonetheless, the optical near-field plays a major role in the enhancement processes and so its understanding is integral to developing a full characterization of these and other plasmonic structures. This talk will summarize recent near-field optical investigations completed by our group and others including those on plasmonic propagation which have resulted in new understandings of plasmonic distribution, have demonstrated controlled perturbation surface plasmon propagation and have led to new directions in apertureless near-field optics.

8269-64, Session 15

Photon confinement to the nanoscale: Potential applications to solar energy conversion and nanomedicine

M. A. El-Sayed, Georgia Institute of Technology (United States)

No abstract available

8269-65, Session 15

On-chip hybrid photonic-plasmonic sensors: theoretical design and experimental demonstration

M. Chamanzar, A. Adibi, Georgia Institute of Technology (United States)

No abstract available

8269-66, Session 15

Tunable plasmonic nanostructures for light trapping and strong field enhancement at the metal surface

A. Polyakov, K. F. Thompson, H. A. Padmore, S. Cabrini, P. J. Schuck, Lawrence Berkeley National Lab. (United States)

There is a significant scientific and technological interest in zero-reflectivity substrates for enhanced light harvesting in applications ranging from photovoltaics[1] to enhanced photocatalysis to photocathodes for the next generation light sources[2]. We have recently realized a practical demonstration of complete light absorption in the metal by placing a set of rectangular nano-grooves narrow than the skin depth on the metal surface[3]. The dimensions of these grooves are very small compared to the wavelength of light. For many applications it is desirable to operate at wavelengths deeper into the NIR compatible with high power lasers such as Ti:sapphire (800 nm) and Ytterbium-based fiber lasers (1064 nm). An omni-directional structure resonant at such wavelengths would have NGs less than 8 nm wide[4], which is a major fabrication challenge. In this work we present a new method for tuning the resonance of a subwavelength metallic grating in post-fabrication by coating the structure with a known dielectric. This method is well suited for converting the resonant structured in the visible to the NIR. Fine control over the resonance position can be readily achieved via atomic layer deposition (ALD) that allows sub nanometer control of the dielectric layer thickness.

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8269-67, Session 15

3D analysis of surface plasmon dispersion for SERS sensor based on inverted pyramid nanostructures

S. Z. Oo, M. D. B. Charlton, Univ. of Southampton (United Kingdom)

Surface-enhanced Raman scattering (SERS) can be used to amplify Raman signals by several orders of magnitude, by utilising plasmon polariton (photonic and surface plasmon mode) coupling to test molecules disposed on a textured metallo-dielectric surface.

In this paper we develop a comprehensive 3dimensional computational model based on Rigorous Coupled Wave Analysis (RCWA) for the purpose of analyzing Propagating and localized surface Plasmon polaritons supported by planar SERS substrates based on periodic arrays of metal coated inverted pyramidal nanostructures. The model is applied to the task of optimization of gold metal thickness and to investigate Plasmon detuning effects due to reduction in pit size by metalisation. We also investigate effects of non-conformal gold coating on the inside of the pits on localized surface Plasmons.

This experiment allows construction of an intuitive picture of Plasmon dispersion behavior due to the changes in lattice periodicity or internal pit width dependent on gold layer thickness. By incorporating different regions of the unit cell into the simulation space we can exclude the flat surface region between pits, allowing identification of propagating surface plasmons and localized pit plasmons in the dispersion maps.

Results show that propagating surface plasmons become coupled to trapped plasmons localized to the side wall of the hole. Plasmon dispersion relations shift to higher wavelength with increasing thickness of gold or increase in hole size. Increasing the gold layer thickness increases the number of plasmon dispersion bands and associated density of states in the range 500nm to 1000nm increasing options for excitation wavelength.

8269-68, Session 15

Nonlinear plasmonics of metallic heptamers

K. Thyagarajan, S. Rivier, O. J. F. Martin, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Second-harmonic generation (SHG) from centrosymmetric nanostructures due to the breaking of inversion symmetry at their surfaces is a well-known phenomenon and is extensively used as a surface probe in nonlinear optical microscopy. In recent years, SHG and its subsequent enhancement using plasmonics has been observed from nanostructures such as sharp metallic tips, nanoantennae and nanodimers. However, the process is still inefficient and an improvement is required. In order to achieve a higher conversion efficiency we investigate experimentally a way to minimize the radiative losses at the fundamental frequency. In the present investigation, we use silver heptamer nanostructures and tune the subradiant mode of the Fano resonance to the fundamental of the pump source while tuning a higher order multipolar term to the second harmonic and in the process we obtain a significant enhancement of the second harmonic signal. A detailed explanation and analysis of this is provided by considering the contribution and effect of varying different parameters such as gap size, radius, thickness, polarization and angle of incident light, as well as the overall symmetry of the structure. In fact, recently gold heptamers have been studied and have indeed shown strong hybridization of their constituent resonant primitive plasmonic modes leading to new hybridized superradiant ‘bright’ and subradiant ‘dark’ modes. The ease of fabrication and possible tunability achievable, make these structures very versatile tools for studying surface SHG in nanostructures.

8269-69, Session 15

Controlled coupling of guided surface plasmon polaritons to InGaAs quantum dots

G. Bracher, K. Schraml, J. Zellmer, C. Jakubeit, M. Blauth, B. Mayer, J. Finley, M. Kaniber, Technische Univ. München (Germany)

We present investigations of the propagation length of guided surface plasmon polaritons (SPPs) along Au waveguides on GaAs and their coupling to near surface InGaAs quantum dots (QDs). Our results reveal SPP propagation lengths from 13.4±1.7 µm to 27.5±1.5 µm as the waveguide width increases from w=2-5 µm. Experiments on active structures containing near surface QDs clearly show that SPPs excite QDs providing a new method to image the SPP mode.

We use low temperature confocal microscopy with polarization control in the excitation and detection channels. After excitation, SPPs propagate along the waveguide and are scattered into the far field at the end. As expected, SPPs are only excited for polarization directions parallel to the waveguide axis (>70% DOP). By comparing length and width evolution of the waveguide losses we determine the SPP propagation length to be 27.5 ± 1.7 µm at 830 nm (w=5µm), reducing to 13.4±1.5 µm for w=2 µm. For active structures containing a sparse ensemble of InGaAs QDs at a precisely controlled distance 7-120nm from the Au-GaAs interface, we probed the QD-SPP coupling. These investigations reveal a unidirectional energy transfer from the propagating SPP mode to the QDs that is used to image the SPP mode in direct space. We will also present preliminary investigations of single QDs coupling to the guided SPPs. The exquisite control of the position and shape afforded by lithography combined with near surface QDs promises efficient on-chip generation and guiding of single plasmons for future applications in nanoscale quantum optics.

Conference 8270: High Contrast Metastructures

Sunday-Wednesday 22-25 January 2012

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8270-01, Session 1

High-contrast grating optoelectronics

C. J. Chang-Hasnain, Univ. of California, Berkeley (United States)

High contrast subwavelength structures can lead to an interesting play of optical waves. This new concept facilitates simple analytic solutions which provides goal-oriented designs for complex wave behavior, instead of goal-searching numerical simulations over the vast parameter space I will discuss various interesting properties by varying grating parameters to yield a very broadband, high-reflectivity mirror for light incident in surface-normal direction or at a glancing angle, or as a high-Q resonator with surface-normal output for many useful applications.

8270-02, Session 1

Surface addressable photonic crystal membrane resonators: generic enablers for 3D harnessing of light

P. Viktorovitch, C. Sciancalepore, Ecole Centrale de Lyon (France); T. Benyattou, Institut National des Sciences Appliquées de Lyon (France); B. Ben Bakir, CEA-LETI (France); X. Letartre, Ecole Centrale de Lyon (France)

Conceptual approaches used to analyse optical properties of High Contrast Gratings and of surface addressable Photonic Crystal Membrane (PCM) Resonators will be briefly presented: it will be shown that both approaches can merge and be reconciled. It will be demonstrated that high reflection mirrors, with arbitrarily adjustable bandwidth, can be designed along the PCM approach, where waveguided slow Bloch modes play the prime role. An example of implementation of large bandwidth PCM reflector is emphasized: it consists in Vertical-cavity surface-emitting lasers (VCSELs) using hybrid III-V / Si microcavities and based on double PCM reflectors. These devices are meant to be compatible with their heterogeneous integration on complementary metal-oxide-silicon (CMOS). It will be shown that the operation of this new class of VCSEL is based on hybrid optical modes, whose properties can be fully monitored by appropriate design of the PCM reflectors: for example specific designs can be implemented for laser emission either in free space, or into silicon waveguides. The latest achievements in technological processing and optical mode engineering will be presented.

8270-03, Session 1

Fabry-Perot phase selection rules for high-contrast gratings

C. J. Chang-Hasnain, Univ. of California, Berkeley (United States)

High contrast near-wavelength dielectric gratings are emerging as a new research field, due to their broadly applicable attributes, which cannot be found in either deep-subwavelength gratings or long-period (diffraction) gratings. These attributes are: (1) broadband ultra-high (~100%) reflectivity and (2) high-Q (>10^7) resonances. Understanding these attributes in simple terms is necessary for near-wavelength gratings to gain broad integration in optical devices.

We have developed an exceedingly simple, yet fully rigorous and precise theory, which completely explains these attributes as two special manifestations of one general physical mechanism. This mechanism is a dual-mode generalization of a Fabry-Perot (FP) resonance effect, whereby the two grating modes perform Fabry-Perot round-trips along the thickness of the grating. We show that all high-reflectivity features match the condition where the half-roundtrip FP phases of the two grating modes are pi radians apart. We also show that all grating resonances match the condition where these half-roundtrip FP phases equal a multiple of pi for both grating modes. Furthermore, if both multiples of pi have the same parity (odd vs. even), the grating resonance becomes high-Q (>10^7), in which case the FP phase lines of the two modes exhibit an anti-crossing behavior (vs. a crossing behavior when the Q is low). The agreement between these simple phase selection rules and the grating reflectivity behavior is excellent for practically all wavelengths, grating dimensions and light polarizations and incidence angles of interest.

8270-04, Session 2

High contrast grating for spatial mode filtering and mode control of VCSELs

F. Koyama, Tokyo Institute of Technology (Japan)

High contrast gratings (HCG) have various unique features such as broadband high reflections, high-Q resonance, spatial control of optical phase and so on. We focus on the angular dependence of HCG, which can be managed by designing grating parameters. The angular dependence of HCG is much larger than that of conventional quarter-wavelength stack multi-layer reflectors while keeping their broadband high reflections. The engineered angular dependence can be useful for spatial mode MUX/DEMUX devices. We present a new function of HCG hollow waveguides with a spatially varied HCG period. A possibility of spatial mode demultiplexer based on HCG hollow waveguides is suggested for use in high-capacity optical interconnects with spatial mode multiplexing. Other interesting applications of the large angular dependence are the transverse mode control of HCG-loaded VCSELs and slow light optical amplifiers. Excess losses for high-order modes results from the engineered angular dependence of HCG. Also, a possibility of compact slow light optical amplifiers is suggested by loading a HCG reflector for slowing light.

8270-05, Session 2

MEMS-actuated optical phased array with high contrast grating mirrors

M. C. Wu, Univ. of California, Berkeley (United States)

Agile optical phased arrays (OPA) not only enable optical beam steering but also beam forming and multiple beam generation. Compact OPAs have numerous applications, including 3D imaging, gesture-based sensing, gaming, LIDAR, precision targeting, navigation, remote sensing, and laser communications. Previously, OPAs have been realized using liquid crystals and photonic integrated circuits with phase modulator arrays. However, liquid crystals are limited to low speed operation, and phase modulator array requires complex integration process to achieve two-dimensional OPA. Micro-electro-mechanical-system (MEMS)-based OPAs have also been demonstrated, however, the trade-offs between resonance frequency and actuation voltage preclude their operation in MHz range. In this paper, we report on a novel MEMS-based OPA that can simultaneously achieve large phase shift (2 pi), high bandwidth (> MHz), low actuation voltage (99.5%) can be achieved in HCG that weights only a few percent of multi-layer distributed Bragg reflectors with similar reflectivity. The single material construction also prevents mirror warping due to mismatch of thermal expansion coefficient. To further reduce the actuation voltage, we integrate the HCG mirror with an all-pass optical filter to amplify the phase shift. Simulation shows that actuation voltage below 10V can be achieved. This project is supported by DARPA SWEEPER (short-range wide-field-of-view extremely-agile electronically-steered photonic emitters) program.

8270-06, Session 2

Novel direction selective filter elements based on high contrast gratings

S. Steiner, S. Kroker, T. Käsebier, E. Kley, Friedrich-Schiller-Univ. Jena (Germany); A. Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

We report on novel concepts for filter elements based on high contrast gratings. We focus on silicon, which is a suitable material due to its very high refractive index of n = 3.677 at 850 nm wavelength. This fact also allows for the realization of novel filter elements offering large tolerances with respect to design parameter variations. Elements based on silicon technology can easily be integrated into existing micro electrical systems and without extensive adaption and thus low fabrication costs are feasible. Our approaches focus on resonant waveguide gratings (RWGs) which are known for their very selective behavior concerning wavelength, polarization and direction of the incident light. Furthermore, it is also possible to combine e.g. direction selectivity with defined polarizing properties in one single element based on RWGs. We discuss concepts for direction selective filters in transmission which expose tuneable angular ranges with high performance. Likewise, the transmission bandwidth is adjustable by means of varying geometric grating parameters such as duty cycle and period. For some application in sensoring it is necessary to employ a filter with an asymmetric angular dependent transmission, which means that the efficiency for positive and negative incidence angle differs. We illustrate the excellent optical properties of the direction selective filter elements by a comparison with the features of metallic structures. Our approaches provide the possibility of multifunctional filter elements which can be easily combined with existing fabrication techniques in semiconductor industry.

8270-07, Session 2

Fabrication and characterization of Si/SiO2 high contrast grating using nanoimprint lithography

Y. Hashizume, Y. Miyake, A. Matsutani, Tokyo Institute of Technology (Japan); H. Ohtsuki, SAMCO, Inc. (Japan); F. Koyama, Tokyo Institute of Technology (Japan)

High contrast gratings (HCG) have various unique features such as broadband high reflections, high-Q resonance, large birefringence, spatial control of optical phase and so on. Sub-wavelength patterning has been typically fabricated using EB lithography followed by dry-etching. On the other hand, nanoimprint lithography is a powerful tool for making large area sub-wavelength scale optical devices with high-throughput fabrication. We developed a thermal nanoimprint lithography process for making sub-wavelength HCG patterns on an SOI substrate. We used a Si-based mold and the MTR-01 plastic resin as a thermal nanoimprint resist material. The process was performed at 170 °C under a pressure of 2 MPa. We carried out the Si dry etching process by Cl2- ICP through thermal nanoimprint resist mask. The grating period, spacing and thickness of the Si/SiO2 HCG structure were 480nm, 360nm and 315nm, respectively. A vertical etching profile and a smooth etched surface, which meet the requirements for Si based HCG structure, were obtained at a substrate temperature of 90 °C. We successfully fabricated large area (1cm x 1cm) HCG with good uniformity in the entire sample. We measured the angular dependence of the reflection spectra of the fabricated HCG. Clear angular dependence of the reflectivity can be seen, which is in good agreement with the modeling result. The engineered angular dependence of HCG could be useful for the mode control of VCSELs and spatial mode multiplexers.

8270-08, Session 3

Slow-light HCG metastructure hollow-core waveguides

W. Zhou, G. Dang, M. Taysing-Lara, U.S. Army Research Lab. (United States); V. Karagodsky, T. Sun, C. Chang-Hasnain, Univ. of California, Berkeley (United States)

We present a new type of Si-based, meta-structure, hollow-core waveguide that has both “slow-light” and low-loss properties, and can be used to provide a long time-delay or a high-Q cavity in chip-scale integrated OE circuits. Conventional waveguides have a high propagation loss when used in a high dispersion region since loss and dispersion cannot be separated. We use high-reflection, high-contrast grating (HCG) metastructures as the 4 claddings/walls of a squared hollow-core waveguide where the guided light is ~100% reflected from the meta-gratings and there is no absorption from the core, therefore the overall loss is ultra-low. This HGC metastructure can be engineered to create a phase-transition between the propagation modes that yield a “0” slope in the dispersion curve (i.e., “0” group velocity). Computational modeling was performed to map the waveguide loss with the dispersion curves and results indicate that there is a slow-light region (group velocity ~0.02C) with very little propagation loss. We have successfully fabricated this meta-structure waveguide using new nano-fabrication techniques which creates 3-D, squared HGC frames that form a waveguide from a 2-D masked surface of a SOI wafer utilizing one self-aligned, cycled, modified Bosch etch process. This process produces deep trenches with controlled sub-micron width variation in the vertical direction which make a precise undercut to form the hollow-core under the top HCG which leaves vertical posts on both sides to form the vertical side HCGs. We will also report our experimental waveguide test results for both propagation loss and group velocity.

8270-09, Session 3

Low loss slow light in high contrast grating hollow core waveguide

T. Sun, V. Karagodsky, Univ. of California, Berkeley (United States); W. Zhou, U.S. Army Research Lab. (United States); C. Chang-Hasnain, Univ. of California, Berkeley (United States)

High contrast grating (HCG) can provide high reflectivity over broad range of wavelengths and incidence angles. In addition, the unique phase dispersion of an HCG can be engineered to facilitate high performance slow light. We propose a novel 2-D hollow core slow light waveguide comprising of two identical HCGs separated by a distance D, whereby HCGs serve as light guiding mirrors. HCG period, thickness and the separation distance D are all comparable to wavelength, which makes the waveguide a compact structure. Both Rigorous Coupled Wave Analysis (RCWA) and Finite Difference Time Domain (FDTD) simulations demonstrate that the guided mode exhibits low loss (~0.2dB/cm) and high slow-down factor (~100) within a >100GHz bandwidth. The unique phase response of HCG eliminates the common trade-off between low loss and high slow-down factor, and both can be facilitated simultaneously.

Lateral confinement in a 3D hollow core waveguide is also investigated, whereby light is reflected by HCGs in both horizontal and vertical transverse directions. The fundamental mode is shown to be fully confined, and FDTD simulations of a 3D structure demonstrate a slow down factor of ~20, and loss as low as 5dB/cm. Further optimization of a 3D structure is currently in progress.

8270-10, Session 3

Attenuation coefficient of periodic waveguides: fast to slow light transition

P. Lalanne, Lab. Charles Fabry (France)

The impact of random imperfections on the propagation of light in single-mode waveguides or fibers is critical for many applications. For weakly confined modes, the transport is dominated by absorption losses or by scattering into radiation modes. The incremental transmission loss per unit length is the same for any waveguide section, and the transmission decays exponentially with the waveguide length , leading to the definition of the attenuation rate coefficient often expressed in dB/cm.

In this work, we evidence that the exponential-damping law is not valid in general for periodic monomode waveguides, especially as the group velocity decreases. This result that contradicts common beliefs and experimental practices aiming at measuring the attenuation rate is supported by a theoretical study of light transport in the limit of very small imperfections, and by numerical results obtained for two waveguide geometries that offer contrasted damping behaviors.

8270-11, Session 4

High contrast gratings: from DUV polarizer to low noise infrared-mirrors

E. Kley, Friedrich-Schiller-Univ. Jena (Germany)

The most common material in electronics is silicon. Its semiconductor properties as well as its role in micromechanics and its transparency in the near infrared make it one of the most important materials ever. Its very high index of refraction, its dispersion and its spectral absorption leads to a couple of interesting applications, especially for High Contrast Metastructures. So it is possible to make silicon wire grid polarisers for the UV region as well as broad band monolithic silicon mirrors with nearly 100% reflectivity. Such mirrors, based on guided mode resonance (GMR) gratings, should be of advantage for low thermal noise applications in cavities in the infrared. The mirrors are made by a T-shaped structuring of the silicon with a depth of 1-2µm. They can also be stacked for improved wavelength and angular acceptance which make them usable for diffractive beam splitters for cavity coupling.

GMR grating based transmission and reflection filters for the infrared up to the visible region can be made also. Beside more or less polarization sensitivity an additional feature, an angular dependent transmission can be designed.

The talk gives an overview of the described elements, its functionalities, fabrication technologies and its application fields.

8270-12, Session 4

VCSELs and silicon light sources exploiting SOI grating mirrors

I. Chung, J. Moerk, Technical Univ. of Denmark (Denmark)

In this talk, novel vertical-cavity laser structure consisting of a dielectric Bragg reflector, a III-V active region, and a high-index-contrast grating made in the Si layer of a silicon-on-insulator (SOI) wafer will be presented. In the Si light source version of this laser structure, the SOI grating works as a highly-reflective mirror as well as routes light into a Si in-plane output waveguide connected to the grating. In the vertical-cavity surface-emitting laser (VCSEL) version, there is no in-plane output waveguide connected to the grating. Thus, light is vertically emitted through the Bragg reflector. Numerical simulations show that both the silicon light source and the VCSEL exploiting SOI grating mirrors have superior performances, compared to existing silicon light sources and long wavelength VCSELs. These devices are highly adequate for chip-level optical interconnects as well as conventional short-distance optical connections. In the talk, device physics will be discussed in detail.

8270-13, Session 4

Wave-front-engineered grating mirror for VCSELs

L. Carletti, J. Mork, I. Chung, R. Malureanu, Technical Univ. of Denmark (Denmark)

High-index-contrast gratings (HCGs), i.e. one- or two-dimensional gratings surrounded by a low refractive index material, have recently been shown to provide many advantageous properties beneficial for different applications as broad high reflectivity bandwidth, simple epitaxial structure and strong single-transverse mode operation. This makes them a strong candidate for substituting conventional Bragg gratings, as applied e.g. in vertical-cavity surface emitting lasers (VCSELs). Another interesting feature of HCGs is phase front control of the reflected beam by engineering of the structural parameters. For integration into VCSELs, wave front control of the transmitted beam is more advantageous. In our approach, a Si-hybrid structure design with sub-wavelength structuring is employed to modify the HCG phase response while maintaining a high reflectivity. We report gratings with spatially dependent phase response for the transmitted beam. This is achieved by locally modifying the grating's periodicity or duty cycle, i.e. fraction of high index material in one grating period. We designed and fabricated HCGs, suitable for VCSELs integration, with either parabolic or linear phase profile to obtain focusing or beam steering. Our numerical and experimental results confirm these features. Experimental data already obtained show beam steering to an angle of about 6°, with good agreement between numerical and experimental results. Integration of these HCGs in VCSELs allows sparing of additional lens systems and could have a considerable impact on the production costs of compact electrical components with laser cavities as well as allowing the realization of more efficient and compact optical devices, e.g. wavelength division multiplexing systems.

8270-14, Session 4

High frequency binary amorphous silicon grating working as wire grid polarizer for UV applications

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Wire grid polarizers are essential optical elements for various applications such as microscopy or imaging systems. A wire grid polarizer consists of a periodical arrangement of conductive wires on a transparent substrate and provide a higher transmission for light with the electrical field vector perpendicular to the wires (TM polarization) than for the parallel counterpart (TE polarization). Furthermore, for an application in the UV spectral region a grating period of less then 200 nm is required. For the fabrication of the grating structure a high frequency resist pattern was generated using electron beam lithography and transferred into the amorphous silicon layer of 80 nm thickness by means of an ICP etching process. The optical characteristic of such a polarizer is a spectral working range of about 200 nm with a discrete maximum of the extinction ratio caused by a minimum in TE polarization. The extinction ratio is defined by the ratio of transmitted TM- and TE-polarized light. A decreasing of the grating period leads to a shifting of the maximum value of the extinction ratio to smaller wavelengths and an increasing of the same. To study these behavior gratings with a period of 140 nm and 120 nm were fabricated. The optical functionality is shown down to a wavelength of 300 nm and the maximum value of the extinction ratio for a period of 140 nm and 120 nm is 177 at a wavelength of 418 nm and 324 at a wavelength of 394 nm, respectively. Experimental and theoretical data are in good agreement.

8270-15, Session 5

Signal propagation effects in HCG hollow-core waveguides

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High-contrast grating (HCG) exhibits ultrahigh reflectivity over broad bandwidth. As light is highly-confined within the air core, HCG hollow-core waveguides (HW) can potentially achieve low loss, small chromatic dispersion, and negligible nonlinearity, simultaneously. It is thus quite promising for low distortion on-chip data communications and integrated systems. HCG-HW also exhibits broad bandwidth and large fabrication tolerance in terms of low distortion operation.

In this paper, we have explored the effects of the HCG-HW on high-speed digital and analog signal propagation. Due to the low distortion effects in HCG-HW, 100-Gb/s on-off keying (OOK) digital signals can transmit over tens of meters with small eye opening penalty (EOP). The EOP increases for higher bit-rate OOK signals, which is largely due to the chromatic dispersion. HCG-HW also provides a good transmission medium for analog signals. Even after 100-m propagation, there is almost no degradation for the third-order inter-modulation distortion (IM3) and the third-order harmonic distortion spur-free dynamic range (THD SFDR). Due to the chromatic dispersion, the second-order harmonic distortion (SHD) SFDR is limited to 107.3 dB/Hz1/2. In addition, HCG-HW shows large radio frequency and optical bandwidth for analog signal transmission. Due to the ultralow nonlinear coefficient, no nonlinearity-induced penalty is observed for both digital and analog signals. Furthermore, a tapped delay-line finite impulse response (FIR) matched filter is designed using HCG-HW. For a linearly chirped microwave pulse, the HCG-HW based matched filter can provide large SNR gain, which is >80% of a theoretical value that can be achieved with an ideal matched filter.

8270-16, Session 5

Optical phased array for far field beam steering with varied HCG

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Optical phased array (OPA) devices for far field beam steering offer expectantly well-known advantages for free-space optical communication systems as they have fast, light weight, and efficient beam scanning capabilities. In the past 30 years, many schemes have focused on the design and fabrication of the optical phase shifting device. However, it's very difficult to design and realize beam steering efficiently and simply. A challenge to the past, an optical phased array for far field beam steering with varied High-Contrast Grating (HCG) waveguides is proposed.

Such HCG waveguide's characteristics as high-reflective index and greater group delay will help to realize a smaller size, shorter coupling path, greater integration, higher diffraction efficiency, variable optical phase delay and greater array factor. Hence it is possible to control the beam steering and beam shape, and at the same time increase energy efficiency by decreasing the array complexity.

Simulation shows slow light waveguide output tunable phase with varied HCG dimensions or index. The far field beam steering effect is presented and will be seen clearly by add array element gradually.

8270-17, Session 5

Low-loss hollow-core waveguide using high-contrast sub-wavelength grating

J. E. Ferrara, Jr., W. Yang, A. Yeh, K. Grutter, C. Chase, V. Karagodsky, D. Parekh, Y. Yue, A. E. Willner, M. C. Wu, C. Chang-Hasnain, Univ. of California, Berkeley (United States)

Over the past few years, hollow-core waveguides have received much attention for their properties at wavelengths where traditional solid waveguides encounter difficulties such as excessive optical absorption and undesirable non-linear effects. They have emerged as excellent alternatives to integrated-circuit technology where immunity to electromagnetic interference, and high operating temperature environments are crucial to high-sensitivity sensors, such as in gaseous sensing. They are also used for other applications such as high-power optical delivery, optical pulse compression, and optical delay lines. Many designs have been shown to efficiently confine light in a hollow-core waveguide such as photonic crystal fibers, ARROW waveguides, and DBR reflectors. However, the reflection principles for these hollow-core waveguides require interactions with multiple layers of very precisely laid-out films, which can be cumbersome to fabricate and make them nearly impossible to form integrated optical components.

In this work, we present a novel form of hollow-core waveguiding that enables chip-scale integration. Light propagates in air along a zig-zag path between very highly-reflective Si metastructures comprised of a single layer of sub-wavelength high-contrast gratings (HCGs). Top and bottom subwavelength HCGs separated by 8um of air and with periodicity perpendicular to the propagation of light are capable of reflecting light at shallow angles with extremely low loss. The HCGs are patterned on SOI wafers with 340 nm-thick Si device layers engraved in a single etch step, and have been measured to have a ~0.4 dB/cm propagation loss. Our work demonstrates the light-guiding properties of HCG hollow-core waveguides with a novel form of lateral beam confinement that uses subtle reflection phase changes between core and cladding HCG regions (without the assistance of side reflectors), and is capable of bending light around 30 mm radius-of-curvature tracks.

8270-18, Session 6

Planar ultracompact silicon/polymer laser for the visible

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All-optical signal processing and short distance optical interconnects are gaining enormous interest due to the steady increase of bandwidth demand in telecommunication and IT industries. The required level of opto-electronic integration demands small form factor devices and new materials with tailored optical properties. For integration with silicon electronic circuits, a major constraint is the strong absorption of silicon at wavelengths below 1100 nm. Here, we demonstrate a hybrid silicon/polymer microlaser emitting at a wavelength of 495 nm based on an integrated planar Fabry-Pérot cavity. The highly reflective mirrors are realized by two periodic subwavelength-sized silicon high contrast gratings that rely on the interplay between diffraction and a phase/intensity engineering of the transmitted wave. Optical gain is provided under pulsed optical excitation by a conjugated ladder-type polymer, which covers these structures. Lasing threshold is below 30 pJ per pulse, and the emitted pulse duration is in the picosecond range. The size of the laser is reduced by an order of magnitude compared to established designs based on photonic bandgap structures. This extends silicon photonics into the visible wavelength range and allows harnessing large classes of opto-electronic materials, such as organic dyes, polymers, and colloidal quantum dots.

8270-19, Session 6

A planar silicon lens for integrated free space optics

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In spite of recent successes in the integration of photonic devices, free-space optics remains today an intrinsically non-planar technology using rather complex and expensive assembly processes. Diffractive optics elements using sub-wavelength binary patterns represent a favorable alternative. They modulate the field amplitude or phase spatial distribution to achieve focusing and other light bending effects. However to date diffractive optics remains quite marginal, confined to a few niche applications. While amplitude modulating elements suffer from poor efficiencies, phase modulating elements showing near ideal performance still require etched features with high aspect ratio in order to achieve an arbitrary phase front modulation. These features are hard to manufacture and sometimes mechanically unstable. In this paper, we show how the use of resonances in high contrast (silicon) non-uniform gratings can boost the phase differential of the transmitted phase front, allowing full wavefront manipulation with feature of aspect ratio less then 1:1. This new type of lens is trivial to fabricate via standard CMOS processes or emerging high volume production methods such as roll-to-roll imprinting. Complex optical systems comprising several optical layers can be accurately and cheaply manufactured in the same way.

8270-20, Session 6

Novel high efficiency vertical to in-plane optical coupler

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Silicon-on-insulator (SOI) waveguide devices are investigated actively for its application in high-density photonic integrated circuits (PIC) due to its strong light confinement and compatibility with standard complementary metal-oxide semiconductor (CMOS) technology. For broad integration, it is desirable to have efficient coupling between PICs and a surface-normal propagating light beam, e.g. output of an optical fiber or free-space optics, or device, e.g. vertical cavity surface emitting lasers (VCSEL). Grating couplers can enable such coupling without cleaving the in-plane devices, which can enable the integration between multicore fiber and in-plane waveguide array.

In this paper, we propose a novel high efficiency vertical to in-plane optical coupler. This structure has a high contrast grating locating upon the silicon waveguide with a certain low index gap. By utilizing the resonance nature of HCG, the coupling efficiency from surface normal incidence to in-plane waveguide can be increased to a total of 93% in both in-plane propagation directions with 50nm 3dB bandwidth. On the other hand, such structure also shows unique properties for the incidence from the waveguide. By varying the HCG dimensions, as period, thickness and duty cycle, the coupler structure can also be designed as in-plane reflector, transmitter or vertical coupler. As an in-plane reflector, a reflectivity of 97% is demonstrated. As an in-plane to vertical coupler, 96% coupling efficiency is achieved with 105nm 1dB bandwidth. Various applications, as WDM MUX and DeMUX, in-plane cavity surface emitting laser, etc, are to be discussed with the combination of the reflector, transmitter and vertical coupler configurations.

8270-21, Session 6

Design of second order grating couplers to detect the angle and polarization of the laser beam

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On-chip fast laser beam tracking finds innumerable applications in the fields of high speed optical interconnects, switches, laser printers, scanners, data conversion systems, alignments, robot visions, microscopy and satellite communications. Popularly used quadrant photodiodes (QPD) can only detect very small variation up to 0.2° reliably. We have designed a 1D high contrast grating coupler (to segregate one polarization only), whose ratio of the power coupled between the two branches gives the information regarding the incident angle of the laser beam. The finite-difference-time domain (FDTD) design shows detection until ±6 degrees but this range can be tuned depending on the incident power of the laser beam, sensitivity of the detector and the spectral-line width of the power coupled. Since the line-width of the grating can be tuned by the number of the grating periods, the sensitivity of such devices also can be easily controlled. A 2D grating coupler has also been designed which shows a high contrast polarization (TE/TM) selectivity greater than 10 over 25 nm wavelength range. Such compact couplers can be used for vertical to in-plane polarization-dependent beam routing, single-snapshot high contrast active imaging, finding the anisotropies within the materials and gas molecules. Since the device also gives the information of the direction of the beam it can be used for tracing a strong infrared source. Since these devices can couple light vertically, and can work properly even without any aperture, the compact packaging and wafer-scale testing is extremely convenient and no cleaved facets are required.

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8270-22, Session 7

Optical phase shifting based on high contrast grating waveguide

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In accordance with the development status and trend of wireless optical communication, we propose that the optical phased array (OPA) technology for wireless optical emission beam control has absolute predominance, such as offering inertialess and precise pointing, and a dynamic focus capability[1,2]. This paper proposes to apply OPA with High Contrast Grating (HCG) waveguide so as to achieve wireless optical transmission device. Such HCG waveguide's characteristics as high reflectivity and greater group delay will help to realize a smaller period, shorter coupling path, greater integration, greater array fill factor, higher diffraction efficiency and variable optical signal delay. Hence it is possible to control the beam steering and beam shape, and at the same time increase energy efficiency by decreasing the array complexity.

Conventional phase shifters need a high voltage but only get a small range of phase shift, which seriously limits the development of OPA. Besides, they are bulky and have high insertion loss. The framework of applying the HCG waveguides to OPA is illustrated in this paper. In this work, the HCG waveguide is demonstrated to construct the phase shifter with compact size, where the slow light property is adopted to enhance the phase change. In our design, the distance between two HCG waveguides is only 1.5um. In such a device, the wavelength tuning approach is applied to implement the angle steering. In our simulation, the tuning angle range is up to 21.17°, while the wavelength is varying from 1650nm to 1670nm. Based on our model of two waveguides, the phase shifters of multiple waveguides can be predicted to improve the steering angle result.

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8270-23, Session 7

Sub-diffraction engineering with high contrast dielectrics

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Structures made of high contrast dielectrics have gained a lot of research interest recently because of the guided mode resonance they supported. Various devices such as broad band, high reflectance dielectric mirror and planar focus lens have been designed and fabricated. In this presentation we show that guided mode resonance can also be harnessed to control light at sub-diffraction scale. Two devices made of high contrast dielectrics are discussed to demonstrate this idea. One is a new type of integrated optical cavity that support a resonant mode with most of the optical field standing in the open space. Compared to other integrated cavities such as photonic crystal defect cavity or micro-ring resonators where most of the field stands inside the dielectrics, here the resonant mode is readily accessible by particles such as atoms, molecules, quantum dots, etc., providing great convenience in applications such as cavity quantum electrodynamics, optical monipulation, optofluidics, etc. The other is a lens that is capable to achieve a focus of deep sub-diffraction size. The geometry is similar to a bull's eye structure but made of high contrast dielectrics. Compared to the plasmonic bull's eye structure, the current one possesses little material loss and resistive heating. Both structure are of completely planar geometry, thus are compatible with conventional micro-fabrication process. The design processes for each device that are based on stochastic optimization will also be introduced. We believe the capability of sub-diffraction engineering from structures of high contrast dielectrics is of great interests for this community.

8270-24, Session 7

Diffractive optical elements based on subwavelength high contrast gratings

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We report on novel concepts for reflective diffractive elements based on high contrast gratings (HCG). To illustrate the possibilities for such devices reflective cavity couplers with three output ports are investigated. In order to realize these three diffraction orders a diffracting period is superposed to a highly reflective HCG. This superposition can be realized with a periodic depth, fill factor or period modulation of the reflector. However, such a modulation of a HCG simultaneously also increases the amount of transmitted light, since the angular tolerance of these high contrast gratings is not large enough. We discuss different approaches in order to enhance the band width with respect to the angle of incidence. It is demonstrated that the angular tolerance can be enhanced by means of stacked reflectors. The functionality of these elements can be intelligibly understood by a decomposition of the stack into its single constituents. Another possibility is the use of gratings with a two-dimensional periodicity instead of 1-d gratings. Here, large reflectivities in the entire angular spectrum can already be retrieved with a single HCG giving rise to an easier fabrication. The contribution contains theoretical modelling and first experimental results. It focuses on the material combination silicon-silica, but the presented concepts also hold for other material combinations with large index contrast and even for monolithic silicon structures. The results can help to reduce the problem of coating thermal noise for optical elements in high-precision metrology.

8270-29, Session 7

High-contrast grating based planar light concentrators

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A new planar light concentrator design is proposed by using unique diffraction properties of high-contrast subwavelength gratings (HCGs). HCGs have the ability to diffract the incoming light at steep angles with very high efficiency. By integrating the HCGs on top of planar glass substrates, light can be guided in the glass leading to high concentration at the edges. Finite difference time domain simulation results show that concentration ratio close to 50 can be achieved by optimizing the grating parameters. These planar light concentrators find application in various areas including concentrated solar power, light pipes and spectrum splitters.

8270-25, Session 8

Acrobatics for thermal emission using metastructures

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In high temperature and vacuum applications, for which heat transfer is predominantly by radiation, the material's surface texture is of substantial importance. Control of thermal emission is of crucial concern in the design of infrared sources, in electronic chip coolants, in high-efficiency photovoltaic cells, and in solar energy conversion. Thermal emission has been shown to be modified by utilizing the high density of states of surface waves (surface plasmon polaritons and surface phonon polaritons) and their long-range propagation. We present subwavelength structures - metastructures supporting surface waves for obtaining polarization manipulation of thermal emission, extraordinary coherent thermal radiation, bandgap in the spectral emission, and a broadband infrared absorption. A spin-dependent dispersion splitting was obtained in a structure consisting of a coupled thermal antenna array. The effect is due to a spin-orbit interaction resulting from the dynamics of the surface waves propagating along the structure whose local anisotropy axis is rotated in space. The dispersion splitting due to the spin-orbit coupling is also known as the key feature in such remarkable effects as the Rashba splitting and the spin-Hall effect, which indicates the generic nature of the discussed phenomenon. The observation of the spin-symmetry breaking in thermal radiation paves the way to manipulate spontaneous emission with the photons' intrinsic degree of freedom and provides the basis for future spinoptics devices.

8270-26, Session 8

Low loss silica on silicon integrated waveguides

A. J. Maker, A. M. Armani, The Univ. of Southern California (United States)

Low-loss waveguides integrated on a silicon substrate are an essential component in the design and fabrication of photonic circuits. For this application, a wide operational bandwidth - from visible to infrared wavelengths - is critical. Previous research has yielded photonic crystal-based waveguides, slab waveguides and embedded waveguides, fabricated from various materials, including silicon, silicon nitride, various polymers and silica. Several of these devices have achieved low, <0.1dB/cm loss in either the visible or the near-IR. However, to obtain effective confinement of light from the visible through the near-IR, it is necessary to develop waveguides which have near-constant loss and minimal non-linear effects across the entire wavelength range.

To overcome this challenge, we have developed a novel silica on silicon waveguide fabricated using conventional lithographic techniques and CO_2 laser reflow. As a result of the etching steps used, the entire waveguide is elevated above the higher refractive index silicon substrate, providing complete optical isolation, and effectively creating an air-clad waveguide. The optical performance of the cylindrical waveguide was determined by coupling light from a series of lasers (658nm to 1550nm) into the waveguide using lensed optical fibers. As a result of the inherent low material loss of silica and the isolation from the silicon substrate, the device has low optical loss (0.7-0.9dB/cm) and linear behavior across the entire wavelength range. With low loss and linear performance, these on-chip waveguides will benefit many applications, including biodetection and integrated photonics.

8270-27, Session 8

Suspended silica beam splitters on silicon with large core-clad index difference

X. Zhang, A. Armani, The Univ. of Southern California (United States)

Optical beam splitters are one of the critical elements in constructing power splitters, modulators, interferometers and (de)multiplexers in integrated optical systems. Beam splitters based on numerous materials, including silicon, lithium niobate, and polymers have been demonstrated previously. However, silica is an attracting alternative because of its inherently very low material loss across a large wavelength range and low susceptibility to both thermal and electro-optic non-linear effects. On the other hand, achieving the required large core-clad refractive index contrast with silica is extremely challenging. In this work, silica splitters with an effective refractive index difference of approximately 0.4 (25%) between the core and clad is achieved. To fabricate the splitter, a dual step photolithography and BOE etching process is used to define the waveguide patterns, and then a XeF_2 etching is used to isotropically undercut the structure to isolate the silica waveguides from silicon; after that, a CO_2 laser is used to reflow the silica waveguides to create the smooth and circular waveguide channels. The splitter is characterized using a tunable 1550nm laser with lensed fiber. The output signal is focused directly into a beam profiler. The device splits power evenly with low crosstalk. The transmission spectrum is quite flat over a wide wavelength range from 1520 to 1630nm. In addition, the splitting ratio doesn't change when the power is changed over an order of magnitude and the output power increases linearly with the input power.

8270-28, Poster Session

Tuning the reflectivity of high contrast gratings based on silicon and silica by means of wet etching with hydrofluoric acid

T. Jacobitz, S. Kroker, T. Käsebier, B. Kley, A. Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

We report on experimental etching techniques to trim the efficiency of high contrast gratings based on silicon and silica. The performance of these gratings is strongly influenced by an interaction of the refractive indices of the materials surrounding the silicon grating with the grating period. In dependence of the fill factor of the silica grating the resonance wavelength can cover a maximal range of about 200 nm. We show that it is possible to tune this resonance wavelength and hence the reflectivity in a very well-directed manner by means of selectively etching the silica grating. This structure basically serves as spacer between the high-index grating made of silicon and the silicon substrate. In order to realize a well-defined adjustment of the grating profiles the etching rates of silica layers with hydrofluoric acid are determined. Acid concentrations of up to 10% are investigated and coatings deposited by different techniques such as electron-beam evaporation, ion plating and thermal oxidation are compared. Also the influence of structuration on the etching rates is investigated. Etching rates of up to 10 nm/min are found to be optimal for the fine adjustment of the silica grating's fill factor during the fabrication process. The work basically helps to improve the maximum reflectivity that can be realized with these high contrast reflectors.

Conference 8271: Quantum Dots and Nanostructures: Synthesis, Characterization, and Modeling IX

Tuesday-Wednesday 24-25 January 2012

Part of Proceedings of SPIE Vol. 8271 Quantum Dots and Nanostructures: Synthesis, Characterization, and Modeling IX

8271-01, Session 1

Quantum optics with nanowire quantum dots

V. Zwiller, Technische Univ. Delft (Netherlands)

Nanowires offer unprecedented freedom in the design of quantum structures. We will present our work on optical properties of quantum dots in nanowires for both emission and detection of light at the single photon level. Among the novel degrees of freedom, the crystal phase where segments of a nanowire can either be Wurtzite or Zincblende offers a new path to obtain quantum confinement. We will also discuss the possibility of obtaining high gain in a reverse biased pn junction nanowire and the possibility of detecting of single photons with a single nanowire device. In addition, light emitting diodes based on nanowire quantum dots enable high efficiency quantum LEDs where a single electron could be coherently turned into photons, providing a much needed interface for quantum information processing.

8271-02, Session 1

Hybrid optoelectronics for light harvesting and light emitting applications

P. G. Lagoudakis, Univ. of Southampton (United Kingdom)

We engineer resonance energy transfer into hybrid organic/inorganic and colloidal/epitaxial semiconductor nanostructures and utilize it as an efficient mechanism to couple these heterogeneous material systems leading to improved efficiencies both in photovoltaic solar and light emitting diode devices.

The brightness, large absorption cross-section and flexibility of colloidal nanocrystal quantum-dots (NQDs) and organic semiconductors render them promising new materials for light harvesting and light emitting applications. However, both classes of material are plagued by low-charge-transfer efficiency that limits the overall power conversion efficiency when compared to silicon-based or epitaxial p-n junction photovoltaics, and epitaxial light emitting diodes. A route to circumvent altogether issues associated to low charge transfer in NQDs and organic semiconductors is to engineer devices that utilize alternative energy transfer schemes to electrical injection and transport while still benefiting from their large oscillator strength.

In nature, funnelling of energy between different chromophores predominantly occurs through a nonradiative dipole-dipole coupling mechanism, commonly referred to as resonance energy transfer. Nonradiative energy transfer does not involve charge transfer or emission and absorption of photons between donor and acceptor and can exceed the radiative energy transfer routinely used in phosphor light emitting devices. Theoretical calculations predict that free quantum well excitons can undergo resonance energy transfer with an order of magnitude higher rate compared to localized, point-like dipole excitons exemplifying the potential of hybrid optoelectronic devices utilising resonance energy transfer as a means to overcome charge transfer related limitations. Here we will present recent advances in the new field of hybrid optoelectronics in architectures where nonradiative energy transfer is used to combine the high carrier mobility of single crystal inorganic semiconductor heterostructures and the versatility offered by colloidal NQDs and organic semiconductors both in light and light emitting applications[1-6].

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8271-03, Session 1

Effect of silver nanoparticles on the spectral properties of rare-earth ions in a sodium borate glass

V. O. Obadina, R. R. Bommareddi, Alabama A&M Univ. (United States)

We made a silver doped sodium borate glass with the composition 65% B_2O_3-33% Na_2CO_3 -2% AgO by the melt quenching technique. Appropriate amounts of the chemicals were mixed and then melted in a box furnace at 1400°C for 1.25 h. The glass was annealed at 200°C to minimize the stress. As made glass did not reveal any absorption or emission in the visible wavelength region. Differential scanning calorimetry (DSC) measurements revealed the glass transition temperature to be 467°C. The glass was heat treated at 520°C for 2 h. Heat treated glass also exhibited a slight change in color to slight yellowish brown. The resulting glass exhibited absorption at 417 nm. When the duration of heat treatment was doubled the absorption strength also increased. Under near resonant excitation it revealed a very strong peak at 423 nm on the Stokes side and a relatively weaker peak at 659 nm. The 423 nm peak is due to enhanced Raman scattering due to the presence of nanoparticles. When the sample was heat treated for 12 h the absorption peak shifted to 391 nm suggesting that the particle morphology changed. Optical images revealed some particles in the micron range of different colors. The particle density increased with the duration of heat treatment. We have prepared glasses embedded with Ag particles and rare-earth ions and investigating the influence of metallic particles on the spectral characteristics of the rare-earth ions and the nature of interaction between the silver particles and rare-earth ions.

8271-04, Session 1

Seeded CdSe/CdS nanorods for multi-photon absorption applications

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Over the last two decades, colloidal semiconductor quantum dots (QDs) has been intensively investigated for potential multi-photon absorption (MPA) applications (e.g. bio-imaging, upconversion lasing, three dimensional data storage and optical limiting etc). This is made possible by the unique characteristics of QDs: size-dependent optoelectronic properties, large MPA cross-sections, relatively high quantum yields, good photostability and flexible surface chemistry. MPA cross-sections of QDs have been found to increase with size, corresponding increase in the density of states. Hence increasing the MPA cross-sections of QDs without significantly degrading its quantum yield or altering its emission wavelength can be highly desirable for example, in multi-photon fluorescence imaging where greater signal may be achieved using less average incident power, thus minimizing sample damage. While the pronounced size-dependence of the emission of fluorescent QDs in the strong confinement regime presents a convenient way to achieve desired emission wavelengths by simply changing the dot size, however, it also simultaneously imposes severe restrictions on the ability to vary the absorption cross-section while maintaining the emission at a required wavelength. Thus from the stand point of wavelength-specific applications, increasing the MPA cross-section of a QD without significantly modifying its size-dependent emission is an important and yet non-trivial challenge to overcome. Herein, we present a clear strategy to enhance the multi-photon absorption (MPA) cross-sections whilst independently tuning the emissive wavelengths of semiconductor QDs using seeded CdSe/CdS nanorod heterostructures is presented. Nonlinear optical properties and carrier dynamics of these nanorod will also be presented.

8271-05, Session 1

Optical properties of mesogen-coated gold nanoparticle self-assemblies

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Self-assembled ordered arrays of nanoparticles are currently attracting great interest due to their potential applications in optics and photonics. In this contribution, we investigate experimentally and theoretically the optical properties of gold nanoparticles (NPs) functionalized with mesogenic ligands. Rod-like nematic liquid crystal molecules are grafted side-on to the NP surface following a ligand exchange reaction. X-ray scattering experiments have revealed that such coatings strongly influences the NP self-assembly, leading to unusual 3D arrangements like the columnar NP chains recently observed. The alignment of the calamitic mesogens introduce an anisotropy in the NP packing geometry, resulting in the formation of strings of NPs surrounded by a sheath of axially aligned mesogens. The combined effect of the ligand's birefringence and the anisotropic arrangement of the plasmonic NPs leads to a strong polarization dependence of the metamaterial's optical properties. To benefit from such effects, we prepared thin films by shearing on solid substrates, so as to induce an in-plane orientation. The alignment of the mesogenic ligands was evidenced by optical polarizing microscopy (OPM) observations. Furthermore, optical spectroscopy reveals a strong dichroic behavior as shown by the huge shift of the plasmonic absorption peak when the linear polarization of the illumination is rotated. The analysis of this shift by rigorous numerical electromagnetic simulations gives evidence that the origin of this enhanced dichroism is due to both the chain-like organization of the NPs and the ligand's birefringence. These results demonstrate the ability to fabricate a self ordered and tunable metamaterial by chemical engineering of the NP ligands.

8271-07, Session 2

Quantum dot enabling coherence barcoding technology

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We present in this conference a coherent optical coding scheme with quantum dot (QD) embedded-microbeads: multicolor QDs in the structure-engineered spherical beads will produce a set of wavelengths of stimulated emission of Whispering Gallery modes, offering a unique identification signature to the beads. The coherent, spectrally-narrow laser emission from the microbeads will overcome the spectral overlap limit and dramatically increase the coding capacity of the QD-encoded microbeads. Stimulated emission from the QD-microbeads has recently been demonstrated in the PI's laboratory. Sharp lasing peaks were observed rising from the spontaneous emission background, which spectrally match the calculated the Whispering Gallery modes with the given microbead size.

8271-08, Session 2

Morphology, optical properties, charge transfer, and charge transport in nanocrystalline quantum dots

M. Dutta, Univ. of Illinois at Chicago (United States)

Structural, optical and electrical studies of several hybrids of organic and inorganic nanostructures as well as core shell nanocrystalline structures will be presented. The effects of thermal annealing on the morphological and photoconductive properties of cadmium selenide quantum dots coreshell quantum dots together with indicate that there are collective events happening due to annealing. Two different types of hybrid structures will be discussed. Optical and electrical experimental results in semiconductor nanostructures in conductive polymers as well as those that were integrated into the organic photosystem I (PS1), as part of an artificial light harvesting complex (LHC) will be presented.

8271-09, Session 2

Transport properties of mid infrared colloidal quantum dot films

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Colloidal quantum dots (CQD) have been studied for more than twenty years and are a suitable way to achieve low-cost devices for optoelectronic applications. To reach long wavelengths for mid-infrared detection or emission, two issues are: (i) the growth of CQD of a small energy gap material and (ii) the competition between the excitonic absorption and the vibrational absorption due to the presence of organic ligands which provide their colloidal stability. HgTe, as a gapless semiconductor, is a good candidate for the mid-infrared. We recently demonstrated photodetection with cut-off wavelengths between 1.7 and 7μm with HgTe CQD of sizes less than or around 10 nm. These preliminary materials where highly aggregated and exhibited a relatively large 1/f noise.

More recently we developed a synthesis which leads to better dispersed CQD, with a well defined excitonic peak in the mid-infrared. As commonly seen with CQD, the as-drop-cast films are insulating, I will describe several processing methods that render the films conductive. Results of ligand exchange, atomic layer deposition and chemical bath deposition will be presented. I will discuss the transport and thermal properties of the optimized new material. In particular, the conductivity of films of these small gap HgTe colloidal quantum dots is strongly temperature dependent, with effects arising both from the intrinsic carrier density as well as from extrinsic doping.

8271-10, Session 2

Fourier spectroscopy on PbS quantum dots

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Colloidal PbS quantum dots (QDs) have attracted ongoing research interests in the past few years. The attraction is carried by both basic research on quantum confined systems and potential applications in optoelectronics and photonics. The advantage of colloidal PbS systems is the fairly straightforward way of sample production. We present an overview of our research on PbS QDs (≈5 nm) formed by a supercritical CO2 fluid process or dispersed by solution deposition onto glass and commercial GaAs wafers. For the characterization of the optical properties we employed BOMEM Fourier spectrometers. The advantage of this technique is its enhanced sensitivity with respect to monochromator-based experiments, enabling large signal-to-noise ratios at comparable low excitation intensities, which are crucial for photoluminescence experiments in order to produce repeatable results. Our data analysis focused on the correlation between Debye temperature and thermally induced band gap variations, whereas the comparison of emission and transmission experiments demonstrates clearly that the absorption related features reveal the intrinsic QDs properties. Another key point of our work is the investigation of the thermal Stokes shift shrinkage between photoluminescence and absorption edge. Our combined transmission and emission results demonstrate that the bleaching temperature of the Stokes shift corresponds to the sum of prominent PbS phonon energies. Finally, our research encompasses a novel aspect of QD application - not the investigation of the QDs itself, but rather their influence on the optical properties of the substrate material. Particularly, we discuss the emission enhancement of GaAs substrates covered with PbS QDs.

8271-11, Session 2

Trap state lifetime analysis of single CdSe/ZnS quantum dots on a thin conductive film

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Colloidal quantum dots (QDs), because of high emission efficiency and wide selectivity of emission wavelength, have been the materials of choice for composing ultra-small optoelectronic devices such as single-photon sources, light emitting devices, and transistors. However, a significant drawback is that the blinking behavior of single QDs reduces emission efficiency, which limits their application to optoelectronic devices. Because the blinking occurs due to the capture of photocarriers from QDs to surface or outside trap state, not only blinking behavior but also trap state should be strongly affected by the substrate. In this paper, to clarify the substrate influence on the emission dynamics of CdSe/ZnS QDs, we measured the trap state lifetimes of single QDs on different substrates (ITO thin film, gold thin film, and glass substrates) using photon statistical analysis methods. From the results, the blinking suppression was observed and the trap state lifetimes as well as the emission counting rates were reduced on ITO and gold thin film substrates. However, on a gold thin film, the reductions of the excited lifetime were observed, while on an ITO thin film substrate, there is little change in the excited state lifetime. Thus, we concluded that the origins of the blinking suppression on a gold and ITO substrates are different, that is, the blinking suppression is due to the fast energy transfer from the excited state on a gold thin film, while that is due to the fast charge transfer from the trap state on an ITO substrate.

8271-12, Session 3

Atomic structure of submonolayer InAs/GaAs depositions for high-speed direct electro-optical data transmission in VCSELs

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Quantum dots (QD) formed from submonolayer depositions are an alternative to QDs grown using the Stranski-Krastanow mode. Submonolayer depositions are expected to yield exceedingly high QD densities above 1011 cm-2 and therefore bear the potential to produce high optical gain for laser devices. Vertical emitting lasers based on InAs/GaAs submonolayer QDs recently demonstrated high-speed error-free operation up to 28 Gb/s and up to 120°C.

We report a fundamental analysis of the atomic structure to understand the growth and we can show the actual spatial structure as applied in VCSEL devices. The investigated structures were grown by MOCVD and contain stacks of 0.5 ML InAs, with GaAs separation layers of 1.5 ML, 2.8 ML, 4 ML, and 16 ML. XSTM measurements demonstrate clearly an island formation instead of a layer-like structure. The InAs is not assembled within single atomic planes, but segregated along growth direction. At each layer where 0.5 ML InAs was deposited, the measured InAs concentration jumps up to $x_{In} \approx$ 15-20%, followed by an exponential decrease. Independent of the GaAs spacer layers a segregation coefficient of ~0.73 was determined. For stacks with 1.5-2.8 ML GaAs separation layers-in the typical range of VCSEL device applications-the In segregates already into the subsequently deposited submonolayers. This result is further supported by photoluminescence measurements, showing that the lateral electronic coupling of the dense InAs-agglomerations within the InAs submonolayer depositions leads to a mixed contribution of localized (0D) and quantum well (2D) states to the excitonic emission.

8271-13, Session 3

Single photon sources for quantum information applications

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Efficient sources of indistinguishable single photons are a key resource for various applications in fields like quantum sensing, quantum metrology and quantum information processing. In this contribution we report on single photon generation based on III-V semiconductor quantum dots (QDs). To increase the emission efficiency and the indistinguishability of the generated single photons, it is essential to tailor the radiative properties of the quantum dot emitters by engineering their photonic environment. We present optimized single photon emitters being based on both micropillar and photonics crystal cavities, for applications in a vertical platform and on-chip in-plane platform, respectively.

8271-14, Session 3

Reducing dephasing in coupled quantum dot-cavity systems by engineering the carrier wavefunctions

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It is well-known that dephasing plays a major role in semiconductor cavity QED systems, and that this effect deteriorates the properties of, e.g., photonic crystal and micropillar realizations of single-photon sources. Even at low temperatures, scattering with phonons leads to decoherence.

The phonon properties may be altered by engineering structures with localized phonon modes [1], such as "phononic" crystal structures [2]. In this contribution we suggest another approach for reducing phonon-induced dephasing, which relies on the asymmetry between electron and hole wavefunctions in the quantum dot. Commonly, in the literature this asymmetry is neglected in analyses of phonon-mediated dephasing effects in semiconductors [3,4]. Our calculations show, that for a cavity QED system with the cavity and quantum dot tuned out of resonance, these assumptions neglect important dynamics.

Our starting point is a recently published theory [5], which considers longitudinal acoustic phonons described by a non-Markovian model interacting with a coupled quantum dot-cavity system. The model is extended to include more realistic carrier wavefunctions. We demonstrate that for idealized spherical, but unequal, electron and hole wavefunctions there exists a non-zero cavity detuning where the phonon scattering is identically zero. The effect is due to a balancing between the carrier deformation potentials and the wavefunction asymmetry. For realistic truncated conical QD structures, analyzed by FEM calculations, a complete suppression of phonon scattering is not observed, but an optimal cavity detuning is still present where the phonon-induced pure dephasing is strongly reduced. We believe this effect can be important for engineering the coherence properties of state-of-the-art QD-cavity structures.

[1] Gavartin et. al., PRL 106, 203902 (2011)

[2] A. Safavi-Naeini and O. Painter, Optics Express Vol. 18 No. 14, 14926 (2010)

[3] U. Hohenester, Phys. Rev. B 81, 155303 (2010)

[4] C. Roy and S. John, Phys. Rev. A 81, 023817 (2010)

[5] P. Kaer et. al., PRL 104, 157401 (2010)

8271-15, Session 3

A room temperature single photon source based on self-organized quantum dots

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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, including colloidal quantum dots, color centers in diamond and self organized semiconductor quantum dots. The latter are especially attractive for an easy integration into compact, electrically driven devices. However, no room temperature single photon emission has been demonstrated for any kind of self-assembled quantum dots so far.

In this contribution, we report for the first time on single photon emission at room temperature from a single, epitaxially grown quantum dot. For that purpose, we prepared self organized CdSe quantum dots embedded between ZnSSe/MgS barriers to provide high quantum efficiency at elevated temperatures. Individual quantum dots are selected by nanostructured metal apertures with diameters down to 200 nm. In photoluminescence, we can track single quantum dot emission up to room temperature in spite of a significant broadening (25 meV) of the quantum dot emission due to phonon interaction.

Photon correlation measurements were performed using a Hanbury-Brown_Twiss-Setup. Even under continuous wave laser excitation, a striking antibunching behavior at room temperature is found. Second-order correlation measurements reveal a surprisingly low value of $g(2)(\tau) = 0.1$ for zero time delay without background subtraction. This confirms the high potential of these quantum dots for future single photon emitting devices operating under ambient conditions.

8271-16, Session 3

Full characterization of an optical field from an InAs quantum dot

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Quantum dots (QDs) are promising nodes for quantum information processing, both as logic gates and sources of nonclassical light. The most important criterion for a QD to serve as a source of single photons is indistinguishability of the emitted photons. We study InAs-based strain-induced QDs, surrounded by GaAs, grown using molecular-beam epitaxy. The QD is fabricated in a planar microcavity. The QD is excited with a pulsed laser, and its emission is coupled into a single-mode optical fiber. We perform full time-dependent characterization of the field emitted by a quantum dot by beamsplitter interference and coincidence detection (Hong-Ou-Mandel (HOM) interferometry). Temporal evolution of the HOM interference provides a measurement of indistinguishability and relates it to characteristics of the emitted field: its temporal extent, spectral (coherence) properties, and the probability of multi-photon emission. Further, apply this result to study the temporal dynamics of excitation and radiative decay of excitons in a QD.

8271-17, Session 3

Telecom band single quantum dots and dot ensembles at elevated temperature

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We investigate the temperature stability and excitation transfer mechanisms of high density InAs/InGaAlAs quantum dots (QDs) grown on InP(311)B substrates, which are important aspects for both QD-laser and single-dot (single-photon) applications. The QD photoluminescence ranges from 1.2 to 1.6 µm including the telecommunication O and C bands and thus can be tuned to the desired wavelength, e.g., by controlling the operation temperature or changing the dot size. The photoluminescence from QD ensembles, selected sub-ensembles and individual QDs was measured at temperatures between 4 and 300 K. To access a small number - and even individual - dots, we fabricated metal-embedded, nanometer sized, tapered mesas with the InP substrate removed, which furthermore allow for a high photon extraction along the optical axis [J.-H. Huh, et al., Jap. J. Appl. Phys. 50 (2011) 06GG02]. All these experiments indicate that the InAs dot samples exhibit no wetting layer - or at least that the dots are not coupled to it - and that the thermal quenching and carrier escape is closely related to the optical gap between QD and InGaAlAs barrier energy. The suggested escape mechanism is correlated electron-hole-pair escape with a typical thermal activation energy corresponding to half the optical gap. The excitation transfer between QDs is investigated for increasing temperatures and proves the transfer to the lowest energy dots which are found to be the most stable in terms of elevated operation temperature. Clear single-dot photoluminescence was observed up to 160 K including the technically relevant liquid Nitrogen temperature of 77 K.

8271-18, Session 4

Evolution of micro-spikes on silicon surface etched by femtosecond laser with different fabrication conditions

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We fabricated micro-spikes on the surface of silicon by using femtosecond laser. By changing the fabrication condition, i.e., the power of laser, the number of laser pulses, the wavelength of laser, and the proportional relation between laser power and pulse number under the same laser fluence, we found many interesting phenomena, which proved there was a relation between laser parameters on the surface morphology. All these results are important for the optimum fabrication of surface micro-structured photovoltaic material with high absorptance and good photoelectric properties, for the practical applications for solar cell, et al.

8271-19, Session 4

Supercontinuum laser for dense nanomaterials characterization and modeling

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Recent innovations in Supercontinuum or “white” laser sources provide a very useful tool to probe nanomaterials physical and optical properties. Onera, the French Aerospace Lab, has developed a fast, in-line and comprehensive optical characterization method. From the combination of hyperspectral, polarized and angular measurements, physical properties of dense nanomaterials are retrieved. Based on achieved results, modeling and inversion techniques are presented to retrieve simultaneously Particle Size Distribution, shape, optical thickness, albedo and refractive index. This technique is applied to a wide range of nanomaterials in suspensions: polymer, metal-oxide (ZnO, TiO_2...) or metallic (Au, Ag) nanoparticles and/or nanowires. Furthermore, prospective applications will be discussed in various fields as chemical atmospheric (eg. aerosol characterization) or aeronautical industries (eg. structures, paint coatings), remote-sensing or laser-imaging...

8271-20, Session 4

Influence of impurities on the luminescence of erbium-doped barium titanate nanophosphors

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In this work, we performed structural and optical characterization of erbium (Er^{3+}) doped barium titanate nanocrystals, synthesized by the sol-emulsion-gel, in order to evaluate the influence of the nanocrystals size and the presence of impurities related to barium carbonate ($BaCO_3$) on the fluorescence emitted by this material. We investigated nanocrystals produced at two different calcination temperature, 700 and 850oC, using Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD) and photoluminescence. From the results of FTIR measurements, we identified the presence of $BaCO_3$ in all samples. While, through the XRD, we characterized the crystalline structure of these materials, estimated the average diameter of nanocrystals of barium titanate and identified the secondary phases related to $BaCO_3$. We found that the studied $BaTiO_3$ nanocrystals showed a cubic structure and the average diameter of crystallites calcined at 700oC, 22.9 nm, is smaller than that obtained for the samples calcined at 850oC, 26.8 nm. Using the Rietveld refinement, the quantification of phases in the diffractograms obtained experimentally was made. We observed that the samples calcined at 700oC have a relative amount of $BaCO_3$ of 9.88%, which is approximately twice that found for the sample produced at 850oC. Finally, the optical measurements showed that the fluorescence intensity is higher for samples grown at 850oC. Our results indicate that the presence of $BaCO_3$ is the main reason for the difference in luminescence efficiency observed for these two systems and, therefore, it is thus an important parameter to be observed in order to obtain more efficient nanophosphors.

8271-21, Session 5

Semiconductor quantum nanostructures by droplet epitaxy

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What makes three dimensional semiconductor quantum nanostructures (QN) so attractive is the possibility to tune their electronic properties by careful design of their size and composition. An often overlooked parameter, which has an even more relevant effect on the electronic properties of the QN, is shape. Gaining a strong control over the electronic properties via shape tuning is the key to access subtle electronic design possibilities. The Dropled Epitaxy (DE) is an innovative growth method for the fabrication of quantum nanostructures with highly designable shapes and complex morphologies. With DE it is possible to combine different nanostructures, namely quantum dots, quantum rings and quantum disks, with tunable sizes and densities, into a single multi-function nanostructure, thus allowing an unprecedented control over electronic properties...

8271-22, Session 5

Self-running gallium droplets on GaAs surface

G. J. Salamo, Univ. of Arkansas (United States)

In this presentation we will discuss self-driven liquid gallium droplet movement on a GaAs (001) surface. The nanoscale footprints of a primary droplet trail and ordered secondary droplets along primary droplet trails are observed on the GaAs surface. A well ordered nanoterrace from the trail is left behind by a running droplet. In addition, collision events between two running droplets are investigated. The exposed fresh surface after a collision demonstrates a superior evaporation property. Based on the observation of droplet evolution at different stages as well as nanoscale pathways, a schematic diagram of droplet evolution is outlined in an attempt to understand the phenomenon of stick-slip droplet motion on the GaAs surface. The present study adds another piece of work to obtain the physical picture of a stick-slip self-driven mechanism in nanoscale, bridging nano and micro systems.

8271-23, Session 5

The impact of growth rate and barrier thickness on the thermal stability of photoluminescence for coupled InAs/GaAs quantum dot heterostructures with quaternary(InAlGaAs) capping

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Multilayer (10 layered) quantum dots were grown using solid source molecular beam epitaxy. Seed layer of InAs QDs was grown at 520°C over 1000Å intrinsic GaAs layer on semi-insulating GaAs (001) substrates and capped with 30Å quaternary $In_{0.21}Al_{0.21}Ga_{0.58}As$ and 90Å intrinsic GaAs layer for samples A and B, while for sample C it was 20Å and 80Å. Growth rate was 0.2011 ML/s for samples A and C whereas it is 0.094 ML/s for sample B. Each coupled active sample was annealed at 650°C, 700°C, 750°C and 800°C. Higher growth rate generated more strain in samples A and C producing more dot families and for sample B these increased with annealing because of the interdiffusion of constituents among the QDs. 750°C annealed samples A and C showed higher integrated PL intensity and activation energy because carriers found lower minimum energy states for relaxation, attributed to higher growth rate. In/Ga interdiffusion caused blue shift in photoluminescence(PL) spectra for samples B and C at higher annealing temperatures, whereas due to greater capping layer thickness almost no shift for sample A due to intermixing of In-Al between the quaternary alloy and wetting layer. Decrease in FWHM due to enhanced carrier relaxation is counterbalanced by non-resonant multi-phonon assisted tunneling processes (which dominates above 250K), suggesting good uniformity. *Our research is first on quaternary $In_{0.21}Al_{0.21}Ga_{0.58}As$ capped InAs/GaAs QDs with varying QD growth conditions predicting probable applications in lasers and solar cells.* DST, India is acknowledged.

8271-24, Session 5

Ground state energy trend in single and multilayered coupled InAs/GaAs QDs capped with InGaAs layers: effect of thickness of InGaAs layer and the RTA treatment

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Vertically coupled multilayered InAs/GaAs QDs covered with thin InGaAs strain reducing layer (SRL) is interesting to address today's technological demand. We report low temperature photoluminescence (PL) investigations for such single and multilayered structures grown using MBE, where SRL thickness is varied. Use of SRL layer within structures is observed to be responsible for high activation energies (E_o) indicating the reduction of the electron phonon interaction in QDs. Deviation of experimental data with Varshni's model suggests that InAs QDs have different properties than the bulk. Extracted theoretical values of E_o are observed to be much higher than that of bulk InAs, while the values of $\beta \geq 120$ K which are close to InGaAs suggests the strong effect of misfit stress and the quantum confinement effects in the structures. Anomalous behavior of ground state (GS) peak linewidth observed especially for annealed multilayer structures indicates probable inter diffusion of In/Ga atoms between QDs and barrier layers. Blue shift of GS peak position with broadened linewidth with loss of intensity in case of 800°C annealed samples can be due to strain driven alloy decomposition as a result of adatom interdiffusion. Presence of SRL layer is observed to prevent the formation of the non radiative centers at high temperature annealing, which usually causes sharp decrease in E_a. This indicates the importance of such structures to be used in optoelectronic applications where the structures are sandwiched between high temperatures grown AlGaAs cladding layers. Acknowledgment: DST, India for financial support.

8271-25, Session 5

III-Sb semiconductor nanopillars grown by selective-area epitaxy

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We demonstrate the synthesis and materials characterization of vertical III-Sb nanopillars (NPs) on highly lattice-mismatched substrates by selective-area epitaxy. Traditional antimonide-based devices are grown on their expensive native substrates. Utilizing the NP approach, III-Sb NPs can be realized on less expensive platforms, making these devices more cost effective. Highly ordered InSb and GaSb NPs are grown on InAs and GaAs (111)B substrates, respectively, patterned with a SiO_2 growth mask (25-nm thick) using a low-pressure (60 torr) vertical Emcore metal-organic chemical vapor deposition (MOCVD) reactor. The pillars have a diameter ranging from 100-300 nm and height from 0.5-1.5 µm. Transmission electron microscopy (TEM) is used to characterize the NP and the interface between pillar and substrate. The III-Sb NPs have reduced twinning compared to that of III-As pillars, indicating better NP crystallographic quality as the twinning can significantly increase carrier scattering in the pillar. Despite the large lattice mismatch (~7.8% for GaSb/GaAs and 6.5% for InSb/InAs), high-resolution TEM reveals no defects at the interface. Strain mapping by geometric phase analysis using STEMCELL [1] shows that the strain is relieved within a few monolayers at the interface and does not propagate into the NP region. Overall, we show highly ordered arrays of III-Sb NPs synthesized under extreme lattice mismatched conditions. Materials characterization by TEM indicates good and defect free NP quality. These III-Sb NPs have potential in the near and mid-infrared range as detectors and emitters.

[1] Grillo, STEM-CELL; available online at http://tem.s3.infm.it/software.

8271-26, Session 5

Carrier dynamic in a hybrid nanostructure with GaSb quantum dots coupled to an InGaAs/GaAs quantum well

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This work investigates the carrier dynamics in a hybrid quantum structure with the self-assembled GaSb/GaAs QDs coupled to an $In_{0.12}Ga_{0.88}As$/GaAs quantum well (QW) through a 3.5 nm GaAs spacer layer. A new transition (QW-QD transition) from the confined electrons in the $In_{0.12}Ga_{0.88}As$ QW to the confined holes in the QDs is observed in the photoluminescence (PL) at a longer wavelength in comparison to the reference GaSb QD structure, offering an alternate approach to extend the QD emission wavelength to 1.55 µm. The hybrid structure also exhibits stronger PL efficiency due to the excess holes tunneling from the QW to the QDs and wetting layer. The tunneling time is experimentally measured to be as fast as ~30 ps under weak excitation condition. Further, the QW-QD transition is type II in nature as verified by the blue-shift of the QW-QD peak with increase in excitation power, a long emission decay time constant, and by a theoretical simulation of the band structure. The larger blue-shift of the QW-QD PL peak (~225 meV) in the hybrid structure compared to that in the reference GaSb QDs (~95 meV) indicates an enhanced coulomb interaction due to the increase in carrier density. This coupled hybrid structure provides the flexibility to engineer the type II band structure for fabrication of opto-electronic devices, including high frequency QD lasers and QD optical modulators.

8271-27, Session 5

Increase in photoluminescence intensity of InAs columnar quantum dots on InP(001) substrate by increasing indium and phosphorous composition in InGaAsP barrier layers

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Electronically-coupled InAs columnar quantum dots (CQDs) on an InP substrate, composed of multi-stacked InAs QDs and thin InGaAsP barrier layers, are promising candidate for an active media of semiconductor optical amplifier (SOA) at 1.55 µm. The features of CQDs are that we can control photoluminescence (PL) wavelength and polarization of CQDs by changing stacking number of InAs QDs as well as thickness and strain of InGaAsP barrier layers. For highly efficient operation of SOA, CQDs with good crystallinity is required. In this study we investigated the influence of the composition of InGaAsP barrier layers on the stacking InAs QDs and the crystallinity of CQDs. We fabricated 12-fold InAs CQDs with different InGaAsP barrier layers by metalorganic vapor phase epitaxy. The bandgap wavelength (λg) of InGaAsP barrier layers were set to 1.26 µm, 1.15 µm and 1.05 µm, corresponding to P composition of 0.4, 0.6 and 0.7, respectively. As λg of barrier layers became short, PL spectra blue-shifted due to increase of quantum confinement effect. Also PL intensity increased about two times as λg of barrier layers became short from 1.26 µm to 1.05 µm, which is independent of the strain of barrier layers. From transmission electron microscopy measurements, surface roughning of CQDs layers and some dislocations were observed as phosphorous composition of barrier layers was decreased, which resulted in the decrease in PL intensity. We believe that increasing phosphorous composition in barrier layers is effective for improving the quality of CQDs.

8271-29, Session 6

Improvement of temperature stability in columnar quantum dots by introducing side barriers with larger bandgap energy for semiconductor optical amplifiers

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We have investigated the temperature dependence of InAs columnar quantum dots (CQDs) surrounded by InGaAsP barriers with different bandgap energies toward high-temperature performance for semiconductor optical amplifiers. It was found that larger bandgap energy in InGaAsP side barriers enabled to increase the quasi-Fermi level separation between the conduction and valence bands from theory. We have fabricated two types of CQD-SOAs with different side barrier energies and compared temperature characteristics. Decrease in the material gains for CQD with a larger side barrier bandgap was suppressed by 20% with increasing temperature from 25 °C to 85°C.

8271-30, Session 6

1.55um InAs/GaAs quantum dot semiconductor saturable absorber mirror

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GaAs based near infrared 1.3-1.55 µm photonic devices have attracted great attention due to low cost, high heat conductivity, and larger band offsets and contrasts of refractive index between the constituent heteropairs, exhibiting a number of advantages over the commercial InP based counterparts. Optical devices working at ~1.55µm play very important roles in major fiber-optic communication systems. Compared to 1.3µm GaAs technology, accessing this wavelength poses significant challenges in materials science and engineering. Capping InAs/GaAs quantum dots (QDs) with quaternary InGaNAs or InGaAsSb layers could result in light emission at 1.5µm, but significantly complicates the epitaxial growth process with strong degradation of optical and material quality of QDs. Over 1.5µm emission wavelength could be obtained from an InAs/GaAs QD structure grown on a thick metamorphic InGaAs buffer layers but repeatability and reliability are issues for such structures.

In this paper, InAs QDs inserted in an asymmetric InGaAs quantum well structure has been proposed and demonstrated to significantly improve the optical quality of 1.55 µm QDs. Both structural and luminescence characteristics have been investigated for these QD samples by atomic force microscopy, transmission electron microscopy and photoluminescence. In addition, to the best of our knowledge, the first QD semiconductor saturable absorber mirror (QD-SESAM) mode-locked laser at 1.55µm has been realized exhibiting 7ps pulse width, without dispersion compensation, from a 60MHz pulse repetition rate Er doped laser. The high dot density and strong photoluminescence emission from these 1.55µm InGaAs/GaAs QD structure make them very promising for many other photonic device applications.

8271-31, Session 6

Optical noise and alpha-factor in inhomogeneous quantum dot ensemble

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Optical noise and alpha-factor in quantum dot lasers have been studied theoretically. The conventional Langevin approach was applied to study intensity noise of the quantum dot laser. Inhomogeneous broadening and gain compression that play major roles in formation of a lasing spectrum of the quantum dot laser and their impact on laser noise were discussed in details in our examination. We found that semiclassical description predicts qualitatively same behaviour for a quantum dot laser as compared to the case of a quantum well. It contradicts the experiments on multi-mode comb lasers where mode partition noise in quantum dot laser was demonstrated to be suppressed. The origin of this contradiction is discussed in terms of complicated charge carrier dynamics in quantum dot ensemble and details of laser design. The charge carrier dynamics also significantly influences the value of alpha-factor in the quantum dot laser operating far above the threshold. We demonstrated that redistribution of carriers between quantum dots with different energies of optical transitions as well as between ground and excited states in the quantum dot are of key importance. Filling of the excited states in the quantum dots may seriously increase alpha-factor to the values higher than unity. We also demonstrated that due to slow carrier relaxation in quantum dots alpha-factor can be frequency dependent. That fact is important to compare experimental data obtained by different techniques and also to study laser properties such as jitter.

8271-06, Poster Session

Computational analysis of the effects of gain material in engineered metal nanostructures

J. Duan, R. Pachter, Air Force Research Lab. (United States)

Compensation for loss in optical metamaterials by introducing gain media has been suggested by Ramakrishna and Pendry (Phys. Rev. B, 67, 201101, 2003). Although progress was made in this area experimentally, analysis of the effects of gain material inclusion for various engineered metal nanostructures to mitigate loss has not been systematically carried out. In this work, we analyze engineered nanostructures with gain material inclusions by applying finite-difference-time-domain simulations. The changes in transmittance, absorption, reflection, were analyzed for an Au NR assembly embedded with InP quantum dots and a fishnet structure with and without inclusion of InAs quantum dots. The results demonstrated that the impedance match was essential for improving transmittance when gain included, and the stronger local electric field strengthened the coupling with gain and made compensation of loss in the system easier.

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8272-02, Session 1

Rare-earth doped YAG nanoparticles for high- and super-resolution upconversion imaging

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Rare-earth ion dopants can yield upconverted fluorescence whose wavelength is shorter than that of the excitation light.

In our work, we study upconverted fluorescence of rare-earth doped yttrium aluminium garnet (YAG) nanoparticles prepared by sol-gel method. Three upconversion mechanisms are observed: two-step excitation, sensitized upconversion, and photon avalanche upconversion. Results of background-free upconversion microscopy of YAG nanoparticles doped with praseodymium, erbium, and thulium are presented. Praseodymium ultraviolet fluorescence can be excited by two-step excitation in the visible. Erbium upconverted green fluorescence can be excited by a number of wavelengths in the red and infrared regions owing to either two-step or avalanche upconversion. Thulium-doped nanoparticles exhibit strong orange-to-blue avalanche upconversion. Upconverted fluorescence in all three species can be sensitized by co-doping with ytterbium. All three species of nanoparticles appear to be absolutely photostable and non-blinking. In addition, super-resolution microscopy similar to stimulated emission depletion (STED) microscopy was demonstrated on Pr:YAG nanoparticles yielding all-optical resolution of 50nm limited mostly by the nanoparticle size. Cytotoxicity tests performed on HeLa cells show harmlessness of YAG nanoparticles. The later fact makes them good candidates for background-free upconversion intracellular imaging. Apart from bio-applications, search for single rare-earth emitting centers in YAG is in progress. Particlularly interesting candidates are trivalent cerium and praseodymium ions. If detected, electron spin of cerium ion at room temperature and nuclear spin of praseodimuim at cryogenic temperature can be manipulated all-optically.

8272-03, Session 1

Nanodiamonds pave the way for fluorescent quantum probes in biology

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Defect centres in diamond have long been identified as promising quantum systems for future communication and computation applications. However, in light of recent experimental demonstrations[1, 2] these single spin systems may find new applications in biology as fluorescent “quantum” probes[3]. The nitrogen-vacancy (NV) defect centre in diamond represents an ideal single spin system for use in biology. It has a broad absorption band from 512-560 nm, sustained fluorescence from 630-750 nm, is chemically inert and exhibits low cyto-toxicity [4]. These defects centres have been used as highly stable fluorescence beacons to track the position and diffusion of diamond nano-crystals in vitro and in vivo. In this work we explore the quantum properties offered by this unique fluorescent emitter in the biological context and demonstrate optically detected magnetic resonance (ODMR) of individual fluorescent nanodiamond nitrogen-vacancy centres inside living human HeLa cells. The ODMR spectrum from the nanodiamond is found to be a unique barcode which can be used for indentifying individual diamond nano-crystals of interest. The ODMR spectrum can also be used as an effective tool for probing the rotational dynamics of the nanodiamond. We demonstrate the successful orientation tracking of a single nanodiamond with acquisition times less than a second and an angular precision of less than a degree. The tradeoff between the ODMR acquisition time and angular resolution will be presented and discussed in terms of future biological applications.

1. Balasubramanian, G., et al., Nature, 2008. 455(7213): p. 648-651.

2. Maze, J.R., et al., Nature, 2008. 455(7213): p. 644-648.

3. Hall, L.T., et al., Proceedings of the National Academy of Sciences, 2010. 107(44): p. 18777-18782.

4. Schrand, A. M. et al., J. Phys. Chem. 111, 2, (2007).

8272-04, Session 2

In vitro and in vivo applications of fluorescent nanodiamonds

H. Chang, Institute of Atomic and Molecular Sciences (Taiwan)

Fluorescent nanodiamonds (FNDs), containing negatively charged nitrogen-vacancy (NV-) centers as fluorophores, have recently emerged as a promising biomarker for in vitro and in vivo applications. The carbon-based nanomaterial is biocompatible, non-toxic, and can be easily conjugated with biomolecules. Uniquely, the built-in NV- centers can emit photostable far-red fluorescence (λ = 600 - 800 nm) when excited by green-yellow light, making it well suited for long-term labeling/tracking of cancer and stem cells, not only in vitro but also in vivo. To prove the concepts, we have studied in detail the exocytosis of FNDs (size ~ 100 nm) from three different cell lines, HeLa cervical cancer cells, 3T3-L1 pre-adipocytes, and 489-2.1 multipotential stromal cells. No alteration in growth and proliferation of the FND-labeled cells was observed for up to 8 days and no substantial excretion of the endocytosed FND particles was found after 6 days of cell labeling. We have also applied the technique to whole model organisms such as C. elegans and nude mice. In vivo imaging of nude mice intradermally injected with FNDs revealed that most of the nanoparticles are accumulated in lymph modes, as confirmed by ex vivo imaging and biodistribution measurements. We acquired transverse section images of the lymph nodes by fluorescence lifetime imaging microscopy to visualize the individual particles in the tissues. We summarize in this talk our recent progress towards the development of FNDs for optical bioimaging with single particle sensitivity, long-term tracking capability, and nanometric resolution in cells as well as in whole organisms.

8272-05, Session 2

Use of upconverting fluorescent nanoparticles for bioimaging

Y. Zhang, N. M. Idris, L. Ong, L. Ang, S. Alonso, National Univ. of Singapore (Singapore)

Lanthanide doped nanocrystals with near-infrared (NIR)-to-NIR and/or NIR-to-visible (VIS) upconversion fluorescence emission have been synthesized. The surface of these nanocrystals have been modified to render them water dispersible and biocompatible. Use of these nanocrystals for bioimaging introduces many advantages, for example, minimum photo-damage to biological samples, weak auto-fluorescence, high detection sensitivity, high light penetration depth, etc. The nanocrystals with small size and tunable multi-color emission have been developed. The emission can be tuned by doping different upconverting lanthanide ions into the nanocrystals. The nanocrystals with core-shell and multi-shell structure have also been prepared, to improve the upconversion efficiency and to tune the emission color. The NIR-to-NIR upconverting nanocrystals have been used for in vitro cell imaging and in vivo animal imaging and cancer cell detection because both the excitation and emission light are in the NIR range and can penetrate through thick tissues. Use of the NIR-to-VIS nanocrystals has also been explored for FRET based biodetection. Although these upconverting nanocrystals are very promising fluorescent materials, their applications in various areas are limited due to the low upconversion efficacy. There is an urgent need to develop new methods to solve this problem.

8272-06, Session 2

Tailoring rare earth doped nano-particles for applications from biology to quantum computing

Z. U. Hasan, A. Konjhodzic, Temple Univ. (United States)

Ultra-small nano-sized fluorescent centers have found their applications in health sciences, sensor technology, nano-photonics and quantum computing. Their widespread use will undoubtedly demand a control over their physical, chemical and optical properties. Properties such as the size of the nanoparticle, toxicity to the environment, the fluorescence wavelength of operation and the duration for which they remain active in human or animal body are all very specific to an application. We have developed a robust and fast technique of producing nanoparticles doped with fluorescent impurity ions and we demonstrate tailoring of atomic properties of these ultrasmall nanoprobes to suit a variety of applications.

With our technique, pulsed laser ablation of a solid target, almost any solid can be used for producing the nanoparticles. The number fluorescent centers, or rare earth ions in the present case, in a particle has been controlled for different applications. We demonstrate doping of as low as one europium fluorescent ion per particle. We demonstrate the tailoring of the ionization state of the rare earth fluorescent ion inside the particle, for example, doubly or triply ionized europium. This photo-bleaching is fast and is accomplished in nanoseconds. This could allow a non-bleachable probe to become photo-bleachable.

The wavelength of fluorescence and its intensity have been tuned by atomic scale tailoring of symmetry and wavefunctions of the center. We show that fluorescence from doubly ionized europium, the fluorescent ion in our nanoparticles, can be tuned in discrete steps from 575-750nm. At the same time, compared to triply ionized europium, the fluorescence intensity has been increased by eight to ten orders of magnitude, approaching the theoretical limit for the strength of emission.

Such strongly fluorescing nanoparticles have uses as single particle single impurity probes in biological tissues and single photon on demand source in nano-photonics. Particles with larger number of fluorescent ions can be used for ultra-small fluorescent markers, IR-visible upconversion based tags, and hardware for quantum computing. The talk is aimed to show the possible atomic tailoring of ultrasmall fluorescent probes for a variety of applications in Health, Biological and Physical Sciences.

8272-07, Session 3

Electrical tunability and correlation spectroscopy of single-photon emission from chromium-based colour centres in diamond

T. Muller, C. Matthiesen, Univ. of Cambridge (United Kingdom); I. Aharonovich, Harvard Univ. (United States) and The Univ. of Melbourne (Australia); Y. Alaverdyan, A. N. Vamivakas, Univ. of Cambridge (United Kingdom); S. A. Castelletto, Swinburne Univ. of Technology (Australia); S. Prawer, The Univ. of Melbourne (Australia); M. Atature, Univ. of Cambridge (United Kingdom)

Chromium based single photon emitters have recently attracted attention as alternatives to the well-investigated NV centre with potentially superior photonic properties. We show that using the electrical Stark shift these centres can be tuned over a spectral range typically three orders of magnitude larger than the radiative linewidth and at least one order of magnitude larger than the observed linewidth. Interdigitated gold gates fabricated on the single crystal diamond are used to apply electrical fields up to 8.5 x 106 V/m, and the polarity can be reversed by applying a reverse bias. The linewidth of the centre remains unchanged under an electric field, and the asymmetric nature of the linear dipole response allows us to infer an atomic configuration lacking inversion symmetry. Based on this and the fabrication protocol we propose a Cr-X or X-Cr-Y type atomic structure for these Cr-based centres, where X and Y are likely to be oxygen, nitrogen or sulphur.

We further characterise the emission properties of chromium centres using a Michelson interferometer for first order correlation (g(1)) measurements of single-photons from chromium centres in diamond microcrystals. The extracted visibility predominantly follows a Gaussian statistics with coherence times on the order of 100 ps. This translates to a spectral linewidth of about 16 GHz which is considerably broader than the 80 MHz expected for a lifetime-broadened line, indicating that the predominant line broadening mechanism in this case is likely to be slow wandering of the resonance caused by fluctuations of the charge environment.

8272-08, Session 3

Near-field coupling of a single NV center to a tapered fiber

T. Schröder, Humboldt-Univ. zu Berlin (Germany); M. Fujiwara, T. Noda, Hokkaido Univ. (Japan); H. Zhao, Osaka Univ. (Japan); O. Benson, Humboldt-Univ. zu Berlin (Germany); S. Takeuchi, Hokkaido Univ. (Japan)

Promising candidates for the realization of quantum information applications are systems of optical resonators combined with tapered fibers. Recently fiber to resonator coupling at cryogenic temperatures, optical phase shift at the single photon level and nano-emitter to cavity coupling has been shown. These are interesting components to build quantum information applications using optical networks and quantum logical gates. A further important step towards such a system is the integration of a single nano-emitter.

Here we demonstrate the near-field coupling of a nano-diamond containing a single NV center to such an optical tapered fiber. The single photons emitted by the NV center can be collected efficiently via the fiber. This fiber integrated single photon source has similar properties as a single emitter - fiber system in which the single emitter is placed on the end facet of the fiber. It also has additional advantages. As the photons coupled to the fiber mode propagate in both directions of the fiber with the same intensity, a 50:50 fiber beam splitter is realized. Absorption measurements can easily be performed as the fiber transmits about 90% of the incoupled light. Furthermore the controlled coupling of the single emitter to a whispering gallery mode resonator will be possible. As it is sitting on the tapered region it can be brought into the vicinity of a high-Q (quality factor) optical resonator mode even at low temperatures. This will allow fundamental cavity quantum electrodynamics experiments and quantum information implementations such as a quantum phase gate.

8272-09, Session 3

Magnetic sensing using NV centers in diamond

A. Yacoby, M. Grinolds, S. Hong, P. Maletinsky, Harvard Univ. (United States)

Detection of weak magnetic fields with nanoscale spatial resolution is an outstanding problem in the biological and physical sciences. For example, at a distance of 10 nm, the spin of a single electron produces a magnetic field of about 1 micro Tesla, and the corresponding field from a single proton is a few nano Tesla. A sensor able to detect such magnetic fields with nanometer spatial resolution would enable powerful applications, ranging from the detection of magnetic resonance signals from individual electrons or nuclear spins in complex biological molecules to readout of classical or quantum bits of information encoded in an electron or nuclear spin memory to the imaging of various condensed matter phenomena.

In this talk I will review our recent experimental approach to such nanoscale magnetic field sensing, using coherent manipulation of an individual electronic spin qubit associated with a nitrogen-vacancy impurity in diamond at room temperature. Three topics will be discussed: Using a magnetic field gradient to spatially resolve individual NV spins with better than 10nm; The control and detection of mechanical motions using NV spins and a monolithic approach for creating magnetometer tips with a single NV center situated 10nm from the surface and its imaging capabilities.

8272-10, Session 3

Coherent control and projective readout of a solid-state spin quantum register

H. Bernien, L. Robledo, R. Hanson, Technische Univ. Delft (Netherlands)

Initialization and readout of coupled quantum systems are essential ingredients for the implementation of quantum algorithms. If the state of a multi-qubit register can be read out in a single shot, this enables further key resources such as quantum error correction and deterministic quantum teleportation, as well as direct investigation of quantum correlations (entanglement). While spins in solids are attractive candidates for scalable quantum information

processing, thus far single-shot detection has only been achieved for isolated qubits. Here, we demonstrate preparation and measurement of a multi-spin quantum register by implementing resonant optical excitation techniques originally developed in atomic physics. We

achieve high-fidelity readout of the electronic spin associated with a single nitrogen-vacancy (NV) centre in diamond, and exploit this readout to project up to three nearby nuclear spin qubits onto a well-defined state. Conversely, we can distinguish the state of the nuclear spins in a single shot by mapping it onto and subsequently measuring the electronic spin. Finally, we show compatibility with qubit control by demonstrating initialization, coherent manipulation, and single-shot readout in a single experiment on a two-qubit register, using techniques suitable for extension to larger registers. These results pave the way for the first test of Bell's inequalities on solid-state spins and the implementation of measurement-based quantum information protocols.

8272-11, Session 3

Single photon source by single NV center in diamond semiconductor

N. Mizuochi, Osaka Univ. (Japan)

The development of solid-state sources of single photons is a major challenge in the context of quantum communication, optical quantum information processing, and metrology. Recently, significant progresses in the realizations of highly efficient nonclassical light sources including sources of entangled photons have been shown in semiconductor quantum-dots. In those realizations, electrical excitation within a diode structure offers practical advantages over optical excitation in future large scale application and integrated system. However, a major obstacle with semiconductor structures so far is the requirement of cryogenic temperatures due to necessity to confine carriers within the dots. Due to their outstanding photostability at room temperature, single defects in diamond and in particular single nitrogen vacancy (NV) center in diamond have been used as single photon source for quantum cryptography and single photon interference by laser excitation. Here we report the realization of a stable room temperature electrically driven single-photon source based on a single NV center in diamond. Subpoissonian photon statistics of electroluminescence is observed. Remarkably the generation of electroluminescence of single defects follows a fundamentally different kinetics than photoluminescence, which is analyzed by carrier recombination. Our results suggest that defects in diamond semiconductor can be used as a stable room temperature electrically driven single-photon source which is crucial for the large-scale applications in quantum information technology.

8272-12, Session 4

Creating filters for shot-noise-limited Ultrasound Optical Tomography (UOT)

M. Sabooni, Lund Univ. (Sweden); H. Zhang, Texas A&M Univ. (United States); L. Rippe, Lund Univ. (Sweden); C. Kim, Washington Univ. in St. Louis (United States); S. Kroll, Lund Univ. (Sweden); P. Hemmer, Texas A&M Univ. (United States)

Large depth imaging in strongly scattering media using UOT relies on collecting the small fraction of light frequency-shifted by ultrasound and assuring that this weak signal is not hidden in the noise from the (non frequency-shifted) carrier light wave. Conveniently any filter with a spectral transmission window will both suppress the carrier wave and delay radiation within its transmission window. This talk will describe filters, where the transmitted light (shifted by the ultrasound) arrives at the detector at a time much later than the scattered carrier radiation and thus is detected on a zero background enabling deep tissue imaging.

8272-13, Session 4

Rare-earth-doped materials with application to optical signal processing, quantum information science, and medical imaging technology

R. L. Cone, C. W. Thiel, Montana State Univ. (United States); Y. Sun, The Univ. of South Dakota (United States); T. Böttger, Univ. of California, San Francisco (United States); R. M. Macfarlane, Montana State Univ. (United States)

Unique spectroscopic properties of rare earth ions in solids enable a variety of recent applications. Within rare earth optical absorption transitions which are already regarded as sharp at room temperature, optical decoherence times as long as 4.2 msec have been measured in our laboratory at 1.6K, equivalent to homogeneous optical linewidths as narrow as 75 Hz. This linewidth reduction of nine orders of magnitude gives linewidths rivaling those of isolated trapped single atoms used at the frontiers of atomic physics.

We design rare-earth-doped crystals, ceramics, and fibers with persistent or transient "spectral hole" recording properties for applications including high-bandwidth optical signal processing where light and our solids replace electronics, quantum cryptography and information science including the goal of storage and recall of single photons, and medical imaging technology for the 700-900nm therapeutic window.

Ease of optically manipulating rare-earth ions in solids enables capturing and processing complex spectral information in 105 to 108 frequency bins. Combining spatial holography and spectral hole burning provides a capability for capturing and processing high-bandwidth RF and optical signals with sub-MHz spectral resolution and bandwidths of tens to hundreds of GHz. Applications include range-Doppler radar and high bandwidth RF spectral analysis, where systems demonstrated in Montana exceed the capabilities of state-of-the-art electronics. Simply stated, one can think of these crystals as holographic recording media capable of distinguishing 105 to 108 different colors.

Ultra-narrow spectral holes also serve as a vibration-insensitive sub-kHz frequency references for laser frequency stabilization to a part in 1013 over tens of ms.

8223-73, Session 4

Signals, noises, and detection schemes in ultrasonically modulated optical imaging

F. Ramaz, Ecole Supérieure de Physique et de Chimie Industrielles (France); M. Gross, Univ. Montpellier 2 (France); A. C. Boccara, Ecole Supérieure de Physique et de Chimie Industrielles (France)

Compared to purely optical diffuse tomography that aims to reveal the spatial distribution of optical properties (absorption and scattering) hybrid techniques that combine light and ultrasounds provide a much better resolution: typical results are of the order of 1/100 of the targeted depth. In ultrasonically modulated optical imaging (also called Acousto Optical Tomography), the part of the light that overlaps the acoustic field is modulated by an ultrasonic beam focused inside the biological tissue. 2-D or 3-D images are generated by scanning the acoustic field across the sample volume. The so-called tagged-photons (created at the position of the focused ultrasonic beam) can be discriminated from background of unmodulated photons. The difficulty of the coherent detections (heterodyning using cameras or photorefractive crystals) that rely on the speckle field modulation is that they are sensitive to its fast (< 1 ms) decorrelation time due to blood flow. Inversely the techniques that use a narrow band pass filter (Fabry Perot or Hole Burning) do not suffer from such decorrelation. When optimized Hole Burning offers the larger optical etendue and should be the best detection technique. We will discuss the performances of each detection scheme in term of signal to noise ratio and illustrate their potential for a realistic bedside experiment.

8223-74, Session 4

Ultrasound-modulated optical tomography of biological tissue using spectral-hole burning

X. Xu, H. Liu, Washington Univ. in St. Louis (United States); S. Kothapalli, Stanford Univ. (United States); P. Lai, Y. Suzuki, L. V. Wang, Washington Univ. in St. Louis (United States)

In ultrasound-modulated optical tomography, coherent detection of the optical signal is difficult because of the multiple scattering of light through a turbid medium. To improve the signal-to-noise ratio in UOT, spectral-hole burning has been proposed as a front end absorptive filtering method, based on its narrow linewidth as well as its immunity to speckle-induced spatial incoherence and speckle decorrelation. Experimental implementation of SHB with a Tm3+:YAG crystal has shown a 13.5 dB transmission improvement of the UOT signal. Images of biological tissues and tissue mimicking phantoms of various thicknesses have been acquired using SHB-UOT. The effect of a finite suppression of the background light on the final SNR is investigated, and further improvement of SHB-UOT is proposed.

8223-75, Session 4

Recent progress in ultrasound-mediated fluorescence

B. Yuan, Y. Liu, The Univ. of Texas at Arlington (United States)

Invited Talk:

Fluorescence imaging techniques can provide unique tissue physiological information and is sensitive to tissue microenvironments. Unfortunately, the highly scattering property of tissue to light has limited most fluorescence measurements either in excised sample slices or superficial in vivo tissues. When detecting fluorescence from deep tissue, the spatial resolution significantly deteriorates. To improve the spatial resolution and maintain the unique functional information of the fluorescence signal, ultrasound-mediated fluorescence (UMF) techniques have been developed recently. Like ultrasound-modulated optical tomography, a highly focused ultrasound beam is usually employed to tag fluorophores. By detecting UMF signal, the functional information of the fluorophore may be quantified with ultrasonic spatial resolution. Recent studies have shown that UMF is experimentally detectable and a fluorescent target can be visualized in a turbid medium with ultrasonic resolution. However, significant challenges for developing UMF techniques exist, such as unclear modulation mechanisms, relatively low signal-to-noise ratio (SNR), and less developed imaging contrast agents, etc. In this talk, the potential modulation mechanisms will be discussed. Methods for improving SNR will also be discussed based on three strategies: (1) increase the sensitivity of the detection system, (2) improve the modulation efficiency via microbubbles, and (3) suppress unwanted background fluorescence emission (via the detection system and imaging contrast agents). To bring UMF techniques to any practical biomedical applications, further improvement of SNR has to be achieved. Development of UMF imaging contrast agents is a promising direction, which will be introduced in this talk based on our recent results.

8223-76, Session 4

The potential of ultrasound-modulated optical sensing in clinical monitoring

T. S. Leung, Univ. College London (United Kingdom)

Near infrared spectroscopy (NIRS) is a widely adopted technique to measure tissue oxygenation non-invasively in human tissues such as the brain and muscle. A number of commercial NIRS clinical monitors have emerged over the past twenty years and they are gaining popularity with many clinical applications. However, in many situations, the region of interest is beneath a superficial layer, e.g., muscle overlaid by a superficial layer of skin and fat, which can affect the accuracy of the NIRS measurement. By applying focused ultrasound in the region of interest, ultrasound-modulated optical (UMO) techniques can potentially provide a measurement less susceptible to physiological changes in the superficial layer. In this talk, we will explore the potential of UMO techniques for clinical monitoring. We will present and compare the depth sensitivity of the NIRS and UMO measurements based on a series of absorption and scattering perturbation experiments. Our results show that in the reflection mode with a source detector spacing of 3 cm, the UMO measurement is more sensitivity to its NIRS counterpart when the ROI is more than 14 mm deep into the tissue in one realistic scenario. However, the most sensitive region of an UMO measurement does not always coincide with the focused ultrasound location. We will also show that by incorporating ultrasound microbubbles as contrast agents, UMO techniques can potentially provide a non-invasive venous oxygen saturation measurement in a vein which is something conventional NIRS techniques cannot achieve because of the high absorption of blood inside the vessel.

8272-14, Session 5

Atom like centers in solids for nanophotonic and quantum devices

Z. U. Hasan, Temple Univ. (United States)

Devices working with a few atoms at the core of their operation not only set the limit of miniaturization, but also define a new level of exploitation of matter, the quantum regime. Therefore, nano-photonics and quantum devices for computing and communication have been vigorously pursued for the last one and a half decade. The practical realization of most of these devices faces challenges mainly on three fronts: i). Implementing the desired quantum mechanical operation on an ensemble of atoms considering their interaction with each other and with the surrounding. ii). Fabrication of such devices with a minimum number of atoms performing the desired operation. iii). The control of these devices with external photons to demonstrate their successful operation.

This presentation will review the progress in tailoring the materials for single atom or at most few atoms based devices. Three different classes of materials have emerged that can be exploited for designing such devices: color centers particularly in the diamond crystal, the traditional rare earth based systems where localized 4fn electronic states are used for quantum manipulation, and lastly rare earth based f-d systems. The focus of our studies is on solids lightly doped with f-d rare earths in the form of nanoparticles and multi-layer thinfilms.

f-d rare earths can be considered as the hybrid of the transition metal (dn electrons) system and the rare earth (fn electrons) systems. These materials provide for the maximum atomic scale tailoring of solids: d-states allow the tunability of pertinent electronic transitions from UV to IR. f-d transitions are strongly electric dipole allowed and therefore maximize the electron photon interaction. Also, in such systems f-d rare earth centers can be tailored to enhance or eliminate the electron-lattice coupling.

With such intricate and extensive tailoring possible, these systems demonstrate the highest density of spectral storage; up to 1000 channels, optical holes, can be made(burned) using the zero phonon line of a single rare earth center. In multi-layer structures this number is multiplied by the number of layers. Such channels can be used in frequency selective wide-band communication and ultra-dense memory. Strongly interacting atomic centers that can be efficiently addressed by photons have the potential to provide systems for quantum computing, single atom devices, single photon sources, and single atom based nano-sensors. For biological applications such nano-probes could potentially provide efficient fluorescent markers and tags in living cells.

8272-15, Session 5

Spectral-hole burning techniques for ultrasound-modulated optical tomography

H. Zhang, Texas A&M Univ. (United States); M. Sabooni, L. Rippe, Lund Univ. (Sweden); C. Kim, Washington Univ. in St. Louis (United States); S. Kroll, Lund Univ. (Sweden); L. V. Wang, Washington Univ. in St. Louis (United States); P. R. Hemmer, Texas A&M Univ. (United States)

Large depth imaging in strongly scattering media using UOT relies on collecting the small fraction of light frequency-shifted by ultrasound and assuring that this weak signal is not hidden in the noise from the (non frequency-shifted) carrier light wave. Conveniently any filter with a spectral transmission window will both suppress the carrier wave and delay radiation within its transmission window. This talk will describe filters, where the transmitted light (shifted by the ultrasound) arrives at the detector at a time much later than the scattered carrier radiation and thus is detected on a zero background enabling deep tissue imaging.

8272-16, Session 5

Organic materials for spectral hole burning and non-hole burning narrowband optical filters

A. Gorokhovsky, College of Staten Island (United States)

An overview of properties and applications of organic materials for narrowband spectral hole burning (SHB) and non- hole burning optical spectral filters will be presented. Main focus will be on the properties important for the filters applications in ultrasound -modulated optical tomography (UOT). In UOT these filters may be used to improve image quality in tandem with the more narrowband SHB filters made of RE ions doped inorganic crystals. The following issues will be reviewed: optical spectra of organic molecules at low temperatures, electron -vibrational spectral structure, zero-phonon lines and phonon sidebands, mechanisms of homogeneous and inhomogeneous broadening, optical dephasing in crystals and glasses, spectral hole burning, mechanisms of transient and persistent photochemical, photophysical and gated SHB, kinetics and quantum efficiency of SHB, SHB in optically thick samples. Organic materials for SHB in red and NIR spectral regions, spectral band engineering, applications for narrowband spectral filtering and comparison with narrowband interference filters will be discussed. In addition, non- hole burning organic materials as secondary absorption optical filters to reduce phone-mediated fluorescence from inorganic SHB crystals in UOT applications will be considered.

8272-17, Session 5

Efficient high-etendue four-wave mixing in a spectral hole-burning medium

B. S. Ham, Inha Univ. (Korea, Republic of); P. R. Hemmer, Texas A&M Univ. (United States)

Real time holography has been used in ultrasound modulated optical tomography demonstrations to extract weak ultrasound tagged light from the intense scattered light emerging from tissue samples. Phase conjugation has also been used to more efficiently direct light to the ultrasound focus in tissue. For both these applications, a high etendue (produce of acceptance angle and area) must be as large as possible. Unfortunately, until now photorefractives demonstrated for such experiments have slow response times, relatively low photon efficiency, and limited acceptance angle due to the small range of allowed grating vector magnitudes. Wavemixing in spectral hole-burning materials promises to have a higher etendue because it supports large grating vectors (signal and reference beam counterpropagating). It can also have relatively fast response times and a high photon efficiency. In a rare-earth Pr3+ doped spectral hole-burning crystal, three orders of magnitude higher photon echo efficiency was observed using ultraslow light. In the photon echoes the signal's amplitude and phases of signal light are recorded in a form of a large enetendue phase grating. Resonant optical transition of Pr3+ ions doped Y2SiO5 at ~606 nm was used for both photon echoes and ultralslow light, where the ultraslow light functions enhanced data absorption and reduced echo reabsorption. Here we discuss potential applications of the controlled photon echoes for high etendue, high resolution bio-imaging applicable to the time-reversed ultrasonically encoded optical focusing.

8223-77, Session 5

Acoustic radiation force assisted ultrasound modulated optical tomography

M. Tang, R. Li, Y. Cheng, C. W. Dunsby, R. J. Eckersley, D. S. Elson, Imperial College London (United Kingdom)

Acoustic radiation force (ARF) is generated when momentum transfers from the propagating acoustic wave to the medium. As it can cause large (but slow) particle displacement and is closely related to tissue mechanical properties, it has potential in assisting ultrasound modulated optical tomography (UOT) by improving the system SNR and bringing additional information about tissue mechanical properties. A mechanical scanning UOT system has been developed including a 532nm laser, an ultrasound system with a 5MHz focused transducer, and a CCD camera. Tissue mimicking phantoms with heterogeneous inclusions of different optical and mechanical properties were exposed to the laser and ultrasound bursts which generated ARF and subsequent shear wave. The CCD camera was positioned on the side of the phantom opposite to the laser to measure the transmitted photons. The phantom was scanned and the image contrast was calculated based on CCD measurements. Both the timing and the length of CCD exposure were adjusted. It has been shown that by using a short CCD exposure time, the optical measurements were not affected by ARF and shear wave. By increasing and optimising CCD exposure time, the SNR of the measurement can be significantly improved by the ARF without losing spatial resolution. At the same time it is shown that our measurements are sensitive to tissue mechanical properties. By acquiring with multiple CCD exposure times, or multiple CCD trigger delay times to track the shear wave propagation, tissues of different stiffness can be detected and quantified.

8223-78, Session 5

Improving signal-to-noise ratio and spatial resolution in ultrasound modulated optical tomography

S. P. Morgan, H. Ruan, N. T. Huynh, M. L. Mather, D. He, J. Crowe, F. R. Rose, B. R. Hayes-Gill, The Univ. of Nottingham (United Kingdom)

(Invited)

Ultrasound modulated optical tomography can reduce the effects of light scattering and improve the resolution of optical imaging systems by 'tagging' light that passes through the ultrasound column.

Ultrasound imaging has benefited from non-linear approaches to improve image resolution and reduce the effects of side-lobes. A system for performing second harmonic ultrasound modulated optical tomography is demonstrated which incorporates both pulsed optical illumination and acoustic excitation. A pulse inversion scheme is employed which involves exciting the ultrasound transducer consecutively with a pulse and then an inverted pulse. Summing the detected pulses allows the second harmonic signal to be extracted. The advantage of this approach is that the second harmonic signal can be obtained while still maintaining a short pulse length of the acoustic excitation. A speckle detection algorithm tailored to this configuration has been developed to optimise signal to noise ratio. Images of absorbing objects embedded in tissue phantoms demonstrate that the method can provide an improvement in image resolution.

The use of ultrasound modulated optical tomography in imaging fluorescent targets is also discussed. This is challenging because the modulated light signal is much smaller than when coherent light is detected. A system is described based on pulsed acoustic excitation and optical detection with a photomultiplier tube. Simple experiments show that by changing the length of the acoustic pulse the image contrast can be optimised. Applications in imaging in regenerative medicine are discussed where tissue is grown in three dimensions within scaffolds and non-destructive evaluation is beneficial.

8223-79, Session 5

Sound light: rendering photoacoustics fluence-independent by adding acousto-optic modulation

W. Steenbergen, A. Hussain, K. Daoudi, Univ. Twente (Netherlands)

A major challenge of photoacoustic imaging is to measure absolute absorption coefficients associated with the concentration of chromophores in tissue. In normal photoacoustics this is not possible because of the unknown optical excitation levels within the tissue. This limitation can be overcome by 'Sound Light', which is a tailored combination of photoacoustic imaging and acousto-optic tissue modulation. In the latter, ultrasound modulates the phase of the light crossing the ultrasound focus, which can be observed in the dynamics of an externally measured speckle pattern. We also have developed a theoretical framework for recombining results of photoacoustics and acousto-optics into absolute absorption coefficients, without the need for calibration. Specific aspects of the method are subsequent injection of light for photoacoustics at two tissue locations, and use of these points as optode location for the acousto-optic part of the method. Included in this strategy is a pure reflection mode implementation in which the points of injection and detection coincide. We will particularly focus on reflection mode Sound Light and on the effects of the size of the injection beam and detection window. Our results will shed light on the potential and limitations of Sound Light to render absolute absorption coefficients, and on the background of the found deviations in terms of the beam size, size of the ultrasound labeling volume and the distance to the tissue surface in relation to the scattering properties of the tissue.

8223-80, Session 5

Non-invasive blood flow measurements using ultrasound modulated diffused light

N. Racheli, A. Ron, C. Metzger, I. Breskin, M. Balberg, R. Shechter, Ornim Medical Ltd. (Israel)

Capillary blood flow is a critical parameter for determining tissue vitality.

Existing optical methods for measuring blood flow such as Diffuse Correlation Spectroscopy (DCS), Laser Doppler, spatial-temporal image correlation spectroscopy (NIR-STICS) and Speckle Imaging suffer each from drawbacks, such as shallow sampling volumes, complexity and expense of apparatus.

Ultrasound based methods such as Ultrasound Doppler are used for monitoring directional flow in relatively big blood vessels and are problematic when applied to capillary flow.

We present a novel non-invasive method for measuring blood flow based on the acousto-optic effect. Blood flow within the sampled volume disturbs the photons' temporal correlation and therefore the spectral component of light fluctuating at the Ultrasound frequency decreases as flow increase, while the spectral width around the ultrasound frequency broadens. A cross correlation of the sampled light with the emitted ultrasound pattern provides a measure of flow within the sampled volume.

The benefits of the presented method are: localized measured volumes, continuous real time measurement, simplicity of apparatus and ease of operation.

We demonstrate the ability of the method to detect flow of scattering fluid using a calibrated flow phantom model. Fluid flow was generated by a calibrated syringe pump and the phantom's sampled volume contains millimeter size flow channels (10% fluid by volume). Results demonstrate linear dependence of flow as measured by the presented technique (FI) to actual flow values with $r=0.97$, $p<0.001$.

8272-18, Session 6

Realizing optimal physical approximation of the partial transpose

H. Lim, Y. Kim, Y. Ra, Pohang Univ. of Science and Technology (Korea, Republic of); J. Bae, Korea Institute for Advanced Study (Korea, Republic of); Y. Kim, Pohang Univ. of Science and Technology (Korea, Republic of)

The partial transpose by which a subsystem's quantum state is solely transposed is of unique importance in quantum information processing from both fundamental and practical point of view. In this work, we present a practical scheme to realize a physical approximation to the partial transpose using local measurements on individual quantum systems and classical communication. We then report its linear optical realization and show that the scheme works with no dependence on local basis of given quantum states. A proof-of-principle demonstration of entanglement detection using the physical approximation of the partial transpose is also reported.

8272-19, Session 6

Closing the detection loophole in EPR-steering experiments

G. J. Pryde, Griffith Univ. (Australia)

Einstein, Podolsky and Rosen first highlighted the apparent nonlocal collapse of the wavefunction when one of a pair of entangled systems is measured [1]. Schrodinger generalized the concept to multiple measurement settings, calling it "steering" [2], referring to the apparent nonlocal influence of Alice's measurement on Bob's local state. Only recently, these concepts were formalized into a quantum information task - EPR-steering - generalizing the original concepts to arbitrary states and measurements [3], and allowing the derivations of EPR-steering inequalities [4] (by analogy to Bell inequalities). EPR-steering can also be viewed independently of fundamental quantum interpretations, by framing the problem as an entanglement verification protocol between two parties in which one of the parties, or her apparatus, is untrusted. In this way, EPR-steering has direct relevance to quantum communications protocols.

I will describe several experiments investigating the EPR-steering phenomenon. We have shown that, both in terms of robustness to noise [5] and complexity of measurement procedures [6], EPR-steering is easier to demonstrate than Bell inequality violations and harder to demonstrate than nonseparability - for example, we have observed EPR-steering of mixed entangled states that can never violate a Bell inequality. Additionally, the use of many measurement settings in EPR-steering can allow the entanglement verification steering process to proceed securely, even in the presence of very high losses. We have demonstrated EPR-steering with the detection loophole (equivalent to that in Bell inequalities) closed, with ~ 50% efficient detectors and over 1km of optical fibre.

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8272-20, Session 6

New results in fault-tolerant quantum computing

G. N. Gilbert, Y. S. Weinstein, The MITRE Corp. (United States)

We explore the explicit construction of Shor states in quantum error correction. We carry out detailed analyses of the effects of errors, paying special attention to the general case of non-equiprobable errors, i.e., the important and realistic situation in which the probabilities for sigma_x, sigma_y and sigma_z errors are not necessarily the same (sigma_x, sigma_y and sigma_z are the Pauli operators). We obtain exact analytical results for the case of a sufficiently small number of ancilla measurements, and obtain leading order terms for the general case. We calculate and analyze the density operators associated to the Shor states we construct.

8272-21, Session 6

Integrated quantum photonics

J. L. O'Brien, Univ. of Bristol (United Kingdom)

Here we report high-fidelity silica-on-silicon integrated optical realizations of key quantum photonic circuits, including two-photon quantum interference and a controlled-NOT logic gate. We have combined waveguide photonic circuits with superconducting single photon detectors. We describe complex quantum interference behavior in multi-mode interference devices with up to eight inputs and outputs, and quantum walks of correlated particles in arrays of coupled waveguides. Finally, we give an overview of our recent work on fundamental aspects of quantum measurement and diamond and nonlinear photon sources.

8272-22, Session 6

Coherent and squeezed vacuum light interferometry: parity detection hits the Heisenberg limit

K. P. Seshadreesan, P. M. Anisimov, H. Lee, J. P. Dowling, Louisiana State Univ. (United States)

The interference between coherent and squeezed vacuum light produces path entangled states. We show that the phase sensitivity of the coherent and squeezed vacuum light interferometry with parity detection saturates the quantum Cramer-Rao bound, which reaches the Heisenberg-limit under certain conditions.

8272-23, Session 7

Dynamics of generation and retrieval of stored excitations in rare-earth ion-doped crystal

E. A. Goldschmidt, Joint Quantum Institute (United States); S. E. Beavan, The Australian National Univ. (Australia); S. V. Polyakov, A. L. Migdall, Joint Quantum Institute (United States); M. J. Sellars, The Australian National Univ. (Australia)

Robust, long-lived quantum memories are important components of many quantum information and communication protocols. We demonstrate coherent generation, storage, and retrieval of excitations on a long-lived spin transition in a rare-earth ion-doped crystal. Such a scheme is an enabling step toward implementing a quantum repeater based on solid-state quantum memory nodes. An ensemble of absorbers with a Λ-type energy level configuration is prepared with all atoms in one ground state. An optical write field transfers atoms to the other ground state via spontaneous Raman scattering, generating collective excitations on the long-lived spin transition. Each excitation is accompanied by a heralding photon, shifted in frequency from the write field by the ground state splitting. An optical read field converts the stored excitation into a phase-matched retrieved photon. As a first step toward generating, storing, and retrieving single atomic excitations, we operate in a high-gain regime where each write pulse generates many excitations. We measure the correlation between the heralding and retrieved optical fields to characterize the write/read protocol. We find that the correlation reaches its theoretical maximum value in a certain temporal window, signifying that there are detection times at which there is negligible noise, and that the correlation does not drop with increasing storage time, signifying that decoherence of the atomic excitations during storage is negligible. We further model the temporal dynamics of the noise components of the fields from the data and find that the main noise component has a different temporal profile than the correlated emission.

8272-24, Session 7

Electromagnetically controlled storage and retrieval of microwave pulses with superconducting artificial atoms

P. M. Leung, B. C. Sanders, Univ. of Calgary (Canada)

Electromagnetically induced transparency is one technique exploited for optically controlled storage and retrieval of pulses and thereby opening the possibility of optical quantum memory. Inspired by this promising optical system, we consider translating the technology from the optical to the microwave domain, specifically for superconducting circuits. In our design, the transmission line is coupled to several superconducting artificial atoms with three or more discrete electronic energy levels. These atoms give the system a microwave analogue of optical depth, and we show that, for the pump field turned off, that an on-resonance transmission field is attenuated according to Beer's Law. Mathematically we model the system as a sequence of atoms coupled to an unpolarized propagating one-dimensional field first using a Lindblad master equation and then converting a transfer matrix method. The system is characterized in terms of transmitted and reflected fields. We show that our scheme is promising for microwave-controlled memory and synchronization within a superconducting circuit quantum information processing device.

8272-25, Session 7

Four-wave mixing storage

J. C. Howell, Univ. of Rochester (United States)

I will discuss recent experiments in four-wave mixing storage and retrieval. I will report on developments with correlated photons, precision measurements and atomic memories.

8272-26, Session 7

Reliable and efficient control of spectral qubits using optoelectronic devices: progress and perspectives

J. Merolla, L. Fufaro, K. Phan Huy, I. Mbodji, Univ. de Franche-Comté (France); S. Massar, E. Woodhead, L. Olislager, Univ. Libre de Bruxelles (Belgium); R. Giust, Univ. de Franche-Comté (France)

Most practical quantum key distribution methods based on entangled photons use time-bin or polarization encoding. These have also been among the preferred methods for investigating the fundamental issue of quantum non locality. Manipulating entangled photons directly in the frequency domain is a relatively unexplored area. Previous work in this direction includes Mandel dip experiments the creation of entanglement in multiple degrees of freedom including frequency and conversion from polarization to frequency entanglement. Recently we have introduced the notion of frequency-bin entanglement which allows a simple description of experiments that manipulate entanglement in the frequency domain. We have also shown how using conventional methods of production by parametric down-conversion, frequency bin entangled photons at telecommunication wavelengths (around 1550 nm) could be manipulated in optical fibers using standard telecommunication components such as electro-optic phase modulators and fiber Bragg gratings. Here, we report the performance of a new automated architecture based on 25 GHz frequency sideband modulation designed specifically for manipulation of frequency-bins, with potential applications such as QKD. The highly stable control of both amplitude and phase of the RF signals driving the electro-optic phase modulators combining with low-noise superconducting single photon detectors allow to realize two photon interferences with raw visibility better than 99%. A violation of a Clauser-Horne inequality by more than 18 standard deviations has been demonstrated using this method. Such results show that frequency-bin photon entanglement is a promising platform for the realization of quantum communication protocols at telecommunication wavelengths.

8272-27, Session 7

Anderson localization and co-localization of spatially entangled photons

A. F. Abouraddy, G. Di Guiseppe, D. N. Christodoulides, B. E. A. Saleh, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

It is well known that a quantum wave function propagating in a disordered lattice may result in Anderson localization (AL). We exploit the analogy between the evolution of quantum mechanical wave function and that of a classical optical field to produce a photonic realization of AL using entangled photon pairs. The appreciation of this analogy has recently produced optical realizations of AL using classical light in disordered arrays of coupled optical waveguides. Although quantum entanglement is an essential resource in quantum information processing, the propagation of spatially entangled photon pairs in an AL system has not been studied heretofore. We predict a new phenomenon that we call Anderson co-localization (AcL) that may be observed in two-photon correlation space. Each spatially extended photon in the entangled pair remains spatially extended while the relative separation between the two photons in correlation space remains invariant upon traversing the disordered system. We also predict that entangled photons co-localize faster than classical light localizes in the same system. Furthermore, we describe a family of two-photon states that are unchanged after propagating through an AL system which we call two-photon AL-eigenstates. We formulate these results using a linear systems theory and consequently we extend the formalism of quantum imaging to incorporate disordered systems.

8274-11, Session 8

A compact source for quantum image processing with four-wave mixing in Rb85

U. Vogl, R. Glasser, P. D. Lett, National Institute of Standards and Technology (United States)

We have built a compact source of intensity-squeezed twin-beams based on four-wave-mixing in atomic Rubidium 85 vapor. The twin-beams are generated via a double-lambda scheme by pumping near the D1-line with a strong laser beam and injecting a probe beam detuned to the ground-state splitting at a small angle relative to the pump, which results in probe-amplification and the generation of a conjugate beam. Since the photons in the probe and conjugate beams are created in pairs, they exhibit intensity-difference squeezing. As squeezing is attainable without the need for a cavity, the generated twin beams are inherently multi-spatial-mode, as has been shown previously by our group.

With a total optical power of 300 mW derived from a free running diode laser and a tapered amplifier to pump the four-wave-mixing process, we achieve 2.5 dB relative intensity squeezing of the twin beams below the standard quantum limit, without accounting for losses.

We achieve a total optical power in the probe and conjugate beams of 100 µW by injecting a 10 µW probe, corresponding to a gain of 5. Higher squeezing is currently limited by low pump power.

We are currently using this squeezed light source to investigate the transfer of quantum correlations through media of anomalous dispersion.

Another interesting prospect is the transfer of quantum correlations from the twin-beams to an ensemble of cold atoms.

The portability of this compact two-by-two foot source allows for interfacing with different experiments with relative ease.

8274-12, Session 8

Controlling the degree of polarization of a coherent beam through spatial-polarization correlations

K. H. Kagalwala, G. Di Giuseppe, A. F. Abouraddy, B. E. A. Saleh, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

It is customary to think that an unpolarized optical beam must be characterized by random fluctuations that result in loss of coherence. We describe here another route through which the degree of polarization of a coherent optical beam traversing a deterministic optical system may decrease. By introducing judicious correlations between polarization and another degree of freedom, namely the spatial parity of the beam along one axis, measurements of the degree of polarization reveal a partially polarized beam. The correlations between the polarization and spatial parity degrees of freedom are intoduced through the use of a polarization-sensitive spatial light modulator (SLM). The SLM modulates the spatial phase distribution of one polarization component only (without affecting its amplitude). Thus by controlling the polarization of an incident Gaussian beam and manipulation of the imparted phase distribution we can implement an arbitrary degree of correlation between polarization and spatial parity which results in complete control over the degree of polarization. We quantify the correlations between spatial parity and polarization using a Bell's-like inequality traditionally used in quantum optics as a test of nonlocality exhibited by two photons in an entangled quantum state. We adapt this inequality to the case of two degrees of freedom carried by a single classical beam and demonstrate its usefulness in quantifying correlations between these correlations. This work elucidates the impact that many ideas recently developed in the field of quantum information processing may have on the study of classical optical coherence.

8272-28, Session 8

Realization of ultra-broadband entangled photons and application to quantum sensing

S. Takeuchi, R. Okamoto, M. Okano, Hokkaido Univ. (Japan); A. Tanaka, S. Subashchandran, Osaka Univ. (Japan); S. Kurimura, National Institute for Materials Science (Japan); N. Nishizawa, Nagoya Univ. (Japan)

Photon pairs correlated in a very short time (a few femto seconds), which has called mono-cycle entangled photons (MEPs)[1] - will be useful for many applications from sensing, metrology to information processing.

As the first step toward the realization of MEPs, here we report the realization of an ultra-broadband parametric fluorescence with bandwidth over 810nm (790nm-1600nm) using a chirped quasi-phase matched(QPM) device, where pump wave length was 532nm. The QPM device is a 2cm-long stoichiometric lithium tantalite (SLT) crystal with the magnesium oxide concentration of 1.0mol-% (MgSLT) with 10% chirping of the poling period (from 8.000 um to 8.825 um).

We will also discuss the application of broadband entangled photons to quantum optical coherent tomography with some recent experimental results.

This work was supported in part by JST-CREST project, Grant-in-Aid from JSPS, Quantum Cybernetics project, FIRST Program of JSPS, Special Coordination Funds for Promoting Science and Technology, and the GCOE programs.

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8272-29, Session 8

Parallel generation of 15 quadripartite cluster entangled states over the optical frequency comb of a single optical parametric oscillator

O. Pfister, M. Pysher, Univ. of Virginia (United States); Y. Miwa, The Univ. of Tokyo (Japan); R. Shahrokhshahi, R. D. Bloomer, Univ. of Virginia (United States)

Quantum computing holds the revolutionary promise of exponentially speeding up such calculations as integer factoring and quantum simulation. Building a practical quantum computer requires a scalable number of individual quantum memory units ("qubits", here "Qmodes"), all individually addressable and controllable without error. In this work, we demonstrated an experimental breakthrough: the generation of a record-size quantum register of 60 Qmodes, in 15 independently entangled quadripartite square cluster states. This massively scalable implementation of a quantum register was all-optical and based on a single optical parametric oscillator (OPO) that emitted quantum electromagnetic fields (the Qmodes) at equally spaced optical frequencies over its optical frequency comb. The OPO had specially engineered nonlinear optical crystal and pump field, which were designed to enable specific continuous-variable entangling, a.k.a. "two-mode squeezing," interactions throughout the quantum comb in order to generate the desired state "top down," in one fell swoop. Technical constraints limited the measured number of generated Qmodes to the reported 60 but we estimated the actual size of our quantum register to be of 180 to 600 Qmodes. This work is a major step toward entangling all these Qmodes together in a single cluster state, in order to achieve a scalable platform for a quantum computer.

8274-13, Session 9

Full-field quantum correlations in position, momentum, and intermediate bases

M. J. Padgett, J. Leach, D. Ireland, Univ. of Glasgow (United Kingdom); G. S. Buller, R. E. Warburton, F. Izdebski, Heriot-Watt Univ. (United Kingdom); S. M. Barnett, A. M. Yao, Univ. of Strathclyde (United Kingdom)

We have developed a new approach to measuring the spatial position of a single photon. Using fibres of different length, all connected to a single detector allows us to use the high timing precision of APD to spatially locate the photon. We have built two 8-element detector arrays to measure the full-field quantum correlations in position, momentum and intermediate bases for photon pairs produced in parametric down conversion. We obtain correlations an order of magnitude below the classical limit.

8274-14, Session 9

Fiber transport of spatially entangled photons

W. Löffler, E. R. Eliel, H. P. Woerdman, Leiden Univ. (Netherlands); T. G. Euser, M. Scharrer, P. J. Russell, Max Planck Institute for the Science of Light (Germany)

High-dimensional entangled photons pairs are interesting for quantum information and cryptography: Compared to the well-known 2D polarization case, the stronger non-local quantum correlations could improve noise resistance or security, and the larger amount of information per photon increases the available bandwidth. One implementation is to use entanglement in the spatial degree of freedom of twin photons created by spontaneous parametric down-conversion, which is equivalent to orbital angular momentum entanglement, this has been proven to be an excellent model system.

The use of optical fiber technology for distribution of such photons has only very recently been practically demonstrated and is of fundamental and applied interest. It poses a big challenge compared to the established time and frequency domain methods: For spatially entangled photons, fiber transport requires the use of multimode fibers, and mode coupling and intermodal dispersion therein must be minimized not to destroy the spatial quantum correlations. We demonstrate that these shortcomings of conventional multimode fibers can be overcome by using a hollow-core photonic crystal fiber which follows the paradigm to mimic free-space transport as good as possible, and are able to confirm entanglement of the fiber-transported photons. Fiber transport of spatially entangled photons is largely unexplored yet, therefore we discuss the main complications, the interplay of intermodal dispersion and mode mixing, the influence of external stress and core deformations, and consider the pros and cons of various fiber types.

8274-15, Session 9

Two-photon cluster states using polarization and spatial modes

E. J. Galvez, M. Novenstern, W. H. Schubert, Colgate Univ. (United States)

We present a method to produce two-photon four-qubit cluster states of polarization and spatial modes. Our technique allows the preparation of non-separable states of polarization with any pair of pure spatial modes. A starting point is to produce the [1/root(2)](0000+1111) state, where two qubits are polarization modes and the other two qubits are spatial modes (e.g., Hermite-Gauss or Laguerre-Gauss eigenmodes). Our experimental method consists of first producing photon pairs in polarization-entangled states. The spatial mode of each photon is projected onto the fundamental mode by passage of both photons through single-mode optical fibers. Each member of the pair then enters a polarization interferometer, where orthogonal spatial modes are encoded with polarization eigenstates. The four-qubit cluster state (1/2)(0000+0011+1100-1111) is obtained by rotating the modes of one photon before entering the interferometer. Our first implementation involves the use of first-order Hermite-Gauss modes, although in principle any pair of orthogonal spatial modes can be used.

8272-30, Session 9

Information in a photon

R. W. Boyd, Univ. of Ottawa (Canada)

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. In this presentation, 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. More generally, we describe how image formation making use of quantum states of light allows dramatic new possibilities in the field of image science. The field of quantum imaging strives to make use of the quantum aspects of light fields to achieve image formation with enhanced performance. One such example that we are studying is the possibility of performing imaging by impressing an entire image onto a single photon. We recently completed one study [1] that shows that by means of a holographic method we can discriminate between two objects even when they are illuminated by only a single photon. In a related study we have shown that we can discriminate among four objects using a single biphoton in a ghost-imaging configuration [2]. We have also studied [3] 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 [4].

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8272-44, Poster Session

UV laser beam switching system for Yb trapped ion quantum information processing

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Qubits based on trapped Yb ions are being investigated as a promising platform for scalable quantum information processing. One challenge associated with the scalability of such a multi-qubit trapped ion system is the need for a UV laser beam switching and control system to independently modulate and address large qubit arrays. In this work, we propose and experimentally demonstrate a novel architecture for a laser beam control system for trapped ion quantum computing based on fast electro-optic amplitude switching and high-fidelity electronic beam shuttering using a MEMS deflector coupled into a single-mode optical fiber. We achieve a rise/fall time of 5 ns, power extinction of 31 dB, pulse turn-on timing jitter of 0.4 ns, and integrated pulse area repeatability of > 99.94% using an electro-optic switch based on a β-BaB_2O_4 (BBO) Pockels cell. A tilting MEMS mirror fabricated using the SUMMiT V process was used to steer UV light into a single-mode optical fiber, resulting in an electronic beam shutter that demonstrated a power extinction of 40 dB and a switching time of 2 µs. The combination of these two technologies allows for high-fidelity power extinction using a platform that does not suffer from temperature-induced beam steering due to changes in modulation duty cycle. The overall system is capable of UV laser beam switching to create the resolved sideband Raman cooling pulses, algorithm pulses, and read-out pulses required for quantum computing applications.

8272-45, Poster Session

Single-qubit quantum gates using magneto-optic Kerr effect

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Magneto-optic Kerr effect (MOKE) is widely used to determine the domains of magnetic materials. Unlike Faraday effect, which can only be observed in magnetically transparent media, MOKE can be observed in materials that are magnetically non-transparent. Depending on the orientation of bias magnetic field, MOKE can be observed in polar, longitudinal, and transverse configurations. However in most materials MOKE is quite low and needs to be enhanced by employing a stack of dielectric layers.

In this paper, we propose the use of MOKE to realize single-qubit quantum gates-Hadamard, NOT, and phase-shift. We consider longitudinal MOKE in reflection geometry. The bias magnetic field is parallel to both the plane of incidence of light wave and surface of the film. In the absence of bias field, incident photons undergo ordinary reflection. Application of the bias field changes polarization of the incident photon and imparts a phase-shift. Specifically, an incident transverse electric (TE) polarized photon acquires a transverse magnetic (TM) polarization upon reflection. The quantum Hamiltonian describing the interaction of quantized light wave (photon) and the applied magnetic field (magnon) is of the form: γ |w0;TE> and |w0;TM> represent TE and TM polarized photon states respectively. The coefficient γ depends on the applied magnetic field. By varying the phase and amplitude of γ, we can realize various single-qubit quantum gates.

8272-46, Poster Session

Decoy-state method for frequency-coded implementation of B92 QKD protocol

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We propose a decoy-state method B92 quantum key distribution protocol using frequency-coding scheme. In frequency-coding scheme, key bits are transmitted as phase of sideband relative to an optical carrier. The phase encoding is achieved by modulating the carrier of average photon number/pulse μ by a microwave signal using an electro-optic modulator. After modulation, the average photon number of carrier and sidebands is μJ0^2 (m) and μJ1^2 (m) respectively, where J0 and J1 are Bessel function of order 0 and 1, and 'm' is modulation index.

In decoy-state method, a legitimate user replaces signal pulses by multi-photon pulses ('decoy' pulses) at random (usually with signal μ < decoy μ). The users then determine the yield of decoy pulses to estimate single-photon transmittance and hence an upper bound on secure key rate. A direct extension of the basic decoy-state method to frequency-coding scheme results in security loss as the eavesdropper can distinguish between signal and decoy states by measuring the carrier photon number without affecting other statistics. Thus, the very aim of decoy state method is lost.

To overcome this security loophole, we require that the ratio of carrier photon number of signal and decoy pulse should be as close to unity as possible. We achieve this by optimizing the carrier ratio to unity so that it becomes difficult to distinguish between signal and decoy states with the help of carrier. We also show the improvement in QBER and key rate as a function of carrier ratio both with and without system noise.

8272-47, Poster Session

Coherent switching and signal processing of stokes waves waveguide array

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In the past two decades there has been a growing interest in the study of discrete or lattice spatial soliton. There are a diversity of fascinating phenomena pertinent to these waveguide array systems, for instance, discrete solitons and diffraction management which offer the potential of fabricating compact, all-optical switching and blocking devices for use in integrated optical systems. While weakly coupled waveguide arrays show different linear properties like anomalous diffraction when compared to continuous media, in the nonlinear regime they have shown analogous behavior where the self- and cross-phase modulation interactions allows the formation of discrete solitons. The dynamics of these waveguide arrays can be modeled by the discrete nonlinear Schrödinger equation (DNLSE), which considers a system of individual waveguides coupled with adjacent waveguides as a set of differential equations.

In a nonlinear waveguide array, the high degree of light localization can enhance the nonlinear optical processes and thus the Kerr nonlinearity provides an effective tool for exploiting nonlinear interactions in switching devices. These predictions have been experimentally verified in nonlinear waveguide arrays based on AlGaAs and LiNbO3, demonstrating soliton interactions such as time-gating, blocking, routing, and other logic functions [1-3].

The monoclinic optical crystal KGW offer a high n2 nonlinear coefficient with low two photon absorption. 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 μm to the 1.5 μm 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 DNLSE offers a method of energy exchange between the fundamental beam and a Stokes-shifted wavelength. Planar waveguides have been fabricated in KGW using both light ion [4] and swift-heavy ion [5] irradiation techniques, and show excellent promise for the fabrication of waveguide arrays with strongly preserved nonlinear properties in the guiding region.

In this paper we propose, to our best knowledge for the first time, to employ the Raman nonlinearity combined with the always present Kerr effect for Raman soliton generation and interactions in a waveguide array. We present numerical modeling of discrete beam interactions in a nonlinear, Raman-active material, such as potassium gadolinium tungstate KGd(WO4)2 (KGW), illustrating the blocking, switching, and wavelength conversion dynamics of this system. We demonstrate using numerical methods the potential of all-optical generation, wavelength conversion and beam steering of spatial solitons in a discrete waveguide array using Raman and Kerr nonlinear processes. With the availability of new highly nonlinear and Raman efficient materials such as KGW, as well as new techniques in creating waveguides with these materials, there is much promise shown for applications of all optical conversion, switching, blocking, and logic functionality. Future work on discrete soliton blocking and steering are being directed towards examination of new features that may be brought by introducing non-stationary Raman response and additional phase mismatch in the waveguides

8272-48, Poster Session

Polarization based quantum information in femtosecond laser written photonic circuits

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Photons are excellent candidates for the experimental benchmarking of quantum information ideas, due to their low decoherence. Integrated optical circuits have recently demonstrated their potentials in overcoming the stability and size limitations that generally affect implementations of quantum optics experiments with bulk components. Anyway, they were operated so far only with path-encoded qubits and fixed polarization state of the photons.

In our work we adopt femtosecond laser waveguide writing to realize novel integrated circuits which are able to support and manipulate polarization entangled photons. This technology yields several advantages such as absence of photolitographic steps, intrinsic three-dimensional capabilities and possibility of cost-effective and rapid prototyping of new devices. The low waveguide birefringence makes this technique suited for applications with polarization encoded qubits.

We demonstrate on-chip integration of beam-splitters both partially polarizing and polarization insensitive, as well as more complex circuits with controlled interferometric phase. This enabled for example entangled Bell states filtration, implementation of discrete quantum walks of entangled photon states with bosonic and fermionic symmetry and the realization of an integrated CNOT gate for polarization encoded qubits.

8272-31, Session 10

Suppression of phonon sidebands in the spectrum of nitrogen vacancy centers in diamond nano-crystals

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The existence of strong phonon side bands in the spectrum of nitrogen vacancy centers (NVCs) is considered a main obstacle for applications to quantum information devices, since the emission into zero phonon line is reduced. Here we report the existence of substrate effects on the zero-phonon transitions and suppression of phonon side bands in the NV center spectrum. We found that SiO2/Si substrate was an effective substrate to suppress the phonon side band from spectra of NV- centers. NVC fluorescence spectra in cryogenic temperatures were measured by depositing diamond nanocrystals on different substrates including glass slides, undoped Si, and silica (1~2um) on undoped Si (SiO2/Si). Statistical distribution of the NV- ZPL intensity to the whole NV- spectrum intensity ratio (Debye-Waller factor in analogous) FD-W at 4K for diamond nano-crystals on the three different substrates were measured. Among which, SiO2/Si substrate was proved to be an effective substrate to maximum suppress the phonon side band of NV- spectrum, with a NV- ZPL FD-W main distribution of 0.11 to 0.13. Same samples have a corresponding NV- ZPL FD-W main distribution of 0.05 to 0.07 on Si substrates, and 0.01 to 0.03 on glass slides. Excitation power dependence of the NV- ZPL FD-W at 4K was measured and compared on three different substrates. The maximum excitation power dependence was found for samples on glass slides with a FD-W change of 24% when laser power changed from 1×104W/cm2 to 2×105W/cm2, and those of samples on Si and SiO2/Si substrate was 5% and 17%, respectively.

8272-32, Session 10

Coupling color centers to optical cavities in single crystal diamond

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Negatively charged nitrogen-vacancy (NV) centers hold great promise for solid state quantum information processing due to their superior properties, such as long spin coherence time, optical spin readout and single photon emission at room temperature. Formation of micro-disks and photonic crystal nano-cavities in single-crystal diamond provides a platform to study strong light-matter interactions between the NV centers and cavity fields. However, fabrication of such devices is extremely challenging. Here, we present a process to fabricate microdisk cavities having good spectral overlap with the zero phonon line of NV centers in single-crystal diamond with quality factor ~ 3000.

A 1.7 microns thick diamond membrane was fabricated through the generation of an underlying sacrificial layer by a high dose ion implantation and thermal annealing. Selective removal of the sacrificial layer using electrochemical etching enabled the membrane to be transferred to a low refractive index material (SiO2) for optical isolation. Epitaxial overgrowth introduced a thin layer (~ 240 nm) of diamond with NV centers embedded within. The original membrane was then etched away and optical cavities were patterned on the overgrowth layer. The demonstration of coupling between NV centers and optical cavities serves as an important milestone for developing diamond integrated quantum photonic networks.

8272-33, Session 10

Towards integrated optical quantum networks in diamond

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Nitrogen-vacancy (NV) centres in diamond are outstanding optical quantum emitters with long spin coherence times that make them one of the best candidates for solid state qubits. For quantum information applications, it is necessary to connect together multiple qubits, a task that so far has been proven difficult. Combining photonic networks with measurement-based schemes is an attractive approach for enabling scalable systems. However, many technical questions remain such as how to fabricate useful optical structures in diamond, and how to control the spectral inhomogeneity and instability of the NV centre's optical transitions.

An essential component of a quantum photonic network based on NV centres is a microcavity for enhancing the emission rate of photons into the zero-phonon line (ZPL). In this talk, I will describe one approach attempted at HP Labs, based on fabricating all-diamond microring and photonic crystal resonators starting from thin single crystal diamond membranes commercially available from Element 6. These structures are made by electron-beam lithography and reactive-ion etching, and are coupled to NV centres incorporated during diamond growth. For single NV centres on resonance with a cavity mode at low temperature, we have observed a spontaneous-emission lifetime reduction corresponding to more than ten-fold enhancement of emission into the zero-phonon line. The ZPL emission in the cavities was coupled into on-chip waveguides thus demonstrating the potential of these structures to build integrated optical quantum networks.

8272-34, Session 10

Diamond nanophotonics and quantum optics

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ndividual color centers in diamond have recently emerged as a promising solid-state platform for quantum communication and quantum information processing systems, as well as sensitive nanoscale magnetometry with optical read-out. Performance of these systems can be significantly improved by engineering optical properties of color centers using nanophotonic approaches. In this work we describe a high-flux, room temperature, source of single photons based on an individual Nitrogen-Vacancy (NV) center embedded in a top-down nanofabricated, single crystal diamond nanowires1, 2, plasmonic nano-apertures3, and diamond-based optical cavities4 and waveguides. Using the nanowire geometry, for example, an order of magnitude brighter single photon source is realized, with an order of magnitude lower pump power, compared to an NV center in a bulk diamond1. By embedding diamond nanowires in metals3, it is possible to further increase photon flux by increasing photon production rate via Purcell effect. To that end, we demonstrated Purcell factors of ~6 in geometry that consists of diamond nanoposts embedded in silver. Finally, recently we demonstrated optical nanocavities and waveguides fabricated directly in thin diamond films5. Single-photon emission of NV centers embedded in diamond ring resonators, featuring quality factors on the order of 10,000, has been demonstrated. These devices could enable strong coupling between photons and NV centers.

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8272-35, Session 10

Tuning nitrogen-vacancy centers to indistinguishability with the DC Stark effect

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For quantum information applications, nitrogen-vacancy (NV) centers in diamond combine many of the advantages of atomic systems (optical access, millisecond spin-coherence times) with the engineering flexibility of solid-state devices. Recent demonstrations of coherent coupling between photons and individual NV-center spins provide a route to integrating NV-center qubits within photonic networks and for on-demand generation of entangled spin-photon pairs. Such applications require the ability to tune the NV-center optical transitions, to compensate for natural sample inhomogeneities which perturb the electronic orbital states. Here we demonstrate the ability to electrically control the orbitals of individual NV centers by applying voltages to micron-scale surface gates. Surprisingly, the local field experienced by an NV center is significantly enhanced by a photoinduced electric field due to photoionization of deep charge traps within the diamond, even in high-purity single-crystal material. Since the photoinduced fields are reproducible as a function of gate voltage and are predominantly directed perpendicular to the diamond surface, we can harness them to obtain three-dimensional control of the local electric field vector with surface gates alone. To demonstrate this technique, we tune the excited-state orbital doublet of a strained NV center to degeneracy, a requirement for several spin-photon entanglement protocols, and then adjust the optical transition frequency, showing that we can tune multiple NV centers to the same degenerate transition energy. This method should enable the coherent coupling of multiple NV center spins to indistinguishable photons within a scalable photonic network.

8272-36, Session 11

All optical preparation, storage, and readout of a single spin in an individual quantum dot

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We demonstrate all optical preparation and storage of a single electron in an individual self-assembled InGaAs quantum dot (QD) and high fidelity measurement of its spin projection by driving a luminescence recycling transition. Hereby, we optically induce spin-charge conversion [1] to convert the spin information into charge occupancy (1e or 2e) and then repeatedly measure the charge occupancy by pumping an excited state of the negatively charged trion. This method is shown to produce signals ≈10000 x more intense per spin than previously utilized approaches [2] facilitating the study of spin dynamics over ultra long (>1ms) timescales. By probing the temperature and magnetic field dependence of the spin dynamics we extract electron and hole Landé g-factors and map out the spectrum and spin structure of hot trion transitions.

The devices investigated are QD spin memory structures that can be switched between two modes of operation; (i) charging, where optically generated holes are removed from the dot whilst electrons remain stored due to the presence of an AlGaAs barrier and (ii) readout, where excitons optically pumped into the dot recombine to produce luminescence [1]. The spin lifetime of the stored electron was measured by monitoring the storage time dependence of the spin blockade as the temperature and magnetic field was varied. Finally, we will also present first investigations of single spin ESR using microwave radiation.

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8272-37, Session 11

Cavity-QED with quantum dots in oxide-apertured micropillars

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Hybrid quantum information systems hold great promises for the development of quantum communication and computing due to the possibility to exploit different quantum systems at the best of their potentials. For example, in order to build a quantum network, photons are excellent candidates for long-distance transmission while quantum states of matter are preferred for local storage and processing. Hybrid (photon-matter) systems can also be used to effectively enable strong nonlinear interactions between single photons, which are a prerequisite for optical quantum computing. In the talk, we will focus on quantum dots in micropillar cavities, describing quantum information schemes involving photon polarization and the spin of a single electron trapped in the dot. Such schemes are based on spin-selective reflection in the weak-coupling regime of cavity quantum electrodynamics. We will then discuss the practical implementation of the proposed schemes in oxide-apertured micropillar cavities. In particular we show experimentally that such cavities support high-quality Hermite-Gaussian transverse optical modes. We then introduce a technique, based on the creation of small surface defects by means of a focused intense laser beam, to permanently tune the optical properties of the microcavity without damaging the cavity quality. This technique allows low-temperature polarization-selective tuning of the frequencies of the modes and the quantum dot optical transitions.

8272-38, Session 11

Single-photon emitters based on fluorine implanted ZnMgSe/ZnSe quantum-wells nanostructures

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Excitons bound to fluorine impurities in ZnSe have the potential for several quantum information applications. Fluorine impurities in ZnSe are particularly well suited for such applications since the nuclear decoherence of the electron spin may be suppressed by isotopic purification and the spin-1/2 19F nucleus with 100% abundance may provide long-lived matter qubits.

The quantum interference between indistinguishable single photons generated by the radiative decay processes of excitons bound to isolated fluorine impurities in ZnMgSe/ZnSe quantum-well (QW) nanostructures has been demonstrated1. The presence of optically controllable electron spins bound to fluorine donors in ZnSe also has been recently confirmed2. These results were based on molecular beam epitaxie (MBE) grown ZnMgSe/ZnSe QWs delta-doped with fluorine donors.

Here, we demonstrate an alternative fluorine doping method via ion implantation. Unlike the epitaxial doping where there is a small possibility of a fraction of fluorine being embedded as ZnF compounds, the ion implantation method introduces only 19F. A precise control of the doping concentration is realized by modulating the dose in a wide range between 1010 and 1013 cm-2. Localized doping can be achieved by selective implantation through a mask which would be otherwise extremely difficult in the purely epitaxial process. Moreover, registration of a single ion into a nanostructure can be achieved with a high efficiency3.

Photoluminescence measurements of fluorine-implanted ZnMgSe/ZnSe QWs nanostructures with a diameter of 100-200nm show the correlation between the number of sharp recombination peaks of excitons bound to fluorine donors in ZnMgSe/ZnSe QWs nanostructures and the implantation dose. The power dependence reveals the saturation of the luminescence intensity related to a donor. The photon statistics and the photon correlation are investigated with a Hanbury-Brown-Twiss setup. Our results show that the ion implantation provides an attractive alternative for introducing fluorine impurities in ZnMgSe/ZnSe QWs.

8272-39, Session 11

Coherence properties of quantum dot resonance fluorescence

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Resonance fluorescence has proven to be a useful technique for studying self-assembled quantum dot (QD) spin dynamics as it enables direct access to the resonantly generated photons and avoids dephasing processes inherent to indirect excitation techniques.

The technical challenge to extract QD resonance fluorescence from the high-index semiconductor matrix lies in the suppression of the excitation laser scattering which is typically many orders of magnitude stronger than QD emission. Using cross-polarisation we achieve a signal to background ratio exceeding 1000 while maintaining an overall photon collection efficiency of 0.6%. These results suggest that spin readout fidelities of 99% are feasible in less than 20 us. The purity of resonance fluorescence allows us to study the coherence of QD resonance fluorescence directly via first-order correlation measurements and via spectral measurements over six orders of magnitude in excitation power. We observe both inelastic and elastic QD scattering and dynamic nuclear spin polarization at low excitation powers and strong excitation-induced dephasing at higher powers. Despite the reduced coherence we are able to demonstrate coherent rotations of the excitonic state up to 22PI.

8272-40, Session 11

Telecommunication-wavelength quantum dot polarization entangled photon-pair source

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For networked quantum information systems a triggered source of single entangled-photon-pairs is an important enabling technology. At shorter wavelengths quantum dots have proved good candidates and we present for the first time an entangled photon-pair source based on a quantum dot (InAs grown on a GaAs substrate) at a telecommunications wavelength. The fine structure splitting is tunable by a vertical electric field in our device and the source is shown to clearly violate Bell's inequality.

The quantum dots were grown by molecular beam epitaxy and feature an InGaAs strain relaxing layer to emit at 1.3 µm. They are embedded within a GaAs quantum well with AlGaAs superlattice barriers and the structure is doped p-i-n in order that the internal electric field may be varied via an applied bias voltage. We investigate the evolution of the Bell state in detail via polarization correlation measurements and demonstrate high fidelity over multiple periods of the evolution of the single exciton state. Measurements are performed after transmission over standard single-mode optical fiber and fidelity to the Bell state of ~0.85 is determined. Convenient entanglement resources will be crucial in the development of quantum infrastructures of the future and networked architectures will require resources compatible with standard optical fiber. Our semiconductor device represents progress towards this for quantum dot sources in this important wavelength region.

8272-42, Session 12

Quantum memory in warm Rb vapor with buffer gas

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Quantum memory (QM) is necessary for long-distance quantum communications and other quantum processing. The QM realization using warm atomic vapor cells and the DLCZ (Duan, Lukin, Cirac, and Zoller) protocol is appealing due to the perceived experimental complexity reduction. However, the previously reported work uses various geometries without complete justification and suffers from sometimes ambiguous results. For example, in the earlier work of Eisaman et al. [Phys. Rev. Lett. 93, 233602 (2004)], quantum correlations have been reported in a cell with Rb vapor and a buffer gas, but either multiple spatial modes or multiple-photon states were employed. Later, Walther et al. [Int. J. Quant. Inf. 15, 51 (2007)] demonstrated QM, but only using electromagnetically induced transparency in a second storage cell, which adds complexity and reduces efficiency. These works ignored the collisional fluorescence reported later by Manz et al. [Phys. Rev. A 75, 040101R (2007)]. In that report, collisional fluorescence was assumed to be an impediment to realizing QM in a warm-vapor cell with a buffer gas. Here we show that appropriate experimental techniques can allow QM to be realized under these conditions. This is accomplished by employing appropriate detunings, filtering, and judicial discrimination against collisionally broadened fluorescence for both Stokes and anti-Stokes photons. We demonstrate quantum correlations in a single-photon, single-mode regime that last a few microseconds in a single cell. To the best of our knowledge, this is the first demonstration of delayed QM based on the original DLCZ protocol in warm atomic vapor with a buffer gas.

8272-43, Session 12

Control of the exciton g-factor in InGaAs quantum dots by electrical and magnetic fields

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We demonstrate strong electrical and magnetic field tuning of excitonic g-factors (Dgex/gex≈60%) in individual composition engineered InGaAs self-assembled quantum dots (QDs) and identify its microscopic origin [1, 2]. Cross-sectional scanning tunnelling microscopy (X-STM) measurements were performed on dots grown under similar conditions [3] to obtain realistic input parameters for modelling. The obtained values for the dot dimensions and In-Ga composition profile were used in the electronic structure calculations utilizing the 8-band k·p envelope function approximation, which revealed that the strong tunability of the exciton g-factor is dominated by the hole via quenching of the orbital angular momentum, the change of the In:Ga composition inside the envelope function playing only a minor role. Our results provide the potential for morphological and structural tailoring of QDs to facilitate local all electrical spin control via g-tensor manipulation [4].

To understand our results we performed realistic 8-band k·p simulations accounting for strain and direct Coulomb interactions. We modelled our QDs as having a truncated lens shape and an inverse trumpet-like In-compositional profile. Calculations reveal that gh tunability is dominated by the contribution of the g-factor due to the angular motion, the remote bands contribution varying only weakly. Our experiments and calculations highlight the strong dependence of the tunability on the In-concentration in the QD, strong gh tunability only being found for comparatively dilute In-concentrations (0.25 - 0.35).

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8272-49, Session 12

Single-atom absorption imaging

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From van Leeuwenhoek's first observation of red blood cells to Bose-Einstein condensates, absorption imaging has played a key role in the advancement of science. While absorption imaging is often used to great effect in optically dense ensembles, the small cross section of atomic transitions makes recovery of an absorption signal from a single atom with standard low-numerical-aperture optics challenging at best. The recent application of high numerical aperture optics with near diffraction-limited performance to atomic systems provides the capability to obtain substantial absorption effects and create strong atom-photon interactions. The latter is a necessary component for creating efficient coupling between photons and atoms in scalable quantum information processing systems.

174Yb+ was confined in a double-needle style RF Paul trap. The ion was laser cooled on the 369.5nm S1/2-P1/2 transition. To illuminate the ion for absorption imaging the cooling light was focused to a few-micron-diameter spot. The illuminate light was then recollimated by a phase Fresnel lens (0.64 numerical aperture) and reimaging onto a cooled CCD camera with 615x magnification. In fluorescence and absorption imaging this optical configuration demonstrated similar spot sizes of 440 nm FWHM. Images of the illumination beam with and without the ion were subtracted to obtain an image of the absorption by a single 174Yb+ atom. Absorption contrasts of up to 3.1(3)% were achieved, in agreement with quantum theory. The dependence of the absorption spot-size and depth on illumination laser detuning and power were found to be generally consistent with previous results for fluorescence imaging.

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8273-01, Session 1

Implementation and applications of quantum Hall physics with optical photons

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Optical signals are considered to be a promising alternative to electronic signals in future circuits. However, disorder in fabrication rapidly degrades the performance, leading to effects such as unwanted signal modulation in transmission. Here we theoretically illustrate the implementation of quantum Hall Hamiltonians for optical photons and we show how topological properties of such optical systems can be exploited to enable robust optical devices such as optical delay lines which are immune to disorder. Moreover, we experimentally investigate the implementation of such ideas in SOI technology.

In our photonic approach to the quantum Hall physics, we consider two dimensional arrays of coupled resonator optical waveguides (CROW) to simulate a 2D magnetic tight-binding Hamiltonian with degenerate clockwise and counter-clockwise modes. Each mode can be selectively driven and quantum Hall behaviors can be observed without breaking the time-reversal symmetry in the tight binding Hamiltonian. In particular, for certain frequency band, the transport is carried out by robust chiral edge states, and therefore, various transport properties are insensitive to fabrication errors.

For the experimental implementation of this model, we use SOI technology to form the two dimensional CROW. The photonic chips are fabricated on SOI wafers with a top Si layer thickness of 220 nm on a 2mum buried oxide (BOX) layer. The thick oxide optically isolates the waveguides and resonators from the substrate and photolithography is used to etch the patterns. Design parameters (waveguide length, width, air gap between rings, etc.) are chosen such that the dynamics of photons is governed by a tight-binding model with a synthetic magnetic field. On-chip grating is used to efficiently couple light from a single-mode fiber to our waveguide.

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p.s.: The presentation can be considered for Silicon Photonics VII, too.

8273-02, Session 1

Population oscillation induced slow light in a nonlinear photonic crystal microcavity

P. Grinberg, J. A. Levenson, A. M. Giacomotti, K. Bencheikh, Ctr. National de la Recherche Scientifique (France); P. Féron, Y. Dumeige, Ecole Nationale Supérieure des Sciences Appliquées et de Technologie (France)

No abstract available

8273-03, Session 1

Slow light enhancement of four-wave mixing in coupled silicon-on-insulator microrings

J. R. Ong, S. Mookherjea, Univ. of California, San Diego (United States)

No abstract available

8273-04, Session 1

Dynamical trapping of light in coupled laser arrays: slow or fast?

Y. Yifat, J. Scheuer, Tel Aviv Univ. (Israel); C. Long, E. Kapon, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

No abstract available

8273-05, Session 2

Atomic prism

J. C. Howell, Univ. of Rochester (United States)

I will report on a prism, which utilizes the steep dispersion between two strongly absorbing resonances. We have shown that we can obtain a linear angular dispersion over several GHz of bandwidth, the number of resolvable frequencies is proportional to the delay bandwidth product of the slow light medium and that the system can be used for precision frequency experiments. The system can be used to spatially separate dense teeth of an optical frequency comb, time-energy entangled photons, and all of the frequencies of an atomic four-wave mixing scheme.

8273-06, Session 2

Slow and stored light with atom-based squeezed light

I. Novikova, The College of William & Mary (United States)

No abstract available

8273-07, Session 2

Light matter interactions on a chip: a new integrated platform for slow and fast light

U. Levy, The Hebrew Univ. of Jerusalem (Israel)

No abstract available

8273-08, Session 2

Effect of Zeeman sublevels on light shifts in CPT-based Raman-Ramsey atomic clocks

G. S. Pati, Delaware State Univ. (United States); S. Shahriar, Northwestern Univ. (United States)

No abstract available

8273-09, Session 3

Slow and fast light in SOAs for microwave photonics applications

P. Berger, Thales Research & Technology (France)

No abstract available

8273-10, Session 3

Sensitivity enhancement in a superluminal semiconductor optical amplifier ring laser

S. Spillane, Los Gatos Research, Inc. (United States); S. Shahriar, Northwestern Univ. (United States)

No abstract available

8273-11, Session 3

Variable delay and sensing using stationary and localized Brillouin dynamic gratings

A. Zadok, Y. Antman, Bar-Ilan Univ. (Israel); N. Primerov, L. Thévenaz, Ecole Polytechnique Fédérale de Lausanne (Switzerland); J. Sancho-Dura, Univ. Politécnica de Valencia (Spain)

No abstract available

8273-12, Session 3

A Brillouin gain based fast light fiber laser for sensing applications

J. Scheuer, Tel Aviv Univ. (Israel); S. Shahriar, Northwestern Univ. (United States)

No abstract available

8273-13, Session 3

Nonlinear wave-mixing processes via slow and fast light: recent developments

Y. Rostovtsev, Univ. of North Texas (United States)

No abstract available

8273-16, Session 3

Nonlinear optics at the few-photon level in photonic crystal fibers

V. Venkataraman, K. Saha, P. Londero, A. L. Gaeta, Cornell Univ. (United States)

No abstract available

8273-14, Session 4

Brillouin scattering for dynamic sensing

M. Tur, Y. Peled, A. Motil, L. Yaron, Tel Aviv Univ. (Israel)

Using a frequency-tailored probe wave we demonstrate two new methods for fast and distributed Brillouin sensing.

Slope-Assisted Brillouin time domain analysis (BOTDA) uses the linear part of the slope of the Brillouin Gain Spectrum,

while fast BOTDA is based on a very fast sweeping of the relative frequency between the pump and probe waves.

Both methods achieved hundreds of Hertzs sensing rates.

8273-15, Session 4

Increasing the scale factor of a ring laser gyro via spectral hole burning

M. Salit, K. Salit, P. E. Bauhahn, Honeywell Aerospace Advanced Technology (United States)

No abstract available

8273-17, Session 4

Toward deep tissue biomedical imaging with slow light and ultrasound

P. R. Hemmer, Texas A&M Univ. (United States); S. Kroll, Lund Univ. (Sweden); L. V. Wang, Washington Univ. in St. Louis (United States); H. Zhang, Harvard Univ. (United States); M. Sabooni, L. Rippe, Lund Univ. (Sweden); C. Kim, Univ. at Buffalo (United States)

No abstract available

8273-18, Session 4

Various applications of slow light in a rare-earth doped crystal

B. S. Ham, Inha Univ. (Korea, Republic of)

No abstract available

8273-19, Session 4

Manipulation of light propagation using optical-nanofiber cavities

K. P. Nayak, K. Hakuta, The Univ. of Electro-Communications (Japan)

No abstract available

8273-20, Session 5

Slow-light in photonic crystal waveguides/ fibers: dispersion tailoring schemes for obtaining a high group index with wide band and low GVD

L. Ren, J. Liang, Xi'an Institute of Optics and Precision Mechanics (China); M. Yun, Qingdao Univ. (China); C. Ma, X. Han, Y. Liu, Xi'an Institute of Optics and Precision Mechanics (China); Y. Tomita, The Univ. of Electro-Communications (Japan)

Phenomenon of slow light has long been a hot research topic due to its promising and potential applications in communication networks, signal processings, optical sensors and nonlinear interactions. Particularly, photonic crystal devices, being capable of supporting slow-light propagation, are much attractive owing to its room-temperature operation and tunable dispersion features. Among them, photonic crystal waveguides (PCWs) are specially used in compact devices, while photonic band-gap fibers (PBGFs) are usually used in short-distance propagation and high sensitive interferometers. In this paper, dispersion tailoring schemes for obtaining a high group index with the wide band and low group velocity dispersion (GVD) are reviewed in both PCWs and PBGFs. For the same perpose, we propose schemes for a slow-pulse propogation in PCWs based on the air-hole shifting method and in PBGFs based on the microfluid infiltration method, respectively. Simulation results using 3D plane wave expansion method and finite-difference time-domain (FDTD) method are given. Pulse distortion and design optimization are also discussed in detail with the consideration of the practical fabrication errors.

8273-21, Session 5

The role of slow wave propagation in nonlinear photonic crystal waveguides

G. Eisenstein, I. Cestier, V. Eckhouse, A. Willinger, Technion-Israel Institute of Technology (Israel); S. Combrié, G. Lehoucq, A. De Rossi, Thales Research & Technology (France); S. Roy, M. Santagiustina, Univ. degli Studi di Padova (Italy)

No abstract available

8273-22, Session 5

Ultra high Q photonic structures on silicon

M. F. Lipson, Cornell Univ. (United States)

No abstract available

8273-23, Session 5

Progress in hollow-core photonic crystal fibre for atomic vapour based coherent optics

T. D. Bradley, Y. Wang, M. Alharbi, C. Fourcade-Dutin, B. J. Mangan, N. V. Wheeler, F. Benabid, Univ. of Bath (United Kingdom) and Xlim Research institute, CNRS, Univ. of Limoges (France)

No abstract available

8273-24, Session 5

Slow and fast light in dispersion engineered photonic crystal cavities

T. F. Krauss, Univ. of St. Andrews (United Kingdom)

No abstract available

8273-25, Session 5

Dark resonances in all-optical analogue to EIT: lossless intensity modulation, force enhancement, and optical antennas

S. Fan, Stanford Univ. (United States)

No abstract available

8273-26, Session 6

Dispersion in a four level n-scheme atomic system with co- and counter- propagating fields

F. A. Narducci, J. P. Davis, Naval Air Systems Command (United States)

No abstract available

8273-27, Session 6

Effect of inhomogneous broadening and buffer-gas collisions on a DPAL based uperluminal laser for precision sensing

T. Abi-Salloum, Widener Univ. (United States); S. Shahriar, Northwestern Univ. (United States)

No abstract available

8273-28, Session 6

Tuning the sensitivity of an optical cavity using slow and fast light

D. D. Smith, NASA Marshall Space Flight Ctr. (United States)

No abstract available

8273-29, Session 6

Rb-based superluminal DPAL laser: properties and applications to sensing

J. Yablon, S. Tseng, S. Shahriar, Northwestern Univ. (United States)

No abstract available

8273-30, Session 7

Slow-light through wave-mixing in liquid crystal light-valves and interferometric applications

S. Residori, Institut Non Linéaire de Nice Sophia Antipolis (France)

No abstract available

8273-31, Session 7

Slow light in fiber sensors

M. J. F. Digonnet, H. Wen, M. A. Terrel, S. Fan, Stanford Univ. (United States)

No abstract available

8273-32, Session 7

Improved spectral performance of Fourier transform interferometer utilizing slow light medium

Y. Zhang, Harbin Institute of Technology (China)

No abstract available

8273-33, Session 8

New physics and new applications with slow light

R. W. Boyd, Univ. of Rochester (United States)

No abstract available

8273-34, Session 8

Microscopic and macroscopic descriptions of electromagnetic-field propagation in nonlinear dispersive and absorbing media

V. L. Jacobs, U.S. Naval Research Lab. (United States)

No abstract available

8273-35, Session 8

Kerr effect in structured superluminal media

X. Angulo-Vinuesa, Consejo Superior de Investigaciones Científicas (Spain) and Univ. de Alcalá (Spain); S. Martin-López, Consejo Superior de Investigaciones Científicas (Spain); C. Caucheteur, D. Kinet, M. Wuilpart, Univ. de Mons (Belgium); A. Denisov, S. Chin, L. Thévenaz, Ecole Polytechnique Fédérale de Lausanne (Switzerland); M. González-Herráez, Univ. de Alcalá (Spain)

Kerr effect accounts for the change in refractive index of a material with the light intensity and appears in all known optical materials. In this presentation we analyze Kerr effect in structured superluminal media (e.g some specific types of resonators). We show that Kerr effect in these structures can be cancelled or even reversed (in comparison with the Kerr effect of the material composing the structure) depending on the group index of the structure. Technological details as well as possible future implications will be discussed.

8273-36, Session 8

Raman-active photonic crystal: dual wavelength slow light, optical memory, and signal processing

I. V. Melnikov, E.L.S. Co. (Russian Federation)

No abstract available

8273-37, Session 8

Slow light: Where does the energy hide?

J. B. Khurgin, The Johns Hopkins Univ. (United States)

No abstract available

8273-38, Session 8

Propagation of slow whispering gallery modes along the optical fiber

M. Sumetsky, OFS (United States)

No abstract available

8273-39, Session 8

Universality in slow light spectra

N. Davidson, R. Pugatch, Weizmann Institute of Science (Israel); D. Bhattacharyya, Santipur College (India); O. Firstenberg, Technion-Israel Institute of Technology (Israel)

No abstract available

8273-40, Session 9

Tunable optical tapped-delay-lines for signal processing applications

A. E. Willner, The Univ. of Southern California (United States)

No abstract available

8273-41, Session 9

Constant- and variable-chirp gratings for a broadband white light cavity for data buffering

X. Liu, H. Yum, Northwestern Univ. (United States); P. R. Hemmer, Texas A&M Univ. (United States); S. Shahriar, Northwestern Univ. (United States)

No abstract available

8273-42, Session 9

Slow-light enhanced optomechanical interactions

A. A. Sukhorukov, The Australian National Univ. (Australia)

No abstract available

8273-43, Session 9

Optomechanical light storage in a silica resonator

H. Wang, Univ. of Oregon (United States)

No abstract available

8273-44, Session 10

Slow-light enhancement of gain in active photonic crystal waveguides

J. Moerk, S. Ek, Y. Chen, P. Lunnemann, F. Wang, K. Yvind, Technical Univ. of Denmark (Denmark)

No abstract available

8273-45, Session 10

Recent progress in on-chip slow light devices

T. Baba, Yokohama National Univ. (Japan)

No abstract available

8273-46, Session 10

Light buckets: stopping light in light capacitors

M. Orenstein, Technion-Israel Institute of Technology (Israel)

No abstract available

8273-47, Session 10

EIT and quantum memory in nanomechanical systems

G. S. Agarwal, Oklahoma State Univ. (United States)

No abstract available

8273-48, Session 11

Enhancing the light-atom interactions using slow light: towards the concept of dense light

L. Thévenaz, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

No abstract available

8273-49, Session 11

Control of transparency: slow and fast light in room-temperature metastable helium-4

R. Ghosh, Jawaharlal Nehru Univ. (India)

No abstract available

8273-50, Session 11

Recent development in slow light with topological electromagnetic modes

Z. Wang, The Univ. of Texas at Austin (United States)

No abstract available

8273-51, Session 11

Amplified stopped light in metamaterial waveguides

K. L. Tsakmakidis, Imperial College London (United Kingdom); E. I. Kirby, Univ. of Surrey (United Kingdom); T. Pickering, O. Hess, Imperial College London (United Kingdom)

No abstract available

8273-52, Session 11

Slow light in a symmetrically-pumped DFB fiber laser with a variable phase shift

I. V. Melnikov, E.L.S. Co. (Russian Federation)

No abstract available

8273-53, Session 11

Deterministic optical rogue waves

C. Bonatto, Univ. Politècnica de Catalunya (Spain); M. Feyereisen, S. Barland, M. Giudici, Institut Non Linéaire de Nice Sophia Antipolis (France); C. Masoller, Univ. Politècnica de Catalunya (Spain); J. R. Rios Leite, Univ. Federal de Pernambuco (Brazil); J. R. Tredicce, Institut Non Linéaire de Nice Sophia Antipolis (France)

Rare extreme events can occur in many different systems in nature. A typical example are rogue waves observed in the oceans, where waves higher than 30 meters are more or less common phenomena. This fact is in contradiction with Gaussian models often used to describe fluctuations of the wave height in the sea [1,2].

Scientist interest on extremely high waves increased substantially during the last decade not only in oceanographic studies but also in other systems such as capillary waves [3] and optical waves [4-7]. Both, from theoretical and experimental point of view there are several questions still remaining unsolved. The physical mechanisms that originate them , the way they develop, the probability for them to occur, the type of system able to generate such extreme events, and the connections between extreme events in systems which are apparently completely different, are being the subjects of intensive research. The understanding of the generation of rare extreme events it is interesting for itself, but also can allow to identify mechanisms to control or suppress the occurrence of such events. In this way, the investigation of the phenomenon in a controllable experimental setup is very important from a practical point of view and offers a great possibility to shade new light in this subject.

In this work we investigate, both theoretically and experimentally, the appearance of rare giant pulses or rogue waves in a semiconductor laser subject to optical injection [8]. We perform a detailed experimental characterization of the parameter region where rogue waves appear, and compare the experimental observations with numerical results from the simplest rate-equation model. It is shown that the sporadic large intensity events can be understood as a result of a deterministic nonlinear process.

By changing the pump current of the injected laser, several dynamical scenarios were identified. Rogue waves were detected inside a chaotic region, for certain levels of bias current. Their typical experimental manifestation occurs in the laser power time series, where sporadic large intensity pulses are observed. To investigate the rarity of the large pulse events, and to confirm the rogue wave character according a certain definition, histograms for the laser intensity were measured.. The analysis of the theoretical model allows a discussion of the mechanisms associated with the appearance of rogue waves. Extensive numerical simulations

were performed to characterize the phase diagram of the system and parameter regions where rogue waves

occur. The role of noise in the system is investigated and its influence to induce or inhibit rogue waves is

discussed.

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Rev. Lett. 107, 053901 (2011)

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8274-01, Session 1

Light's orbital angular momentum: diffraction and applications

J. M. Hickmann, Optics and Materials Group (Brazil)

The rich relationship between the azimuthal phase of light possessing OAM and diffraction phenomena has a number of interesting effects and has motivated researchers to make new discoveries. Even traditional single slit, double slit, and aperture-iris diaphragm diffraction problems, can yield novel physical interpretations because of the unusual phase distribution of light possessing OAM.

In this paper, we review the study of the diffraction problem, in the Fraunhofer regime, by different configuration such as single slits, triangular apertures and slits, square aperture and slit for different values of m. We show that depending on the configuration it is possible to measure the topological charge in an easy and directly way, to shape square and hexagonal vortex and intensity optical lattices as well as, at single photon level, to test Born's rule and to measure the OAM of single photons.

We also investigate the use photon OAM's two-dimensional properties to extend the double-slit to a two-dimensional triple-slit configuration in the shape of an equilateral triangle, obtaining a bidimensional triangular interference pattern at photo-count level, whose size depends on the OAM amount. Our results confirm that only pairs, here associated to path and azimuthal phases, contribute to the two-dimensional photon detection probability, as established by Born's rule.

8274-02, Session 1

Mechanically induced image rotation: analogy of the Faraday effect for orbital angular momentum

M. J. Padgett, S. Franke-Arnold, G. M. Gibson, Univ. of Glasgow (United Kingdom); R. W. Boyd, Univ. of Ottawa (Canada)

A spinning window is predicted to slightly rotate the transmitted image. We enhance this effect by using green light and a window made from ruby. The ruby acts as a slow light medium, increasing the length of time that light spends in the medium and giving image rotations of several degrees. In the orbital angular momentum basis set, such rotations are analogous to the Faraday effect for the rotation of polarisation (spin angular momentum).

8274-03, Session 1

Cholesteric polymers and the orbital angular momentum of light

W. Löffler, H. P. Woerdman, Leiden Univ. (Netherlands)

Conventional optical activity is connected to the polarization of photons, now theory suggests that an analogous effect could exist for the orbital angular momentum (OAM) of light, which is a spatial, or topological, property of photons. Few experimental investigations of this issue have been done, especially an experiment testing both analogies of the manifestations of optical activity, circular dichroism and optical rotation, in the same system. For polarization, these are associated with the absorptive and dispersive part of a chiral response of the medium, and if they have counterparts in OAM space, they would correspond to OAM-dependent extinction and OAM-intermodal dispersion. The latter would manifest itself as a rotation of a Hermite-Gauss mode.

We discuss our recent experimental results on this issue for the case of a cholesteric polymer: This is in particular interesting since the helically-arranged molecules resemble the helical wavefronts of the OAM probe light precisely. We test for interaction with strongly focussed light where spin-orbit coupling is significant. Our improved experimental results set new bounds on such an effect in cholesteric polymers, and we can firstly exclude possible effects due to spin-orbit coupling. Since the existence of such an effect would have pronounced influence in many fields, we discuss further required experiments and present ideas on how to actually observe the effect which could be phrased "topological activity".

8274-04, Session 1

Optical superchirality and electromagnetic angular momentum

D. L. Andrews, M. M. Coles, Univ. of East Anglia Norwich (United Kingdom)

The intrinsic helicity of electromagnetic fields with circular polarization provides a widely employed basis for chirally sensitive spectroscopic techniques such as circular dichroism, and the link with photon spin is well understood. Recently, interest has been created by proposals to exploit 'superchiral' electromagnetic fields, as may for example be generated in the vicinity of planar chiral metamaterials, in the expectation of securing higher levels of sensitivity to the local chirality of complex material structures. Here the link between the associated helicity and optical angular momentum is less well developed, and there are fundamental questions of physicality to resolve. To address these issues invites a consideration of the most appropriate, general metrics for optical chirality, and their physical interpretation. In this connection the chirality density, a time-even pseudoscalar, was reintroduced recently by Cohen and Tang as a measure of disparity between the rates of excitation of chiral molecules with differing handedness. The work reported here deploys this and other tensor measures originally introduced by Lipkin, all of which have been shown, through Maxwell's equations, to signify conserved dynamical quantities for an electromagnetic field in a vacuum. Using Fourier mode expansions in the molecular formulation of quantum electrodynamics, the photonic basis of chirality density is explored with reference to arbitrary polarization states, and shown to relate directly to the angular momentum of the electromagnetic field. The analysis of multi-mode beams with complex wavefront structures affords a deeper understanding of the degree of interplay between optical chirality and optical angular momentum.

8274-05, Session 1

Measuring the orbital angular momentum density for a superposition of Bessel beams

A. Dudley, I. Litvin, A. Forbes, CSIR National Laser Ctr. (South Africa)

Since the discovery of light beams carrying orbital angular momentum (OAM), many techniques for the measurement of OAM have been developed, ranging from interferometers to computer generated holograms. In this report we theoretically calculate and experimentally measure the OAM density of a coherent superposition of two non-diffracting Bessel beams. Although the intensity pattern of the superimposed field rotates at a fixed angular velocity (which is due to the differing wave-vectors of the component fields), we show that the magnitude and direction of the OAM is dependent on the radial position within the field. We outline a simple approach using only a spatial light modulator to measure the OAM density for a superposition of non-diffracting Bessel beams. The modal decomposition is executed by obtaining the inner product of the incoming field with a predetermined match filter, which is programmed on to a spatial light modulator, for various OAM values and at particular radial positions. Since the weighting coefficients can be experimentally measured as a function of the radial co-ordinate and the azimuthal mode, by measuring the on-axis intensity of the inner-product, the OAM density can be measured directly and we show that our measurements are in good agreement with predicted values. The ability to measure the OAM distribution of optical fields has relevance in optical tweezing, and quantum information and processing.

8274-06, Session 1

A higher order Poincare sphere representation

G. Milione, R. R. Alfano, The City College of New York (United States)

A recently proposed higher order Poincare sphere constructed from the total optical angular momentum eigenstates of circular polarized optical vortices and the higher order states of polarization of vector vortex beams is presented. The higher order Poincare sphere is built up from higher order Stokes parameters that serve as the sphere's cartesian coordinates. An experimental method with which to measure the higher order Stokes parameters in terms of a spin and orbital angular momentum decomposition of a light beam analogous to conventional polarimetry is also discussed. In the prescribed higher order Poincare space there exist multiple spheres which can be manipulated to represent various spatially inhomogeneous states of polarization. This novel representation is applied to facilitate the description of various vector polarization beams which can be considered as linear combinations of orthogonal circular polarized optical vortex beams of opposite topological charge. such as radial and azimuthally polarized cylindrical vector beams, the recently demonstrated full Poincare beams, and hybrid vector beams. Additionally, the higher order Poincare sphere representation offers a convenient analysis of the spin-orbit conversion of q-plates.

8274-07, Session 2

Current reversals in a deterministic optical rocking ratchet

K. P. Volke-Sepúlveda, A. V. Arzola, J. L. Mateos, Univ. Nacional Autónoma de México (Mexico)

The study of transport induced by symmetry breaking under unbiased forces has flourished as one of the most active and diverse fields in recent times. It includes the study of the so called Brownian motors and ratchets, initially motivated by the transport of molecular motors, but soon extended to many other domains in classical and quantum physics. Recently, we presented an experimental realization of a deterministic optical rocking ratchet [A. V. Arzola et al. Phys Rev. Lett. 106: 168104 (2011)]. We obtained a systematic motion of microparticles and demonstrated that it is possible to control their average velocity and their direction of motion in real time by properly tuning experimental parameters. We have extended our study in order to establish the conditions for observing the crucial effect of current reversals in deterministic conditions, phenomenon predicted more than a decade ago, but experimentally demonstrated for the first time in our system.

8274-08, Session 2

Picolitre rheology of gaseous media using a rotating optically trapped birefringent microparticle

Y. Arita, A. McKinley, M. Mazilu, Univ. of St. Andrews (United Kingdom); H. Rubinsztein-Dunlop, The Univ. of Queensland (Australia); K. Dholakia, Univ. of St. Andrews (United Kingdom)

Lateral translation and rotation of particles may lead to measurement of viscosity by equating optical forces/torques with Stokes drag forces/torques present. The optical rotation and measurement of birefringent particles has been presented previously with the applications for microrheology of liquids. Whilst particles may be trapped in air and vacuum, the application of trapped particles in the domain of microrheology has been restricted to aqueous media. We present a technique to measure the viscosity of picolitre volumes of gaseous medium using rotating microparticles. The rotation of microparticles is achieved by trapping a birefringent spherical vaterite crystal with a circularly polarized light. Transfer of angular momentum from the circularly polarised beam to the particle causes the rotation. The transmitted light is analysed to determine the applied torque to the particle and its rotation rate. The applied torque is determined from the change in the circular polarisation of the beam caused by the vaterite and the rotation rate, which is equal to the viscous drag torque on the rotating spherical particle. Assuming that the size of the rotating particle is known the viscosity of the surrounding gas can then be determined. Using this technique we measured the viscosity for picolitre volumes of air, argon and carbon dioxide at room temperature, which agree well with established values. In the domain of thermodynamics and cold quantum gases this opens up new prospects for accurate measurements of gas viscosity in a highly localised volumes and constrained geometries.

8274-09, Session 2

Optical recoil of electromagnetic radiators with asymmetric radiation pattern

J. Song, J. Shin, Y. Lee, KAIST (Korea, Republic of)

The mechanical effect of light is now opening the possibility of manipulating small objects. Mainly, two kinds of optical forces were investigated for the optical manipulation. One is scattering force. It can levitate micrometer sized dielectric particles. The other is gradient force. Using the force, it was demonstrated that sub-micrometer sized polarizable particles can be trapped in the high or low field intensity region, depending on the dielectric constant of the object relative to that of the surrounding medium.

In this work, we suggest another kind of optical force, "recoil force," which makes an electromagnetic radiator recoil by the amount of the photon momentum it generates. We show that the recoil force computed by Maxwell's stress tensor method is equivalent to that by Poynting vector integration in the far-field sphere. Therefore, the radiator with asymmetric radiation pattern will receive net recoil force since the distribution of poynting vector does not balance. By comparing the recoil force of three kinds of dipolar oscillators, we confirm that only radiator with asymmetric radiation pattern receives non-zero recoil force. To evaluate the recoil force, we define a quantity, "force conversion efficiency," which is the recoil force normalized to the total radiated power in the unit of 1/c.

In addition, we suggest directional nano-optical antenna as efficient force generator. When driven by local dipole oscillators, the directional nano-optical antenna emits photons in asymmetrical way to receive net recoil force. The force conversion efficiency of the directional nano-optical antenna exhibits resonant behavior near the antenna mode.

8274-10, Session 2

Optical negative force: tractor beam and beyond

C. Qiu, National Univ. of Singapore (Singapore); A. Novitsky, Technical Univ. of Denmark (Denmark)

The optical force will be discussed for certain special laser beams with and without gradient fields, which comes into new concepts of optical micromanipulation and realizing the tractor beams and even curved beams towing objects. We demonstrate the significance of interfering a single beam with suitable classic polystyrene or magnetodielectric particles (for example, suitable size or magnetic response), which can manipulate the force to pull the particle continuously owing to negative photon pressure. The particle can be towed along a straight line toward the source as a tractor beam and possibly along a curved trajectory. We will show how the requirement and feasibility of such vector beams should be exploited to exert pushing or pulling forces, report the material-independent conditions for negative optical force, and present beam generation mechanism acting as the tractor beam. This phenomenon of light-driving force opens new paths to particle separation/pulling and optical micromanipulation.

8274-11, Session 3

A compact source for quantum image processing with four-wave mixing in Rb85

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We have built a compact source of intensity-squeezed twin-beams based on four-wave-mixing in atomic Rubidium 85 vapor. The twin-beams are generated via a double-lambda scheme by pumping near the D1-line with a strong laser beam and injecting a probe beam detuned to the ground-state splitting at a small angle relative to the pump, which results in probe-amplification and the generation of a conjugate beam. Since the photons in the probe and conjugate beams are created in pairs, they exhibit intensity-difference squeezing. As squeezing is attainable without the need for a cavity, the generated twin beams are inherently multi-spatial-mode, as has been shown previously by our group.

With a total optical power of 300 mW derived from a free running diode laser and a tapered amplifier to pump the four-wave-mixing process, we achieve 2.5 dB relative intensity squeezing of the twin beams below the standard quantum limit, without accounting for losses.

We achieve a total optical power in the probe and conjugate beams of 100 µW by injecting a 10 µW probe, corresponding to a gain of 5. Higher squeezing is currently limited by low pump power.

We are currently using this squeezed light source to investigate the transfer of quantum correlations through media of anomalous dispersion.

Another interesting prospect is the transfer of quantum correlations from the twin-beams to an ensemble of cold atoms.

The portability of this compact two-by-two foot source allows for interfacing with different experiments with relative ease.

8274-12, Session 3

Controlling the degree of polarization of a coherent beam through spatial-polarization correlations

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It is customary to think that an unpolarized optical beam must be characterized by random fluctuations that result in loss of coherence. We describe here another route through which the degree of polarization of a coherent optical beam traversing a deterministic optical system may decrease. By introducing judicious correlations between polarization and another degree of freedom, namely the spatial parity of the beam along one axis, measurements of the degree of polarization reveal a partially polarized beam. The correlations between the polarization and spatial parity degrees of freedom are intoduced through the use of a polarization-sensitive spatial light modulator (SLM). The SLM modulates the spatial phase distribution of one polarization component only (without affecting its amplitude). Thus by controlling the polarization of an incident Gaussian beam and manipulation of the imparted phase distribution we can implement an arbitrary degree of correlation between polarization and spatial parity which results in complete control over the degree of polarization. We quantify the correlations between spatial parity and polarization using a Bell's-like inequality traditionally used in quantum optics as a test of nonlocality exhibited by two photons in an entangled quantum state. We adapt this inequality to the case of two degrees of freedom carried by a single classical beam and demonstrate its usefulness in quantifying correlations between these correlations. This work elucidates the impact that many ideas recently developed in the field of quantum information processing may have on the study of classical optical coherence.

8272-28, Session 3

Realization of ultra-broadband entangled photons and application to quantum sensing

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Photon pairs correlated in a very short time (a few femto seconds), which has called mono-cycle entangled photons (MEPs)[1] - will be useful for many applications from sensing, metrology to information processing.

As the first step toward the realization of MEPs, here we report the realization of an ultra-broadband parametric fluorescence with bandwidth over 810nm (790nm-1600nm) using a chirped quasi-phase matched(QPM) device, where pump wave length was 532nm. The QPM device is a 2cm-long stoichiometric lithium tantalite (SLT) crystal with the magnesium oxide concentration of 1.0mol-% (MgSLT) with 10% chirping of the poling period (from 8.000 um to 8.825 um).

We will also discuss the application of broadband entangled photons to quantum optical coherent tomography with some recent experimental results.

This work was supported in part by JST-CREST project, Grant-in-Aid from JSPS, Quantum Cybernetics project, FIRST Program of JSPS, Special Coordination Funds for Promoting Science and Technology, and the GCOE programs.

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8272-29, Session 3

Parallel generation of 15 quadripartite cluster entangled states over the optical frequency comb of a single optical parametric oscillator

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Quantum computing holds the revolutionary promise of exponentially speeding up such calculations as integer factoring and quantum simulation. Building a practical quantum computer requires a scalable number of individual quantum memory units (“qubits”, here “Qmodes”), all individually addressable and controllable without error. In this work, we demonstrated an experimental breakthrough: the generation of a record-size quantum register of 60 Qmodes, in 15 independently entangled quadripartite square cluster states. This massively scalable implementation of a quantum register was all-optical and based on a single optical parametric oscillator (OPO) that emitted quantum electromagnetic fields (the Qmodes) at equally spaced optical frequencies over its optical frequency comb. The OPO had specially engineered nonlinear optical crystal and pump field, which were designed to enable specific continuous-variable entangling, a.k.a. “two-mode squeezing,” interactions throughout the quantum comb in order to generate the desired state “top down,” in one fell swoop. Technical constraints limited the measured number of generated Qmodes to the reported 60 but we estimated the actual size of our quantum register to be of 180 to 600 Qmodes. This work is a major step toward entangling all these Qmodes together in a single cluster state, in order to achieve a scalable platform for a quantum computer.

8274-13, Session 4

Full-field quantum correlations in position, momentum, and intermediate bases

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We have developed a new approach to measuring the spatial position of a single photon. Using fibres of different length, all connected to a single detector allows us to use the high timing precision of APD to spatially locate the photon. We have built two 8-element detector arrays to measure the full-field quantum correlations in position, momentum and intermediate bases for photon pairs produced in parametric down conversion. We obtain correlations an order of magnitude below the classical limit.

8274-14, Session 4

Fiber transport of spatially entangled photons

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High-dimensional entangled photons pairs are interesting for quantum information and cryptography: Compared to the well-known 2D polarization case, the stronger non-local quantum correlations could improve noise resistance or security, and the larger amount of information per photon increases the available bandwidth. One implementation is to use entanglement in the spatial degree of freedom of twin photons created by spontaneous parametric down-conversion, which is equivalent to orbital angular momentum entanglement, this has been proven to be an excellent model system.

The use of optical fiber technology for distribution of such photons has only very recently been practically demonstrated and is of fundamental and applied interest. It poses a big challenge compared to the established time and frequency domain methods: For spatially entangled photons, fiber transport requires the use of multimode fibers, and mode coupling and intermodal dispersion therein must be minimized not to destroy the spatial quantum correlations. We demonstrate that these shortcomings of conventional multimode fibers can be overcome by using a hollow-core photonic crystal fiber which follows the paradigm to mimic free-space transport as good as possible, and are able to confirm entanglement of the fiber-transported photons. Fiber transport of spatially entangled photons is largely unexplored yet, therefore we discuss the main complications, the interplay of intermodal dispersion and mode mixing, the influence of external stress and core deformations, and consider the pros and cons of various fiber types.

8274-15, Session 4

Two-photon cluster states using polarization and spatial modes

E. J. Galvez, M. Novenstern, W. H. Schubert, Colgate Univ. (United States)

We present a method to produce two-photon four-qubit cluster states of polarization and spatial modes. Our technique allows the preparation of non-separable states of polarization with any pair of pure spatial modes. A starting point is to produce the [1/root(2)](0000+1111) state, where two qubits are polarization modes and the other two qubits are spatial modes (e.g., Hermite-Gauss or Laguerre-Gauss eigenmodes). Our experimental method consists of first producing photon pairs in polarization-entangled states. The spatial mode of each photon is projected onto the fundamental mode by passage of both photons through single-mode optical fibers. Each member of the pair then enters a polarization interferometer, where orthogonal spatial modes are encoded with polarization eigenstates. The four-qubit cluster state (1/2)(0000+0011+1100-1111) is obtained by rotating the modes of one photon before entering the interferometer. Our first implementation involves the use of first-order Hermite-Gauss modes, although in principle any pair of orthogonal spatial modes can be used.

8272-30, Session 4

Information in a photon

R. W. Boyd, Univ. of Ottawa (Canada)

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. In this presentation, 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. More generally, we describe how image formation making use of quantum states of light allows dramatic new possibilities in the field of image science. The field of quantum imaging strives to make use of the quantum aspects of light fields to achieve image formation with enhanced performance. One such example that we are studying is the possibility of performing imaging by impressing an entire image onto a single photon. We recently completed one study [1] that shows that by means of a holographic method we can discriminate between two objects even when they are illuminated by only a single photon. In a related study we have shown that we can discriminate among four objects using a single biphoton in a ghost-imaging configuration [2]. We have also studied [3] 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 [4].

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8274-34, Poster Session

Enhanced near-field properties of a gap of TiO2 nanosphere pairs for photocatalysis optical trap

T. Honda, M. Terakawa, M. Obara, Keio Univ. (Japan)

Localized near field in a nanostructure has attracting much attention as a template for size selective optical trapping beyond the diffraction limit. The near-field optical trapping has mainly been studied by using metal substrates such as Au nanodot pairs, periodic Al nanoslits, and nanoapertures in an Au film. In this paper, we newly design a near-field optical trap for size-selective photocatalysis by using pairs of poly rutile TiO2 nanospheres. The enhanced near-field distribution in a gap between the nanospheres was simulated by FDTD (Finite-Difference Time-Domain) method. The simulation system consists of two nanospheres of 200 nm in diameter placed on a silica (n = 1.45) substrate in water. The excitation wavelength is 400 nm, as an excitation wavelength of the rutile TiO2 photocatalyst at band edge spectrum of 413 nm. The corresponding band gap is 3.0 eV. A maximal enhanced electric field intensity in a 5 nm gap between the TiO2 spheres is enhanced by a factor of 13 compared to the incident intensity. The 400 nm excitation laser is used for both near-field generation and photocatalyst pumping. The optical force to trap samples and the charge distribution inside the nanosphere were simulated based on the near-field intensity distribution. The samples will be trapped in the highest intensity near-field zone by optical force. The charge density is increased on the nanosphere's surface. These results suggest that the pairs of TiO2 nanosphere is used for near-field optical trap which provides size-selective photocatalysis for potential applications in medicine and water biology.

8274-35, Poster Session

Tracking phase singularities in optical fields

J. Borchardt, M. Duparré, S. Skupin, Friedrich-Schiller-Univ. Jena (Germany)

Phase singularities in optical fields (vortices) have attracted a lot of interest over the past decades. On the one hand, vortices are interesting because of their topological properties, on the other hand they offer possibilities to probe or apply optical forces on matter.

Optical vortices in a propagating beam can undergo rich dynamics, e.g., singularities can change their relative lateral position, two singularities of opposite charge can be born or annihilated etc. Because the overall properties of those vortex beams can be characterized by their singularities, it is of great interest to locate them in the beam cross-section, to quantify their charge and to determine their trajectories.

Here, we present an algorithm solving this task for arbitrary beam propagation problems. The basic procedure ("singularity finder") searches for local minima of the field intensity, i.e., potential locations of phase singularities. The topological charge of each possible singularity is determined by integrating along closed paths. Now, in the beam propagation, after each step the "singularity finder" is called to determine positions and charges of all singularities in the beam cross-section. Finally, the trajectories and charges of all singularities are visualized.

As a testbed for our tracking algorithm we use the motion of selected singularities in multi-mode optical fibers. Trajectories of the break-up of high charge singularities due to (even weak) distortions of the fiber are observed. Furthermore, we believe that our tracking algorithm may be also useful to characterize decay and stability of higher-order spatial solitons in, e.g., nonlocal nonlinear media.

8274-36, Poster Session

Laser guidance-based cell sorting in a microfluidic biochip

W. Qin, L. Schmidt, Z. Ma, H. Yao, Clemson Univ. (United States); X. Peng, Shenzhen Univ. (China); X. Yuan, Nankai Univ. (China); B. Gao, Clemson Univ. (United States)

Laser guidance technique has been demonstrated to be able to detect cells with very high sensitivity by simply measuring the guidance speed. Consequently, it has high potential to be applied in the field of cell sorting, which plays an important role in fundamental life science and biomedical applications. Comparing with conventional active sorting methods, laser guidance-based passive optical sorting technique is noninvasive and easy to control. It relies on the intrinsic optical properties of cells, such as refractive index, shape and size. In this study, we develop a microfluidic chip to achieve a lab-on-a-chip cell sorting with the assistance of laser guidance. Polydimethylsiloxane (PDMS) is used to make the chip with soft lithography. It can be reversibly sealed to a coverslip through van der Waals bonding, creating a leakless microchannel. A laser diode (Intense 6020-9MM-CP, 827 nm), integrated into a TCLDM9-TE-Cooled mount, serves as the guiding laser source. Its beam is reshaped by a pair of prisms to achieve high beam quality. A single mode optical fiber is mounted into the PDMS chip to transmit another laser (CW, 800 nm, 2W maximum power) for propelling cells to different subchannels. The cells, flowing in the microfluidic channel while being laser guided, are captured by a high-speed camera (Photon Focus MV1-D1312I). CUDA compatible GPU-Tesla 1060 and Quadro FX 1800 are utilized to assess the cell moving speed in real time with a imaging rate ofapproximately 130 to 170 frames per second. Once identifying a cell with the target speed, the imaging system will quickly send a signal to trigger the 2W laser beam to laterally move the cell into a desired subchannel, leading to cell separation.

8274-37, Poster Session

Observation of speckle instability in Kerr random media

S. Residori, U. Bortolozzo, Institut Non Linéaire de Nice Sophia Antipolis (France); P. Sebbah, L'Institut Langevin (France)

Large intensity fluctuations of light diffusing through random media originate from the interference of the multiply scattered waves. The resulting speckle pattern can be viewed as a fingerprint of the disorder configuration of the medium and therefore is highly sensitive to scatterer motion. In the presence of nonlinearity, the speckle may become instable as a result of the positive feedback provided by the scattering medium, even in absence of scatterer motion. This instability was predicted for nonlinearities exceeding a certain threshold value and demonstrated by Skypetrov and Maynard [1] using a stationary self-consistent theory.

Here, we demonstrate experimentally speckle instability in a scattering two-dimensional nonlinear disordered system. We employ a photorefractive liquid crystal light valve (LCLV), which combines a nematic liquid crystal (LC) layer with a thin monocrystalline photorefractive crystal (BSO) in the form of a cell wall [2]. Controlled random orientations of the LC layer are obtained by projecting onto the BSO layer computer-generated random patterns via a spatial light modulator. The beam of a HeNe laser crossing the LCLV is transversely scattered by the randomly modulated nematic refractive index, as it bounces back and forth between the plates surrounding the LC. The nonlinearity is provided by the reorientational Kerr effect of the nematic LC. Above a certain threshold intensity, the HeNe speckle pattern starts to blink at a specific frequency, which is the signature of the speckle instability. The threshold is also found to be disorder dependent [3]. Localization regimes can eventually be attained depending on the distribution of disorder.

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8274-38, Poster Session

Structural features of the diffraction field

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Optical diffraction fields have in general a spatial complex structure and some times can generate focusing regions, in this work we describe the focusing region associated with highly symmetric transmittances, analyzing its associated phase function. We show that generic features can be studied from a differential equation for a focusing geometry, which is obtained through angular representation for diffraction fields, according to the choice of the parameters involved, the diffraction field presents a new focusing region whose geometry and spatial evolution can be described with the only analysis of the phase singularities avoiding the integral representation.

8274-39, Poster Session

Diffraction characteristics of optical and polarization vortices generated by an axially-symmetric polarizer

M. Sakamoto, K. Oka, R. Morita, Hokkaido Univ. (Japan)

White-light optical and polarization vortices have attracted attentions because of potential applications such as the ultrafast spectroscopy and the astronomical coronagraph. We previously developed an achromatic method to generate white-light vortices by use of an axially-symmetric polarizer (ASP) illuminated by a circularly-polarized light. This method has a feature that it is free from the spatial- and topological-charge-dispersions. With this method, we have demonstrated the generations of ultra-wideband optical and polarization vortices.

In this presentation, we report the experimental study on the diffraction characteristics of the vortices generated by the ASP. First, regarding the optical vortex with uniform polarization, the observed diffraction pattern has a dark core whose diameter rapidly increases with the distance from the ASP, whereas the beam diameter does not expand so much. This behavior is significantly different from that of the Laguerre-Gaussian beam whose core diameter is scaled by the beam diameter. On the basis of the numerical simulation, the experimental results were described as the Fresnel diffraction from a point-like vortex at ASP, whose core diameter is considerably small.

Second, when a light with radially-linearly polarization (space-variant linear polarization) from ASP is diffracted, we observe the polarization change within the central narrow region of the diffracted beam. In this region, the linear polarization turns into the elliptical polarization and its major axis is tilted from the radial direction. This phenomenon is explained by the decomposition of the radially-lineally polarized light into a plane wave and a point-like optical vortex which are respectively circularly-polarized with opposite handedness.

8274-41, Poster Session

Broadband orbital angular momentum manipulation using liquid crystal thin films

Y. Li, J. Kim, M. J. Escuti, North Carolina State Univ. (United States)

We introduce two high efficiency thin-film optical elements to generate and control the orbital an-gular momentum (OAM) of various light sources: a broadband q-plate and a broadband forked po-larization grating (FPG). OAM manipulation is achieved by complex and locally varying alignment of a thin layer of liquid crystal (LC) polymer acting on the Pancharatnam-Berry phase. A q-plate generates one of two pure light OAM states or superpositions of them depend on incident polariza-tion. As a diffractive element, an FPG further modulate the linear momentum of light simultaneous-ly with OAM and automatically separates the two possible output OAM states in far field. So that a pure state input will always be transformed by FPG to pure helical beams. The broadband response is implemented by a stack of sub-layers of LC with opposite twist handedness chiral agents that compensate the chromatic dispersion of retardation using the effect of twist. A significant increase of bandwidth over conventional narrowband q-plates and FPGs is demonstrated, which enables them as single elements to operate on a wide range of wavelengths with no need of any tuning. Both elements are efficient (> 90%) and thin, which easily fit into optical systems and enhance the ability of manipulating multiple wavelengths in applications such as optical trapping and high capacity information.

8274-16, Session 5

Formation of optical flux lattices for ultra cold atoms

G. Juzeliunas, Vilnius Univ. (Lithuania)

Currently there is a great deal of interest in creating an artificial magnetic field for ultra cold atoms using the geometric gauge potentials [1]. The coupling with light fields modifies the atomic internal states making them position dependant. This provides geometric vector and scalar potentials. The method can generate a non-zero effective magnetic field for non-trivial spatial arrangements of the laser fields and/or position-dependent detuning of the atom-light coupling. In these approaches the effective magnetic flux over the atomic cloud increases linearly with the cloud dimensions. Recently it was shown that the magnetic flux induced by the geometric potentials can be made proportional to the surface area of the atomic cloud and thus be considerably increased by exploiting the optical flux lattices [2]. For this it was suggested to use the light fields containing an array of vortices and anti-vortices produced by two standing waves with a time-phase difference. If additionally the detuning of the atom-light coupling exhibits an oscillatory position-dependence, a non-staggered magnetic flux can be formed over such an optical lattice. In this talk we first present a general background of the optical lattices for ultra-cold atoms. Subsequently we explore the optical flux lattices, and also propose and analyze a novel scheme for creating a square flux lattice using the Raman transitions.

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8274-17, Session 5

Optical eigenmodes for imaging applications

S. Kosmeier, M. Mazilu, A. C. De Luca, J. Baumgartl, T. Vettenburg, K. Dholakia, Univ. of St. Andrews (United Kingdom)

We decompose the light field in the focal plane of an imaging system into a set of optical eigenmodes. Then the superposition of these modes is identified, that optimizes the imaging process for a certain purpose. In practice the modes are implemented using a spatial light modulator. The optical eigenmodes of a system can be determined fully experimentally, taking aberrations into account. Alternatively, theoretically determined modes can be encoded on an aberration corrected spatial light modulator. Both methods are shown to be feasible for applications.

To achieve subdiffractive light focussing, optical eigenmodes are superimposed to minimize the width of the focal spot within a small region of interest. In conjunction with a confocal-like detection process, these spots can be utilized for laser scanning imaging. With optical eigenmode engineered spots we demonstrate enhanced two-point resolution compared to the diffraction limited focus.

Furthermore, in a ghost imaging fashion, optical eigenmodes are capable of phase sensitive indirect imaging. Therefore, the superposition of modes is determined that maximizes the intensity resulting from the light-sample interaction. Numerically we show the phase sensitivity by projecting optical eigenmodes onto a Laguerre-Gaussian target with a unit vortex charge. Experimentally the method is verified by indirect imaging of a transmissive sample.

Finally, we utilize optical eigenmodes for non-scanning full-field Raman imaging by maximizing the Raman signal from the sample in a chosen spectral range. Experimental validation of this concept is given by Raman imaging of polystyrene beads.

8274-18, Session 5

Bio-optofluidics cell sorter

J. Glückstad, Technical Univ. of Denmark (Denmark)

I will outline the specifications of a portable Biophotonics Workstation we recently have developed that utilizes high-speed spatial light modulation to generate an array of currently up to 100 reconfigurable laser-traps making 3D real-time optical manipulation of advanced structures possible with the use of joysticks or gaming devices. The fabrication of microstructures with nanometer-sized features, for example a nano-needle, coupled with the real-time user-interactive optical control allows a user to robotically actuate appended nanostructures depending on their intended function. These micro-platforms carrying nanotools are seen to have potential uses in a variety of micro-biological experiments. Optically actuated nanoneedles may be functionalized or directly used to perforate targeted cells at specific locations or force the complete separation of dividing cells, among other functions that can be very useful for the group of microbiologists.

8274-19, Session 5

Combined acoustic and optical trapping

G. Thalhammer, R. Steiger, S. Bernet, M. Ritsch-Marte, Innsbruck Medical Univ. (Austria)

We present the simultaneous implementation of acoustic and optical trapping of living micro-organisms within a microfluidic environment. Optical trapping uses focused laser beams and offers a very precise and flexible way of handling individual small particles, but the comparatively weak optical forces are a limiting factor if one wants to scale this method for trapping of many or large particles. On the other hand, the larger wavelength of ultrasound allows one to separate and simultaneously confine a large number of particles within a rather large volume by acoustic forces. We are able to levitate much larger particles against gravity compared to what is possible with optical forces alone. Furthermore, the low intensities that are needed for acoustic trapping lead to a very small impact on the viability of trapped cells or micro-organisms. On the other hand, the rather large wavelength of ultrasound makes the selective handling of single, small particles with acoustic forces alone a challenging endeavor. Our approach instead combines the high precision, selectivity and flexibility of optical forces with the large scale trapping abilities of acoustic forces. We employ our recently developed optical trapping technique that we called optical macro-tweezers, which offers a much larger working distance and field of view than conventional single beam optical tweezers and therefore is well suited for a combination with acoustic trapping.

8274-20, Session 5

Laser trapping-induced phase transition of individual smectic liquid crystal micro-droplet showing size-dependent dynamics

A. Usman, W. Chiang, T. Uwada, H. Masuhara, National Chiao Tung Univ. (Taiwan)

Phase transition of smectic liquid crystalline micro-droplets of 4'-n-pentyl-4-cyanobiphenyl (5CB) dispersed in D2O induced by highly focused laser beam was studied using polarizing optical microscopy (POM) imaging. High refractive index of the droplets compared to surrounding liquid renders them to be polarizable and easily trapped by the external electric light field even at low laser powers. We found that there are two distinctive optical trapping properties with a clear threshold power; (i) below which the droplet is optically trapped and its intrinsic lamellar configuration remains intact, and (ii) above which the optical trapping is followed by smectic-to-transient twisted molecular reconfiguration (phase) transition throughout the inside of the droplet, although the droplet size is larger than the focal spot. For a droplet of 2.5-micrometer-diameter, the threshold power at the center of the focal spot is ~0.47 GW/cm2, two orders of magnitude higher than optical Fréedericksz transition in corresponding nematic 5CB thin film. The threshold power depends on the droplet size. Considering that the LC droplet is a self-organized structure with droplet-liquid interface energetic controlling the molecular orientation inside the droplet through the interfacial anchoring effect, we proposed that the likely mechanism of the phase transition involves optical reorientation at focal volume, leading to symmetry breaking throughout the inside of confined droplet and modification of droplet-liquid interfacial anchoring effect. We demonstrate the relevance of the proposed mechanism in term of the droplet size-dependent threshold power, and we will discuss these findings in detail.

8274-21, Session 5

Enhanced near field properties of gold nanoparticle pairs for size selective trap

K. Hirano, M. Terakawa, M. Obara, Keio Univ. (Japan)

We present the enhanced near field of the gap between gold nanoparaticle pairs for nanosize selective optical trap. For far-field optical tweezers, the accuracy of manipulating nanoparticles is perturbed with the Brownian motion in a colloidal medium. The particle motion stems from the weak restoring force of the optical trap which serves as an optical spring. Furthermore, the trapping volume of far-field optical tweezers does not become smaller than a half the wavelength due to the diffraction limit. Therefore, optical near-field trap using surface plasmons enhanced field is attracting much attention in order to eliminate these drawbacks, and we focus on gold nanoparticle pairs which are well known to have a high field enhancement in the nanogap. Optical properties of pairs of gold particles have been studied in terms of plasmon resonance shifts, heterodimers and the interparticle distance. Previously, a very narrow gap was mainly discussed because high field enhancement is necessary for sensitive nanosensors. Here, we investigate gold nanoparticle pairs which have a broad gap so as to trap atoms, quantum dots, small viruses, etc. Even with a broad gap, we achieved the high field enhancement factor by optimization of sphere diameter (wave length = 1064 nm). This has the advantage over far-field tweezers: only the samples which are smaller than the gap are trapped, and it will act as an efficient "optical sieve". The fabrication of this trap will be discussed.

8274-22, Session 6

Machine vision for a compact biophotonics workstation

J. Glückstad, Technical Univ. of Denmark (Denmark)

We develop a BioPhotonics Workstation (BWS) that utilizes machine vision to allow a more compact hardware setup while still maintaining reliable performance in three dimensional optical manipulation. Using a low NA counter-propagating beam geometry, the BWS is capable of long range 3D optical trapping while allowing room for side view microscopy. Simultaneous and independent optical manipulation and specialized side view microscopy techniques provide allows more interactive biological studies wherein samples can be spatially arranged or moved around while performing techniques like spectroscopy, pH analysis, and other fluorescence microscopy. Being a tool for interdisciplinary studies, decreasing the footprint and making a more user friendly interface of the BWS becomes necessary. With less expensive and less quality hardware, it is necessary to get the most performance through intelligent software design. One of the major tradeoffs of having a compact setup is having traps that are less stable in the axial direction. The use of lower power lasers decreases trapping stiffness while low cost optics introduce aberrations and non uniformities in the beam's intensity. These shortcomings are solved using dynamic vision based feedback on particle positions. The axial positions of particles are tracked in real time through side view imaging and the programmable counter-propagating beams are corrected to counteract any deviations from the desired positions. Furthermore, machine vision enables automated identification which can be used for cell or particle sorting and tracking of more complex structures such as 2-photon polymerized fabricated microtools.

8274-23, Session 6

The Bessel beam random access trap

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We report on the investigation of crossed-Bessel-beam and hybrid Bessel-Gauss configurations for optical trapping of microscopic particles. The non-diffractive nature of the Bessel beam removes the need for high-NA optics, granting unprecedented optical and mechanical access to the sample volume. Crossed beam configurations allow creating trapping volumes with small aspect ratio, in comparison to single-beam Bessel traps that create wave-guide-like structures. Scanning the intersecting beams using galvo mirrors allows placement of the trap sites randomly within the sample volume. We demonstrate this novel technique by capturing, manipulating and characterizing 1 to 10 micron-sized fused silica beads in aqueous solution confined in square capillaries with a volume of a few cubic millimeters. The trap is characterized using force measurement based on power spectral density analysis of particle positions. Laser Power dependence of the properties of the trap is also investigated. We further demonstrate sorting of particles, utilizing the random access nature of the crossed-Bessel trap, and discuss sorting and interrogation strategies involving combinations of Bessel and Gaussian beams. The large working distance and mechanical access granted by the Bessel Random Access Trap will lend itself to a variety of applications in microfluidics, immunology and other biological assays.

8274-24, Session 6

Molecular interactions between carbon nanotubes and DNA

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Carbon nanotube-DNA hybrids show great potential for applications in nanotechnology and bioengineering, such as drug delivery, biosensors, and imaging. Fundamental studies of the molecular interactions between carbon nanotubes (CNTs) and DNA molecules will lead to in-depth understanding of the structural and functional properties of this nanobiohybrid. In this work, we have combined a sensitive CNT transistor with state-of-the-art dual-trap optical tweezers to investigate the complex mechanical and electrical coupling between suspended CNTs and DNA at a single molecular level. Here, a CNT transistor was inserted into a microfluidic chamber and located by scanning photocurrent measurements. Each end of a DNA tether was attached to a microbead and held by an optical trap. When the DNA tether was moved close to the suspended CNT by optical tweezers, the negatively-charged DNA molecule can change the local electrostatic environment around the suspended CNT, which can be detected by exploring the local photoconductivity change of the CNT transistor. Moreover, dual-trap optical tweezers can be used to attach and detach the DNA molecule from the suspended CNT and thus to directly measure the mechanical interactions between a single CNT and a single DNA molecule. These fundamental experiments allow us to directly measure the molecular coupling between CNTs and DNA, as well as provide a new platform to probe electrical and mechanical interactions in other CNT-biohybrids.

8274-25, Session 7

Optical vortex lines in self-focusing nonlinear media: loops, links, and knots

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Optical vortices in defocusing media, similar to quantised vortices in atomic Bose-Einstein condensates with repulsive interactions, appear as the dark notches on a modulationally stable background of a transversely broad laser beam or a condensate cloud. These so-called dark vortex solitons are stabilized by the balance between the centrifugal force from the vortex core and the nonlinear defocusing of the surrounding wave trying to fill the notch. In contrast, vortices in optical self-focusing media appear, most notably, in the form of doughnut shaped self-localised beams on a zero background, or bright vortex solitons. These beams are generally unstable as the intensity ring gets split into fundamental (bell-shaped) solitons by azimuthal modulational instability. Here we demonstrate that optical vortices also appear spontaneously in the field of a stable fundamental soliton. We study numerically the topology of the soliton field perturbed by various initial deformations, such as twist, and observe the formation of vortex loops, spirals, and more complex structures such as links and knots. A small variation of parameters leads to vortex lines reconnections, transforming and destroying knots as well as forming new knots. We conclude that, while the vortex knots are unstable, their spontaneous appearance is a robust phenomenon. Our more detailed analysis is based on internal modes of a stable fundamental soliton in saturable medium, as an example of collapse-free Kerr-type nonlinearity. It allows to identify the physical mechanism sufficient for wave knotting as the combined action of the monople and quadrupole internal modes.

8274-26, Session 8

Tailored light fields for complex optical structuring and organisation

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Complex light fields, tailored to a specific application, have found wide applications in recent years, in particular in optical micromanipulation. We introduce the concepts of non-diffracting and self-similar beams and discuss their capabilities to create structured optical landscapes with complex distributions of orbital and spin angular momentum. While both beam classes feature highly structured transverse intensity distributions, their propagation properties differ significantly. Non-diffracting beams are characterized by their propagation invariant transverse intensity distribution. In contrast, self-similar beams feature the same transverse shape in any plane, including the Fourier plane, except for a (known) scalar scaling factor. Of particular interest are non-diffracting Mathieu beams and self-similar Ince-Gaussian beams because their ellipticity provides an additional parameter and thus increases the diversity of transverse intensity distributions significantly compared to light fields with circular or Carthesian symmetries. While non-diffracting beams enable axially extended potential wells, self-similar beams can be focussed and enable axial intensity gradients. Thus, non-diffracting Mathieu beams are ideally suited for stacking particles and extending complex two-dimensional microstructures into the third dimension. On the other hand, Ince-Gaussian beams can be readily generated in conventional holographic optical tweezers without the necessity for extensive modifications, simply by introducing a novel calculation scheme for the hologram calculation. We demonstrate optical organisation and optical funnels, exploiting the smooth spreading of Ince-Gaussian beams during propagation.

8274-27, Session 8

Fine topological structure of coherent complex light created by carbon nanocomposites in LC

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Liquid crystals doped by carbon nanotubes are actual objects both fundamentally and for applications. Fine complex light structure, optical singularities and electroconductivty of liquid crystal doped by multi-walled carbon nanotubes (MWCNTs) were observed and investigated firstly. Nematic 5CB host doped by nanotubes with 20÷30 nm diameter and 2/5÷10 µm length was put in 20 µm cell. Concentration limits for nanotubes were found when they gather spontaneously due to Van der Waals attraction and Brownian drift to compact micro scale clusters with stochastic fractal borders at 0.0025÷0.025 and 0.025÷0.05 wt. % for "long"/"short" nanotubes. Electrical conductivity of nanocomposite grows strongly at percolation transition. 5CB molecules anchor to MWCNTs and form micro scale interfacial layer with strong inner stresses. They create complex light with optical singularities and fine topological structure around clusters and between. Elaborated theory is in full agreement with experimental results.

Applied electric field under Freedericksz transition generates observed firstly multiband inversion walls with periodic changes of LC director orientation at cross-section around clusters and between them in full agreement with built theory. Inversion walls relax completely when field is switched off, i.e. induced stresses in 5CB host are in Hook's low limits. They form sometimes segmented closed loops between neighbor nanotubes clusters. Propagating laser beam scatters on sinuous borders of nanotubes clusters and creates multitude of optical vortices already on the output plane of LC cell with nanocomposite.

At whole, physical "road map" from nano dopants to micro/macro LC nanocomposites was built. Their possible applications are discussed.

8274-28, Session 8

Nonlinear mixing of optical vortices

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Optical vortices are the singular points where the field goes to zero and around which the phase screws up as an n-armed spiral, with n the topological charge [1]. In nonlinear optical systems their statistical properties have been investigated and shown to provide the scaling laws that are associated to the route towards space-time chaotic behaviors [2]. More recently, the controlled generation of optical vortex beams, that is, Laguerre - Gaussian modes possessing one or more singular points, has been revisited in view of useful applications, as the exchange of angular momentum between light and matter [3], the realization of optical tweezers [4,5] and quantum computation [6].

Here, we show that optical vortex beams can be generated via two-wave mixing in a nonlinear medium and, that such interaction creates new topological charges following the conversion rules imposed by the nonlinear mixing process in the medium. The experiments are realized by letting two optical vortex beams, previously synthesized via holographic masks, to interact in a Kerr-like medium [7,8]. The wave-mixing between the beams carrying the optical phase singularities is modeled in the mean-field approximation, providing the conversion rules for the topological charges obtained after the vortex-mixing. The predictions confirm the experimental observations both for integer and fractional charges of the interacting beams [9].

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8274-29, Session 8

Generation of highly confined optical bottle beams by photonic nanojet effect

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We report on the generation of optical bottle beams by Photonic Nanojet effect. The beam is generated by manipulating the illumination of a dielectric microsphere from which the photonic nanojet emerges on the shadow-side surface. To observe such exotic beams, the illumination has to be engineered, which is performed in the present contribution by carefully adjusting a superposition of an aberrated focused Gaussian beam and a truncated Bessel-Gauss beam, that serve as an illumination of circularly symmetric rings with phase differences. For observation and illumination engineering, a high-resolution interference microscope (HRIM) setup is used that allows monitoring the amplitude and phase distributions in space. Focusing annular illumination leads to experimental Bessel beam where the seperation distance of the side lobes is readily controlled by the numerical aperature (NA) of the focusing lens or objective. The amount of spherical aberrations and the NA makes it possible to adjust the side lobes of the focused Gaussian beam, too. For the case of one side lobe, the spot resembles an optical bottle beam with a strong confinement due to the Nanojet effect. When multiple side lobes contribute to illuminate a dielectric microsphere, a chain of three-dimensional (3D) optical bottle beams appears instead of a single Nanojet spot. Such optical-bottle-beam-like Nanojets are different from conventional optical bottle beams. The first bright spot emerging from the sphere surface shows the highest intensity due to the Nanojet effect, which creates a strong light confiment on the vicinity of the sphere surface due to the scattering phenomenon of the dielectric microsphere. Following a thorough characterization of such beams, we briefly discuss their applications for optical trapping and sorting.

8274-30, Session 8

Experimental control over soliton interaction in optical fiber by pre-shaped input field

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Femtosecond optical soliton dynamics and interaction in optical fiber play crucial roles the nonlinear shaping of the electric field during propagation. Particularly in supercontinuum generation, soliton effects such as light trapping, bound pair formation, rogue wave generation, Raman self-frequency shift (RSFS) and intersoliton energy redistribution through stimulated Raman scattering all take place simultaneously due to the presence of numerous solitons.

We present our experimental setup which allows for injecting amplitude- and phase shaped fs-pulses into a photonic-crystal fiber (PCF). This way, we can synthesize and inject

solitons of arbitrary temporal width as well as trains of solitons of arbitrary relative width, delay, phase, and amplitude. Using this setup, we experimentally investigate contemporary, fundamental theoretical work on soliton interactions. As one example, we measure the so-called “soliton force” and study its dependence on the relative group velocity. As another example, we investigate to which extent the so-called “soliton molecules” can be synthesized experimentally.

We also investigate the possible applications of the setup; the pre-shaping and the nonlinear PCF can be thought of as a “nonlinear pulse shaping” device, not only capable of shaping fields in phase and amplitude, but also - thanks to the PCF nonlinearity - of frequency converting fields, e.g. through the RSFS. As one example, we demonstrate that we have access to sufficient degrees of freedom that we can generate a pair of output solitons of almost arbitrary relative delay 0-10 ps and relative frequency 0-2000 cm-1.

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8274-31, Session 9

Tangled nonlinear driven chain reactions of all optical singularities

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We have shown that polarization singularities develop through topological chain reactions of developing speckle fields driven by photorefractive nonlinearities induced by incident laser beam [2-4]. All optical singularities (C points, optical vortices, optical diabolos,) are defined by topological structure of a correspondent wavefront and tangled by singular optics lows [4]. Therefore, they have develop in tangled way by six topological chain reactions driven by nonlinear processes in used nonlinear medium (photorefractive $LiNbO_3$:Fe in our case): C-points and optical diabolos for right/left polarized components areas, orthogonally left/right polarized optical vortices underlying them. Linearly polarized L lines separating right/left polarized areas are defined by evolution of optical field handedness in relatively big areas.

All elements of chain reactions consist from loop and chain links when nucleated singularities annihilated directly or with alien singularities in 1:9 ratio [3]. The topological reason of statistics was established by low probability of far enough separation of born singularities pair from existing neighbor singularities and influence of L lines. All of them were analyzed and measured by special elaborated technique. The hierarchy of singularities govern scenario of tangled chain reactions was defined.

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8274-32, Session 9

Twisted longitudinally polarized field in focal region

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In recent years, tight focusing properties of radially polarized beams are studied intensively. Most interesting feature of the radially polarized beam is the formation of sharper, stronger and non propagating longitudinal electric field around the focal point. The existence of a stronger longitudinal field of tightly focused radially polarized beam has many attractive applications such as particle acceleration, fluorescence imaging, optical trapping, and Raman spectroscopy.

Here we report the numerical studies on the generation of twisted longitudinally polarized beam by the superposition of two tightly focused radially polarized beams with different spiral phase shift. The total intensity distribution and polarization components are calculated using vector diffraction theory. It is observed that the total intensity and polarization components have the property of rotation. The field distribution has a spiral pattern due to the difference in the spiral phase shift between two beams. Rotation of the intensity distribution before and after the focal plane is the manifestation of difference of the Gouy phase shift of individual beam. This superposition technique can synthesize a variety of beam patterns that have the property of spiral phase as well as the rotating intensity and polarization distribution.

Presence of the spiral phase in the longitudinal polarization component will give extra degree of freedom. Rotation of longitudinal field distribution is expected to find useful applications in the field of high resolution microscopy, surface plasmon resonance, and particle manipulation. The results presented here will be useful for understanding the interaction of vectorial vortices with the scalar vortices.

8274-33, Session 9

Polarization singularities in optical Gaussian beams

E. J. Galvez, S. Khadka, W. H. Schubert, S. Nomoto, Colgate Univ. (United States)

We study polarization singularities present in optical beams prepared by non-separable superpositions of collinear high-order Laguerre-Gauss modes in orthogonal polarization states. This is done using a polarization interferometer with diffractive optical elements in each arm. Final polarization states, linear or circular, are specified once the beams are recombined. Linear polarization singularities are prepared by superposition of circularly polarized Laguerre-Gauss modes of different spin and orbital helicity but same spatial order. Circular polarization singularities are prepared by similar superpositions but with Laguerre-Gauss modes of different order. Suitable modal combinations allow the creation of desired singularity indices.

Conference 8275: Laser Refrigeration of Solids V

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8275-11, Poster Session

Thermal imaging with high spatial and temperature resolution

D. V. Seletskiy, The Univ. of New Mexico (United States) and Air Force Research Lab. (United States); S. D. Melgaard, M. Sheik-Bahae, The Univ. of New Mexico (United States)

Based on a highly sensitive differential spectroscopy technique, we present a non-contact method of optical-scanning thermal imaging with possibility of sub-thermal-wavelength spatial resolution. This technique is general and can also be applied to imaging of strain or impurity distributions at the surfaces of semiconductors. This procedure is particularly well suited for near-field imaging, and investigation of thermal transport on the nanoscale. Applications to optical refrigeration in semiconductors will be discussed.

8275-17, Poster Session

Novel photon blockade schemes for thermal link applications

D. V. Seletskiy, The Univ. of New Mexico (United States) and Air Force Research Lab. (United States); J. Trevino, S. D. Melgaard, M. Sheik-Bahae, The Univ. of New Mexico (United States)

Optical refrigerator is based on an optical heat removal from a cooling element by satisfying conditions of anti-Stokes fluorescence. This imposes a challenge of optically shielding a payload from the anti-Stokes radiation. Therefore, a link between the cooling element and a payload (the thermal link) has to exhibit high thermal conductivity while blocking the fluorescence and scattered laser light in a non-absorbing manner. In this paper we examine photon blockade structures ranging from textured kinks to hybrid systems involving light-shedding geometries and semiconductor-based epitaxially-grown distributed Bragg mirrors.

8275-18, Poster Session

Polarization-resolved optical metrology for noncontact thermometry

M. Ghasemkhani, D. V. Seletskiy, M. Sheik-Bahae, The Univ. of New Mexico (United States)

Noncontact temperature measurements with large (thermal) dynamic range are desirable in many applications. Aside from interferometric techniques, fluorescence intensity and spectral shape have been exploited in the past for sensitive thermometry in luminescent materials. Here, we present a novel method that utilizes the polarization-sensitive reflection and/or transmission of light from (through) an optical material without relying on any fluorescence. A balanced photodetector will measure the difference signal corresponding to two orthogonal polarization states with high singal-to-noise ratio. Temperature variations of <10mK have been measured but, with further improvements, 2mK or lower should be achievable.

8275-01, Session 1

Optical cooling of Nd-doped solids

A. J. Garcia-Adeva, R. Balda, S. Garcia-Revilla, M. Al Saleh, J. Fernandez, Univ. del País Vasco (Spain)

In this work we present a comprehensive review of recent work carried out by our group in the field of optical refrigeration of Nd-doped solids. Several infrared thermography measurements in Nd-doped KPb2Cl5 crystals and micro-powders both above and below the barycentre of the 4F3/2 are presented. These include some of our most recent ones obtained by employing a novel technique that allows one to perform differential temperature measurements. The role of both the direct anti-Stokes absorption processes and those assisted by either excited state absorption or energy transfer upconversion in the cooling process is discussed.

8275-02, Session 1

Emission dynamics of holmium-doped potassium lead chloride

N. J. Condon, S. R. Bowman, S. P. O'Connor, U.S. Naval Research Lab. (United States); R. S. Quimby, Worcester Polytechnic Institute (United States)

Single-crystal holmium-doped potassium lead chloride, Ho:KPb2Cl5, was grown using a modified Bridgman technique similar to that previously used to successfully grow Er:KPb2Cl5 single crystals. Absorption spectra were acquired from the ultraviolet through the infrared, and these data were used to perform a Judd-Ofelt analysis. Visible emission spectra were acquired at several different pump wavelengths and the fluorescence lifetimes of many of the significant transitions in the visible and infrared were measured. These lifetimes were found to be in good agreement with the predictions of the Judd-Ofelt analysis. The 5I7 → 5I8 transition exhibited a fluorescence lifetime comparable to the lifetimes observed in fluoride hosts. In analogy to the ~1.5 μm transition of Er:KPb2Cl5, in which optical cooling has been demonstrated previously, this transition is an excellent candidate for optical cooling: It is an unquenched transition between the ground state and the first excited state in a host where excitations resulting from upconversion are expected to decay primarily via radiative pathways. Thus, we are studying this material's potential usefulness for optical refrigeration in the eye-safe 2 μm spectral region where high-power laser sources are becoming increasingly available.

8275-03, Session 1

High sensitivity spectroscopic and thermal characterization of cooling efficiency for optical refrigeration materials

S. Melgaard, D. Seletskiy, M. Sheik-Bahae, The Univ. of New Mexico (United States); M. Tonelli, A. Di Lieto, Univ. di Pisa (Italy)

Since recent demonstration of cryogenic optical refrigeration, a need for reliable characterization tools of cooling performance of different materials is in high demand. We present our experimental apparatus that allows for temperature and wavelength dependent characterization of the materials' cooling efficiency and is based on highly sensitive spectral differencing technique or two-band differential spectral metrology (2B-DSM). First characterization of a 5% w.t. ytterbium-doped YLF crystal showed quantitative agreement with the current laser cooling model, as well as measured a minimum achievable temperature (MAT) at 110 K. Other materials and ion concentrations are also investigated and reported here.

8275-04, Session 1

Intracavity laser cooling using a VECSEL

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We report the first observation of intracavity laser cooling inside of a VECSEL. An InGaAs quantum well active region emitting around 1030 nm allows the VECSEL to reach output powers in excess of 10 W using a 1% transmission output coupler. A 5% doped Yb:YLF crystal is placed inside the cavity under Brewster angle in the Ec orientation, which results in approximately 6% loss per cavity round trip. The cooling sample is mounted on microscope cover slips to minimize conductive thermal load, such that the dominant loads are convective due to the air ambient, and radiative. We monitor sample temperature using a thermal camera and differential luminescence thermometry (DLT). Cooling of approximately 0.5 K is observed.

To reach lower temperatures, the sample, supported on optical fibers, is placed inside a vacuum chamber, to effectively eliminate convective and reduce conductive thermal load. The window of the vacuum chamber is placed inside the cavity at Brewster angle to avoid reflection losses; the cavity end mirror is also placed inside the vacuum chamber, so no additional window is needed. Using DLT, cooling of 20 K is observed. Under similar conditions, but utilizing a non-resonant multi-pass pumping scheme, cryogenic operation of an optical refrigerator down to 155 K has previously been reported, when exciting a Yb:YLF crystal near the E4-E5 Stark manifold transition.

Furthermore, we are developing a compact and efficient integrated cryocooler device, which combines the VECSEL chip and cavity in the same vacuum chamber as the cooling crystal and payload.

8275-05, Session 1

All fiber approach to solid-state laser cooling

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A light weight, compact, vibration-less and micro-scale cooler based on optical refrigeration using an all-fiber approach is being developed. Specifically, a single mode Tm^{+3}-doped fiber laser with high electrical-to-optical efficiency (> 20% E-O) and power up to 100W has been built to pump a Tm^{+3}-doped glass fiber, which is designed to provide the cooling action on the affixed heat source. The all-fiber cooling system has several key features: 1) its cooling power benefits from high optical confinement in the fiber core; 2) the all-fiber system can conveniently transfer part of the heat to a remote location, and 3) both active fibers and passive coupling fibers are potentially capable of surviving in harsh space conditions. Fiber designs for minimizing fluorescence re-absorption and guiding the waste photons will be presented and discussed. Theoretical modeling of optical cooling in the fiber and thermal modeling of the entire fiber cooler are being performed in parallel with the experiments.

8275-06, Session 2

Optical filtering of Stokes lines for cooling

G. Bahl, M. Tomes, T. Carmon, Univ. of Michigan (United States)

To be completed.

Invited by Prof. Mansoor Sheikh-Bahae.

8275-07, Session 2

Laser cooling of atoms by collisional redistribution of fluorescence

U. Vogl, National Institute of Standards and Technology (United States) and Joint Quantum Institute (United States); A. Sass, M. Weitz, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany)

We have experimentally demonstrated cooling of an atomic gas based on collisional redistribution of fluorescence, using rubidium atoms subject to 200 bar of argon gas pressure. The frequent collisions in the ultradense gas transiently shift a far red detuned laser beam into resonance, while spontaneous decay occurs close to the unperturbed atomic resonance frequency. During each excitation cycle, a kinetic energy of order of the thermal energy kBT is extracted from the dense atomic sample. We presently achieve cooling in a heated gas from an initial temperature of 410°C down to -120°C temperature in the laser beam focus within 100 ms.

8275-08, Session 2

Laser cooling of solids by stimulated Raman scattering and fluorescence

S. C. Rand, Univ. of Michigan (United States)

Optical refrigeration is very effective in gases because the Doppler effect can be harnessed as a powerful tool for cooling. In solids, where the Doppler effect is ostensibly absent, cooling efforts to date have relied entirely on anti-Stokes fluorescence which attains only modest cooling rates and temperatures (T>100 K) compared to gases. Better methods of radiative cooling of solids are needed. Potential applications include “radiation-balanced” solid state lasers, improved gravitational wave detectors, cooling of compact frequency references, low-noise infrared imagery in space, and superconducting electronics. All-optical cooling to sub-Kelvin temperatures from ambient therefore continues to be an important objective of research on this topic. This paper describes a new, high-efficiency approach to laser cooling of solids that is directly applicable to rare earth solids and may be adaptable to semiconductors. Here the combination of a resonantly-enhanced Raman transition (4fn→4fn) and fast incoherent pumping on an inter-configurational transition (4fn→4fn-15d) of a RE3+ ion is proposed for efficient solid state laser cooling that conserves momentum and energy and improves on methods with inherently slow decay rates. A key feature of this method is the detuning of single photon transitions from the absorption peak by the Stokes shift of the longest wavelength fluorescent emission transition, so that neither excited nor ground state configuration relaxation produces net heating, regardless of the magnitude of the Stokes shift. Also, while the description above refers to a single optical axis, the method is readily extendable to three dimensions using variable detuning and three orthogonal pairs of pump beams to address all vibrational degrees of freedom of the solid. Phonon selection rules will be discussed and theoretical single-pass cooling rates for Ce:YAG shown to exceed multi-pass capabilities of anti-Stokes cooling and to yield temperature-independent cooling rates through the cryogenic region.

8275-09, Session 2

Pulsed laser cooling for cavity-optomechanical resonators

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In this work we demonstrate how a sequence of fast pulses creates an approximation to the cooling (beam-splitter, anti-Stokes, red sideband) operator x_m x_c + p_m p_c proportional to a b^+ + a^+ b, where, a, is the annihilation operator of the cavity and x_c,p_c are its quadrature operators, b is the annihilation operator of the mechanical oscillator with corresponding x_m,p_m. The technique is shown to be experimentally feasible in both the good cavity (frac{kappa}{nu} 1) limits.

Physical Setting

Cavity optomechanical systems fundamentally involve an optical cavity field which couples to a mechanical resonator due to radiation pressure. The optical (mechanical) mode, oscillating at a frequency w (nu) is characterized by a relaxation timescale kappa (gamma_{m}). The optical mode is driven by a detuned laser field of frequency w_{l} with a strength W. The Hamiltonian corresponding to this system reads:

H=Delta ax a+nu bx b+frac{g_{0}}{sqrt 2}ax a(bx+b)+W(ax e^{-iphi} +a e^{iphi})

where phi is the initial phase of the driving, Delta=w_{l}-w and g_{0} is the optomechanical coupling rate between oscillator and cavity modes.

Linear Approach

We now wish to model the dynamics of the system, so as to derive a pulse sequence that efficiently adds a cooling operator to the Hamiltonian. This sequence can then serve as a starting point for numerical optimization both in the linear and fully non-linear settings. In the limit where g_{0}llnu, one may, for now, avoid the complexity of the full non-linear coupling, by considering a linearized version of the problem.

As this scheme makes use of rapidly changing driving, the usual procedure to linearize the Hamiltonian in cannot be trivially applied. Rather, we move to a frame co-moving with the state of the cavity, equivalent to an interaction picture with respect to the non-coupled part of the cavity Hamiltonian. In this frame, a, is by definition a small perturbation, and this allows to drop the quadratic term of the coupling, giving a compact expression of the Hamiltonian:

H=Delta ax a + nu bx b + (G(t)a+G^{*}(t)ax)x_{m}+|G(t)|^{2}x_{m}

with G(t)=ig_{0}e^{-i(Delta-ikappa) t}int_{0}^{t}Omega(t’)e^{i(Delta-ikappa) t’}dt’.

The linear behavior of the dynamics admits the use of the covariance matrix approach

We will denote by {-Gp_{c}x_{m},H_0,Gp_{c}x_{m}} the effective Baker-Campbell-Hausdorff (BCH) equivalent of the three Hamiltonians (H_{0} as in eq.,(ref{linear}) for G=0), at the strong driving limit, with a corresponding durations (t_{1},t_{f},t_{1}), where G=left|G(t)right|. This transformation is equivalent to the substitutions p_mrightarrow p_m+G t_1p_{c} and x_crightarrow x_c-G t_1x_{m}, obtaining:

H= H_{0}+2G t_{1} nu p_{c}p_{m}-2G t_{1} Delta x_{c}x_{m}.

Setting Delta=nu and adding a further 4G t_{1} Delta x_{c}x_{m} pulse, a cooling operator has been generated cite{foot2} at resonance. The requirements on the laser power for this sequence to work can be estimated to Omega gg dcdot maxleft(nu,kapparight)^{2}/g_0, eq.,(ref{analytical}), assuming 1/d of the pulse time is allowed for, G, to adopt a new value. This requirement can be considerably relaxed and cooling rates increased by the use of optimal control.

Optimal Control

Optimizations have been performed using QLib cite{QLib}. We have taken multiple approaches to the optimizations presented here: (a) initially optimizing on the pulse amplitude only and subsequently optimizing both amplitude and phase; (b) using the analytically derived sequence in eq.,(ref{analytical}) as an initial point of the optimization; (c) “pushing” sequences to shortened times and / or higher dissipating cavities by a series of optimizations with increasingly constraining parameters, where the result of optimization, n, serves as the initial conditions for optimization, n+1, and, of trivially (d) random starting conditions and simultaneous optimization of all control parameters.

8275-10, Session 3

Laser cooling with lead-salt colloidal quantum dots doped in a glass host

G. A. Nemova, R. Kashyap, Ecole Polytechnique de Montréal (Canada)

Laser cooling of solids with anti-Stokes fluorescence, which was proposed by Pringsheim in 19291 and experimentally realized for the first time in Yb3+-doped ZBLANP sample by Epstein's research team in 1995,2 continues to be one of the most interesting and promising directions in current laser physics. Laser cooling of solids with anti-Stokes fluorescence has already been observed with Yb3+, Tm3+, and Er3+ ions in wide variety of low phonon hosts. In 2009, the first cryogenic operation with a temperature drop ~150 K was demonstrated in Yb3+:LiYF4 crystal.3 During the last decade, semiconductor nano-crystal or quantum dot(QD) doped glasses have attracted a great deal of interest due to their potential applications in the optical communication band range.4 Semiconductor QDs, which bridge the gap between cluster molecules and bulk materials, can be considered as artificial atoms with tunable electronic transitions. Like traditional ions doped in hosts, QDs may exhibit Stokes and anti-Stokes fluorescence. We consider theoretically, laser cooling with PbSe QDs doped in a glass host. It is shown that unique properties of the PbSe QDs such as very short (~0.3µs) lifetime of the excited level and very large absorption cross section compared with RE ions (by a factor of ~1e4), allows not only increased efficiency of the cooling process and a dramatic acceleration of this process, but also provides a possibility for the use of new hosts with relatively high maximum phonon energy, so far considered un-suitable for laser cooling with the RE ions.

[1]. P. Pringsheim, Z. Phys. 57, 739 (1929).

[2]. R. I. Epstein et al., Nature (London) 377, 500 (1995).

[3]. D. V. Seletskiy et al., Demonstration of an optical cryocooler CLEO/IQEC 2009 (Postdeadline submission).

[4]. N. O. Dantas et al., J. Non-Cryst. Solids 352, 3525 (2006).

8275-12, Session 3

Indium fluoride glass fiber

M. Saad, IRphotonics Inc. (Canada)

Fluoride glasses are the only material that transmit light from ultraviolet to mid-infrared and can be drawn into industrial optical fibers.

The mechanical and optical properties of new indium fluoride glass fibers have been investigated. Multimode fiber 100/150 microns, has very high mechanical strength (80 kpsi) and optical loss as low as 0.2 dB/m between 2 and 3 microns. Unlike chalcogenide glass fibers, indium fluoride fiber has a wide transmission window from 0.3 to 5.5 microns without any absorption peak. Indium fluoride glass fibers are the technology of choice for all application requiring transmission up to 5 micron such as infrared contour measure (IRCM) and chemical sensing.

Furthermore, Indium fluoride glasses have low phonon energy and can be heavily doped and co-doped whit rare-earth elements. Therefore they are very promising candidates for infrared fiber lasers.

This paper will include indium glass and fiber thermal, mechanical and optical properties.

8275-13, Session 3

Peculiarities of optical cooling effect in ytterbium-doped ferroelectric lithium niobate crystal

V. G. Babajanyan, Institute for Physical Research (Armenia)

In the work results of detailed investigations of polarized absorption and luminescence spectra of LiNbO3:Yb3+ crystals performed at room temperatures are presented. Anti-Stokes luminescence registered for this crystal in the wavelength region near the 980 nm under the optical excitation at the 1064 nm allows evaluation of main characteristics of the possible laser cooling effect. The spectroscopic data are shown, that for realization of optical cooling effect in this anisotropic material it is more profitably to use the π-polarized excitation. Based on obtained results the optical cooling efficiency versus pump wavelength and minimum achievable temperature for the sample under study were calculated.

Certainly, the lithium niobate crystal is not a low-phonon matrix as compared with fluorides and chlorides, and its relatively strong crystalline field results in the larger splitting of the ground multiplet, which is unfavorable condition for minimal achievable temperature. However, this material will have a greater cooling efficiency in temperature range at least from 300 up to ~ 200 K, since the difference between the energy of photons taking part in each elementary act of optical refrigeration will be larger.

In addition, the use of ferroelectric doped crystal as solid-state optical cooling medium will permit instead of rather complicated and indirect methods to measure much more easily the temperature of the sample by means of pyroelectric effect inherent to doped polar materials. This will allow a temperature control immediately during the laser cooling by measuring pyroelectric charges, accumulated on polar faces of the ferroelectric sample under optical irradiation.

8275-16, Session 3

Development of highly doped passivation in the GaInP/GaAs double heterostructure for use in laser cooling

D. Bender, J. Cederberg, Sandia National Labs. (United States); C. Wang, M. Sheik-Bahae, The Univ. of New Mexico (United States)

Current refrigeration technology for cooling space-based IR focal plane arrays and sensors uses mechanical cryocoolers reaching temperatures down to approximately 75-120K. Such systems contain moving parts, which in time can wear out and contain refrigerants which can leak. These properties limit reliability and operational lifetime. Mechanical coolers produce vibrations which can lead to blurring during image acquisition. A balanced assembly minimizes vibrations, but does so at the expense of increased payload mass. A solid state optical cryocooler is an attractive alternative. Cryogenic temperatures have been achieved with rare-earth doped crystals but a direct band-gap semiconductor offers the advantages of direct integration with on-board sensors and opto-electronics as well as the possibility of lower overall temperatures. Cooling of a bulk semiconductor has not yet been realized. It has recently been theorized that high levels of n-doping in candidate semiconductor double heterostructures can reduce the minority carrier density at the GaInP/GaAs interface and increase nonradiative lifetime (G. Rupper, JAP, 2010). We will report on attempts to fabricate the GaInP/GaAs heterostructures with high (10^19 cm-3) doping density in the GaInP passivation layer grown by MOCVD. Further, we will report on the impact to nonradiative lifetime. Comparisons will be made to the nonradiative lifetime obtained with more modest levels of doping density (10^17 cm-3).

8275-14, Session 4

Heat removal technologies for use with optical refrigerators

R. I. Epstein, K. J. Malloy, The Univ. of New Mexico (United States)

Compact, vibration-free optical refrigerators can be used with medical sensors, microscopes, night vision systems and other terrestrial applications. To reap the full benefits of these cryogenic cooling devices, the parts of the cooling system that expel the waste heat into the environment must not be massive or generate vibrations or microphonics. In this talk we will describe two new heat removal technologies that are well matched to work with optical refrigerators: EnergyWrap thin-film electrocaloric refrigerators and FLOWFins solid-state heat removal fins.

8275-15, Session 4

Laser cooling and upconversion processes in crystals and glasses with high erbium concentrations

Z. U. Hasan, J. W. Lynch, Temple Univ. (United States)

This talk will review our work on the cooling in hexa-chloro-elpasolite, Cs_2NaYCl_6, doped with high concentration of Erbium, (~80% or more) using the 4I15/2- 4I9/2transition at 800 nm. A comparison is made with other two hosts, ZBLAN glass and KPb_2Cl_5 crystal, with >1% of erbium. Prospects of cooling in the eye-safe communication wavelength region, using the 4I15/2-4I13/2transition of erbium at ~ 1.5 micron in hexa-chloro-elpasolite host will also be presented.

Conference 8276: Vertical-Cavity Surface-Emitting Lasers XVI

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8276-01, Session 1

The next generation of high speed VCSELs at Finisar

L. A. Graham, R. Johnson, G. D. Landry, D. Gazula, H. Chen, J. A. Tatum, J. K. Guenter, A. N. MacInnes, B. Hawkins, Finisar Corp. (United States)

Commercial demand for optical transceivers operating at 14Gbps is now a reality. It is further expected that communications standards utilizing 850nm VCSELs at speeds up to 28Gbps will be ratified in 2012. We report on the development and productization of 850nm VCSELs for several applications, including high speed (both 14Gbps and 28Gbps) operation to support the continued fulfillment of data communication demand.

8276-02, Session 1

Emcore's 1 to 25 Gb/s VCSELs

N. Li, C. Xie, W. Luo, C. J. Helms, C. Liu, Q. Sun, L. Wang, C. Lei, R. Carson, EMCORE Corp. (United States)

In this talk, we will present Emcore's new 850 nm vertical-cavity surface-emitting lasers (VCSELs), Ultralase, designed universally to be operated at data rates from 1 to 14 Gb/s. They were based on hermetic-by-design chip platform and were released to production in early 2011. First, we will discuss Ultralase's device designs, manufacturing processes, DC and AC characteristics, equivalent circuit models as well as comprehensive reliability qualifications. Secondly, we will present performance of Emcore's transmitter optical subassembly (TOSAs), parallel optic modules (S12, CXP) and active optical cables (QDR and FDR) with Ultralase VCSELs inside. Lastly, we will briefly go over recent progress on 20 and 25 Gb/s VCSELs development using the same chip platform as Ultralase. Targeting the same nominal oxide aperture size of 7.5 um, we have successfully demonstrated 3-dB bandwidth of 14 GHz and 13 GHz at 25°C and 85°C, respectively, with bias current as low as 6 mA. More details of device performance will be presented.

8276-03, Session 1

Reliability study of 1060nm 25Gbps vcsel in terms of high speed modulation

T. Suzuki, S. Imai, S. Kamiya, K. Hiraiwa, M. Funabashi, Y. Kawakita, H. Shimizu, T. Ishikawa, A. 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 energy-saving light sources. To improve data capacity and system reliability further, an increasing number of VCSELs with higher speed and enhanced reliability are required.

10-Gbps VCSEL arrays are commercially available, and there are some reports on VCSELs over 20 Gbps. However, few of them study reliability, although it is more difficult to ensure reliability as well as higher speed performances.

Our VCSEL structures utilizing double intra-cavity for no current-flow in DBR layers together with Al-free InGaAs/GaAs QWs enable us to achieve low power consumption and high reliability of 30 FIT/channel.

Lifetime of a VCSEL is conventionally defined as 2 dB down of its output power, however in terms of high-speed modulation over 10 Gbps, threshold current rather than power degradation might determine the modulation characteristics and consequently lifetime of a VCSEL.

This paper therefore presents preliminary reliability test results of 25-Gbps VCSELs. Accelerated aging test was performed over 600 hours at 120 degC with 36 kA/cm2, which is equivalent to 90-190 years in normal operation (at 40 degC, 18 kA/cm2). The threshold currents changed no more than 20%, which is small enough for stable 25-Gbps operation. Actually we observed no remarkable changes in modulation characteristics such as 25-Gbps eye patterns and relaxation oscillation frequencies after the aging.

It is experimentally proved that 1060nm VCSELs have great potential as high-speed and reliable light sources in parallel optical interconnect.

8276-04, Session 1

980-nm VCSELs for optical interconnects at bandwidths beyond 40 Gb/s

W. H. Hofmann, Technische Univ. Berlin (Germany)

The copper-induced communication bottleneck is inhibiting performance and environmental acceptance of today´s supercomputers. Vertical-cavity surface-emitting lasers (VCSELs) are ideally suited to solve this dilemma. Indeed global players like Google, Intel, HP or IBM are now going for optical interconnects based on VCSELs. The required bandwidth per link, however, is fixed by the architecture of the data center. According to Google, a bandwidth of 40 Gb/s has to be accommodated. We recently realized ultra-high speed VCSELs suited for optical interconnects in data centers with record-high performance. The 980-nm wavelength was chosen to be able to realize densely-packed, bottom-emitting devices particularly advantageous for interconnects. These devices show error-free transmission at temperatures up to 155°C.Serial data-rates of 40 Gb/s were achieved up to 75°C. Peltier-cooled devices were modulated up to 50 Gb/s. These results were achieved from the sender side by a VCSEL structure with important improvements and from the receiver side by a receiver module supplied by u2t with some 30 GHz bandwidth. The novel VCSELs feature a new active region, a very short laser cavity, and a drastically improved thermal resistance by the incorporation of a binary bottom mirror. As these devices might be of industrial interest we had the epi-growth done by metal-organic chemical-vapor deposition at IQE Europe. Consequently, the devices were fabricated using a full three-inch wafer process, and the apertures were formed by proprietary in-situ controlled selective wet oxidation. All device data were measured, mapped and evaluated by our fully automated probe station.

8276-05, Session 2

VCSEL-based slow light photonics: switching, modulation, amplification, and beam steering

F. Koyama, Tokyo Institute of Technology (Japan)

The manipulation of the speed of light has been attracting much interest in resent years. Slow light observed in photonic crystals, semiconductor amplifiers and micro-resonators has been studied for optical buffer memories, optical delay lines and so on. Also, the low group velocity dramatically reduces the size of various optical devices such as optical amplifiers, optical switches and nonlinear optical devices. Slow light can be seen in Bragg reflector waveguides with their large waveguide dispersion. The Bragg reflectors (DBR) are composed of quarter-wavelength stack multi-layers. The slow down factor is the ratio of the group velocity of slow light versus that in conventional semiconductor waveguides. When we propagate light operating near the cutoff wavelength in the device, we are able to obtain a large slow down factor. Near the cutoff wavelength, the low group velocity is caused by the large waveguide dispersion in Bragg reflector waveguide. It is also noted that low polarization dependence can be obtained in our slow light waveguides, which is difficult in 2D photonic crystal waveguides.

We proposed and demonstrated a slow light modulator, slow light detector, optical amplifiers, slow light switches and beam scanners with a Bragg reflector waveguide, which enables size reduction using a slow light effect. Our VCSEL-based structure with slowing light gives us various unique features such as polarization independence, low power consumption, the integration capability with VCSELs and so on. In this paper, we will review our recent research activities on VCSEL-based slow light devices. Their new functions and integration with VCSELs will be discussed.

8276-06, Session 2

Recent advances on CW current injection blue VCSELs

S. Wang, T. Lu, H. Kuo, National Chiao Tung Univ. (Taiwan)

The GaN-based vertical cavity surface emitting lasers with hybrid mirrors have been demonstrated in CW operation at room temperature. The laser structure is composed of a 29-pair high-reflectivity AlN/GaN bottom DBR, a 7-lamda cavity region, and a 10-pair SiO2/Ta2O5 dielectric DBR. The laser structure has utilized a thin ITO layer of 30 nm as the transparent conducting layer, combining with a thin heavily doped p-type InGaN contact layer to reduce the optical loss while maintaining good current spreading capability. On the top of the InGaN multiple quantum well, an inserted AlGaN electric blocking layer plays a role to prevent the carrier overflow. At room temperature, the laser has a threshold current at 9.7 mA and current density corresponding to 12.4 kA/cm2. The spontaneous emission coupling factor of the GaN-based VCSEL was estimated to be about 5x10-3. Furthermore, the laser device has good electrical characteristics with a low turn-on voltage and the series resistance of 4.3V and 180 Ω, respectively. In order to improve the optical confinement of these devices, we investigated a microcavity light emitter with a buried AlN current aperture, which can also be used as a lateral optical confinement layer. The output emission has a dominant emission peak wavelength at 440 nm with a very narrow linewidth of 0.52 nm, corresponding to a cavity Q-value of 846 at a driving current of 5 mA. Further optimization of crystal growth quality in this structure would promise to realize low threshold GaN-based VCSELs or GaN-based polariton lasers.

8276-07, Session 2

Long-wavelength high-contrast grating VCSEL

C. J. Chang-Hasnain, Univ. of California, Berkeley (United States)

No abstract available

8276-08, Session 2

High-power vertical-cavity surface-emitting lasers for solid-state laser pumping

J. Seurin, G. Xu, A. Miglo, Q. Wang, R. Van Leeuwen, Y. Xiong, W. Zou, D. Li, J. D. Wynn, V. Khalfin, C. Ghosh, Princeton Optronics, Inc. (United States)

In a solid-state laser, a semiconductor diode laser or flash-lamp is used to pump a doped glass or crystalline rod gain material. A common configuration is comprised of an 808nm edge-emitter semiconductor laser stack pumping a neodymium-doped yttrium aluminum garnet (Nd:YAG) crystal rod from the end or from the sides to produce high-brightness lasing at 1064nm. Such solid-state lasers have wide-spread applications across the medical, industrial, and defense fields because of the high-energy high-quality beams they can deliver.

Vertical-cavity surface-emitting lasers (VCSELs) have emerged as a promising candidate for pumping of solid-state lasers, as they can be configured into high-power two-dimensional arrays and modules of arrays (e.g. Seurin et al., Proc. SPIE 6908, 690808 2008). VCSELs emit in a circular, uniform beam which can greatly reduce the complexity and cost of coupling optics. Their narrow and stable emission spectrum is well suited to the narrow absorption spectrum generally observed for solid-state gain media. The superior reliability of VCSELs greatly enhances the robustness of solid-state laser systems and enables high-temperature operation.

We will discuss recent developments on kW-class VCSEL pumps for solid-state lasers. Results on VCSEL modules designed for end-pumping and for side-pumping will be presented. Coupling is achieved via simple optics and in some cases the VCSEL pump can even be directly butt-coupled to the gain medium. We will also highlight the advantages of the VCSEL technology over the more conventional edge-emitter laser and flash-lamp technologies for solid-state laser pumping.

8276-09, Session 3

Long-wavelength VCSELs for sensing applications

M. Ortsiefer, Vertilas GmbH (Germany)

Long-wavelength VCSELs based on material systems other than the well-known GaAs-based one and emission wavelengths beyond 1.3 µm have seen a remarkable progress over the last decade. This success has been accomplished by using highly advanced device concepts which effectively address the fundamental technological drawbacks related with long-wavelength VCSELs such as inferior thermal properties and allow for the realization of lasers with striking device performance. In this presentation, we will give an overview on the state of the technology for long-wavelength VCSELs in conjunction with their opportunities in applications for optical sensing. While VCSELs based on InP are limited to maximum emission wavelengths around 2.3 µm, even longer wavelengths up to the mid-infrared range around 3 µm can be achieved with VCSELs based on GaSb. For near-infrared InP-based VCSELs, the output characteristics include sub-mA threshold currents, up to several milliwatts of singlemode output power and ultralow power consumption. New concepts for widely tunable MEMS-VCSELs with tuning ranges up to 100 nm independent from the material system for the active region are also presented. Today, optical sensing by Tunable Diode Laser Spectroscopy (TDLS) is a fast emerging market. Gas sensing systems are used for a wide range of applications such as industrial process control, environmental monitoring and safety applications. With their inherent and compared to other laser types superior properties including enhanced current tuning rates, wavelength tuning ranges, modulation frequencies and power consumption, long-wavelength VCSELs are regarded as key components for TDLS applications.

8276-10, Session 3

Design of high power VCSEL arrays

H. Moench, J. Kolb, P. Pekarski, J. Pollmann-Retsch, M. Stroesser, Philips Research (Germany); M. Miller, Philips Technologie GmbH U-L-M Photonics (Germany); G. Heusler, R. Dumoulin, X. Gu, A. Pruijmboom, Philips Lighting B.V. (Netherlands)

High power VCSEL arrays can be used as a versatile illumination and heating source. They are widely scalable in power and offer a robust and economic solution for many new applications with moderate brightness requirements. The use of VCSEL arrays for high power applications enables multiple benefits: Full wafer level production of VCSELs including the combination with micro-optics; assembly technologies allowing large synergy with LED assembly thus profiting from the fast development in solid state lighting; an outstanding reliability and a modular approach on all levels. The design of high power VCSEL arrays requires a concurrent consideration of mechanical, thermal, optical and electrical aspects. Especially the heat dissipation from the loss regions in the VCSEL mesas into the surrounding materials and finally towards the heat sink will be discussed in detail using analytical and finite element calculations. These can be extended to include the influence of cooler designs and the use of insulating submounts. Guidelines will be derived for shape, size and pitch of the VCSEL mesas in an array and optimised designs will be presented. These predictions are confirmed by measurements on several practical modules as well for top-emitting structures as for bottom-emitting structures. System solutions up to several kW have been successfully built including optics and electrical power supplies. They will not only illustrate the presented design principles but also give an outlook on new applications.

8276-11, Session 3

Surface topography and optical performance measurement of microlenses used in high power VCSEL systems

I. Erichsen, S. Krey, TRIOPTICS GmbH (Germany)

The recently emerged demand for lasers with specific intensity distributions has led to the development of high power VCSEL systems. These consist of arrays of high power VCSELs combined with microlenses and field lenses allowing for intensity distributions tailored to the needs of each specific application.

One of the basic conditions for getting ideal intensity distributions is the use of high quality microlenses. Therefore a Shack-Hartmann based instrument has been developed for the measurement of these lenses in reflection as well as in transmission. In addition the form tools used for the microlens production can be measured with this set up. The comparison of measured surface profiles and optical properties with the particular design values then allows for optimization of the manufacturing process.

Besides the aspheric shape of the lenses their very small size poses a considerable challenge. In order to utilize the full area of the Shack-Hartmann sensor a high degree of magnification is required, thus asking for high quality illumination and magnification optics. In addition high positioning accuracy, mechanical stability of the set up and vibration damping are absolutely necessary.

We are going to present the latest results on surface topography and optics performance measurements on microlenses which are used in high power VCSEL systems.

8276-12, Session 3

Broadly tunable high repetition rate amplified 1310nm VCSELs for optical coherence tomography

V. Jayaraman, Praevium Research, Inc. (United States); J. Jiang, Thorlabs Inc. (United States); B. Potsaid, Massachusetts Institute of Technology (United States); G. Cole, Advanced Optical Microsystems (United States); J. Fujimoto, Massachusetts Institute of Technology (United States); A. Cable, Thorlabs Inc. (United States)

MEMS tunable vertical cavity surface emitting laser (VCSEL) development, over the past two decades, has primarily focused on communications and spectroscopic applications. Because of their narrow line-width, single-mode operation, monolithic fabrication, and high-speed capability, MEMS VCSELs also present an ideal optical source for emerging swept source optical coherence tomography (SSOCT) systems. Application of VCSELs to SSOCT has required expansion of VCSEL tuning range, amplification of VCSEL output power, and proper engineering of MEMs actuators for wide deflection repetitively swept operation. In this paper, we describe the design and performance of broadly tunable MEMS VCSELs targeted for SSOCT, with an emphasis on 1310nm operation and its importance for emerging real-time biological imaging applications. We describe the VCSEL structure and fabrication, employing wafer-bonded fully oxidized GaAs/AlxOy mirrors in conjunction with InP-based multi-quantum well active regions. We also describe the optimization of MEMs speed and frequency response for SSOCT. Key results include 1310 nm VCSELs with 120nm dynamic tuning range at imaging rates near 1MHz, representing the widest VCSEL tuning range and some of the fastest swept source imaging rates thus far obtained. We also describe how low-noise semiconductor optical amplification boosts average optical power to the required 40mW levels, provides advantageous re-shaping of the optical spectrum, and enables superior OCT imaging quality. Finally, we present measurements of VCSEL dynamic coherence length, with demonstrated values longer than that of any other rapidly swept SSOCT source.

8276-13, Session 3

A compact, portable, and low cost generic interrogation strain sensor system using an embedded VCSEL, detector, and fibre Bragg grating

G. C. B. Lee, Aston Univ. (United Kingdom); B. Van Hoe, Univ. Gent (Belgium); Z. Yan, K. Sugden, D. Webb, O. Maskery, Aston Univ. (United Kingdom); G. Van Steenberge, Univ. Gent (Belgium)

We demonstrate a compact, portable and low cost generic interrogation strain sensor system using a fibre Bragg grating configured in transmission mode with a vertical-cavity surface-emitting laser (VCSEL) light source and a GaAs photodetector embedded in a polymer skin.

The interrogation system employs a low cost microcontroller with a current source IC to control the VCSEL drive current. By varying the VCSEL driving current and using the red shift of the VCSEL wavelength change enables a low-cost read-out of the fibre sensor based on the transmitted photocurrent. The photocurrent value is read and stored by the microcontroller. Additionally, the photocurrent data is sent via Bluetooth to a computer that presents the live data in the form a real time graph. The interrogation unit is intended to be a portable system with the ability to 'plug and play' a fibre Bragg grating that satisfies the tuning range of the VCSEL. With a matched grating and VCSEL the system is able to automatically scan and lock the VCSEL to the most sensitive edge of the grating.

Commercially available VCSEL and photodetector chips are thinned down to 20 µm and integrated in an ultra-thin flexible optical foil using several thin film deposition steps. A dedicated micromirror plug is fabricated to couple the driving optoelectronics to the fibre sensors. The resulting optoelectronic package can be embedded in a thin, planar sensing sheet and the host material for this sheet is a flexible and stretchable polymer. The result is a fully embedded fibre sensing system, a photonic skin.

A variety of gratings have been trialled with the system and a proof of principle has been demonstrated. Further investigations are currently being carried out to determine the stability and robustness of the embedded optoelectronic components.

8276-14, Session 4

1060nm VCSEL development at Furukawa for parallel optical interconnect

M. Funabashi, S. Imai, K. Takaki, S. Kamiya, H. Shimizu, Y. Kawakita, K. Hiraiwa, J. Yoshida, T. Suzuki, T. Ishikawa, N. Tsukiji, A. Kasukawa, Furukawa Electric Co., Ltd. (Japan)

Invited

8276-15, Session 4

Commercial VCSELs and VCSEL arrays designed for FDR (14 Gbps) optical links

R. King, S. Intemann, S. Wabra, Philips Technologie GmbH U-L-M Photonics (Germany)

The increasing need of bandwidth is the driving force for the continuing development of higher speed VCSELs. As 10 Gbps VCSEL solutions increasingly penetrate the market, new technologies developped for Active Optical Cables and Optical Interconnects, define the requirements set for VCSEL technology. In this paper we will focus on INFINIBAND's 14 Gbps FDR level. VCSELs specifically designed for FDR data rates (14 Gbps) and matched to TIA and VCSEL driver chip set from a leading supplier will be introduced and discussed. Accumulated data rates of 14 Gbps (single channel), 56 Gbps (1x4 arrays, e.g. QSFP form factor), and 168 (1x12 arrays, e.g. CXP form factor) are addressed. The employed technology is based on our established platform of 10 Gbps VCSELs and thus taking loan from a huge database of technological and production experience as well as reliability data. In addition to device performance and reliability data particular attention is paid to link performance parameters that are majorily influenced by VCSELs. As an outlook, activities towards EDR data rates and preliminary data on device performance will be presented and discussed.

8276-16, Session 4

High speed tunable and fixed wavelength VCSELs for short reach optical links and interconnects

A. Larsson, J. Gustavsson, Å. Haglund, B. Kögel, P. Westbergh, E. Haglund, Chalmers Univ. of Technology (Sweden)

Our recent work on high speed oxide confined VCSELs for short reach optical links and interconnects is reviewed. With proper active region and cavity designs, and techniques for reducing capacitance and thermal impedance, our 850 nm VCSELs have enabled 40 Gbit/s transmission. A technique for controlling the spectral width using an integrated mode filter has been implemented and its effects on VCSEL dynamics have been analyzed. A MEMS-technology for wafer scale integration of tunable high speed VCSELs, intended for reconfigurable optical interconnects, has also been developed. A tuning range of 18 nm and transmission at 5 Gbit/s have been demonstrated.

8276-17, Session 4

Bidirectional multimode fiber interconnection

R. Michalzik, A. Kern, D. Wahl, Univ. Ulm (Germany)

Invited Paper:

We report the fabrication and properties of 850 nm wavelength AlGaAs/GaAs-based transceiver chips, in which vertical-cavity surface-emitting lasers (VCSELs) and photodiodes are monolithically integrated. Various types of devices allow half- and full-duplex bidirectional optical interconnection at multiple Gbit/s data rate over a single butt-coupled glass or polymer-clad optical fiber with diameters in the 50 to 200 µm range. Whereas metal-semiconductor-metal (MSM) photodiodes are employed for fiber with diameter of at least 100 µm, PIN-type photodiodes are more promising in combination with standard 62.5 or 50 µm graded-index multimode fibers. Data transmission rates up to 10 Gbit/s are feasible. This interconnect solution is attractive owing to obvious advantages like lower volume and weight and potentially lower system cost. Applications will be found in automotive, home, industrial, or in-building networks.

8276-18, Session 4

Energy-efficient VCSELs for "green" data and computer communication

P. Moser, Technische Univ. Berlin (Germany); J. A. Lott, VI Systems GmbH (Germany); P. Wolf, G. Larisch, A. Payusov, G. Fiol, Technische Univ. Berlin (Germany); N. N. Ledentsov, VI Systems GmbH (Germany); W. Hofmann, D. Bimberg, Technische Univ. Berlin (Germany)

We present record energy-efficient oxide-confined 850 nm single mode vertical-cavity surface-emitting lasers (VCSELs) for optical interconnects. Error-free performance at 17 and 25 Gb/s across 100 m of multimode optical fiber is demonstrated showing ultra-low dissipated power of only 69 fJ/bit (< 0.1 mW/Gbps) and 99 fJ/bit, respectively. This performance is achieved without changing any of the voltage or current driving parameters up to 55 °C. The total energy-to-data ratios at 17 Gb/s are 83 fJ/bit at 25 °C and 81 fJ/bit at 55 °C. We also present error-free transmission at 17 Gb/s across 1 km of multimode optical fiber with an energy-to-data ratio of 99 fJ/bit. The devices meet already today the requirements of the International Technology Roadmap for Semiconductors (ITRS) for 2015. We demonstrate that energy-efficient data transmission across multimode fiber can be extended to transmission lengths up to 1 km. To date our VCSELs are the most energy-efficient directly modulated light-sources for data and computer communication across all distances up to 1 km of multimode optical fiber.

8276-19, Session 5

Progress on single mode VCSELs for data- and tele-communications

N. N. Ledentsov, J. A. Lott, VI Systems GmbH (Germany)

(Invited) To be determined

8276-20, Session 5

Reducing the spectral width of high speed oxide confined VCSELs using an integrated mode filter

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The high speed performance of oxide confined 850 nm VCSELs has improved over the last few years, reaching modulation bandwidths in excess of 20 GHz and enabling data transmission at 40 Gbit/s. This is made possible by the use of strained quantum wells for improved differential gain, an active region design for low gain compression, a cavity design for reduced photon lifetime, and multiple oxide layers for reduced capacitance. However, the use of multiple oxide layers leads to increased index guiding, giving the VCSEL a pronounced multimode behavior and large mode spacing which results in a spectral RMS width in excess of what is acceptable for VCSELs with a reasonably large oxide aperture.

To enable a reduction of the spectral width, we have incorporated an integrated mode filter in our high speed VCSEL design. Suppression of higher order transverse modes is accomplished by dry etching of a shallow surface relief for mode selective loss. With the diameter of the surface relief being half the diameter of the oxide aperture and the depth of the surface relief being a quarter wavelength for efficient mode discrimination, we have been able to reduce the spectral RMS width from 0.9 nm to 0.45 nm. The small signal modulation bandwidth is 17 GHz, which is sufficient for 25 Gbit/s large signal modulation. However, the modulation bandwidth is reduced compared to a VCSEL without mode filter (22 GHz) as a result of an increased photon lifetime and therefore increased damping of the modulation response.

8276-21, Session 5

Planar single mode photonic crystal VCSELs

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Planar index guided proton-implanted photonic crystal vertical-cavity surface-emitting lasers are fabricated and characterized. Index guiding from the photonic crystal improves the performance of the lasers by stabilizing the light-current curve, reducing the threshold current, and enhancing the differential quantum efficiency. Examination of the etch depth dependence of laser efficiency as well as the lasing spectra reveal various mechanisms that affect the laser performance and modal properties such as optical loss, device heating, and spectral gain-resonance alignment. Photonic crystal designs can be chosen which result in vertical-cavity surface-emitting lasers that operate single mode and produce high output power even for conditions of blue-shifted gain relative to the cavity resonance.

8276-22, Session 5

Mode suppression in metal filled photonic crystal vertical cavity lasers

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Photonic crystal (PhC) vertical cavity surface emitting lasers (VCSELs) have been widely researched because of their ability to achieve single mode lasing at any wavelength using the same PhC structure. The most common PhC VCSEL design consists of a periodic arrangement of air holes etched into the top distributed Bragg reflector (DBR) mirror. Transverse mode suppression is achieved because of the lower gain and larger mirror loss for higher order modes. For a wide range of etch depths, side mode suppression ratio (SMSR) exceeding 35dB can be achieved. To increase the range of designs with high SMSR, we investigated partially filling the PhC holes with a lossy metal. The increased loss of the fundamental mode and the increased SMSR were calculated for various metal filling thicknesses. For air hole PhC structures that originally had SMSR below 20dB, adding 60nm of palladium (Pd) is adequate to increase the SMSR to above 35dB with only a 0.1cm-1 increase in the fundamental mode's mirror loss.

8276-23, Session 5

Thermal characteristic of polarization switching in vertical-cavity surface-emitting lasers

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This research investigated the thermal properties of the polarization-switching hysteresis loop (PSHL) in vertical-cavity surface-emitting lasers (VCSELs). This is an important topic of PS in VCSELs. In experiments, the current modulation frequency and ambient temperature of VCSELs were varied to study their thermal effects on PS, resulting in rich dynamics. At constant ambient temperatures, the PSHL broadens as the modulation frequency increased and narrows as the modulation frequency decreased. The assumption for this experiment is that the polarization switching occurs as the temperature of active region reaches the PS temperature, and the temperature in the active layers is caused by current self-heating effect. Under constant modulation frequency operations, the PHSL moved to a higher current as the ambient temperature increases and broadens apparently when the modulation frequency increased. The temperature gradients in VCSEL active region was proposed in this case. The immediate thermal effect in laser's L-I curve was also studied in this research. The experiments show that the thermal effect plays a major role in PS and PSHL. These results contribute to the understanding of the mechanism of VCSEL's polarization switching.

8276-24, Session 6

Surface micromachined MEMS tunable VCSEL at 1550 nm with >60 nm single mode tuning

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Tunable VCSEL are key components in applications such as gas spectroscopy and telecommunications. Their inherently short cavity enables wide single mode tuning ranges due to their large free spectral range. Especially their low power consumption makes them attractive for the fast growing market of telecommunication.

The presented device consists of two main parts: An InP based half-VCSEL consisting of the active semiconductor part with a fixed DBR at the bottom and a movable DBR-membrane on top. The membrane is deposited via low temperature PECVD. Due to an intrinsic stress gradient, the membrane bends upwards after etching away an implemented sacrificial layer. Both parts embed an air-gap with variable thickness. Electro-thermal heating of the movable DBR-membrane increases the air-gap length which shifts the resonant wavelength to higher values. A mode hop free single mode tuning range >60 nm with fibre coupled optical output powers >1 mW over the entire tuning range (peak power of >2 mW) is presented. An integrated buried tunnel junction enables side mode suppression ratios >40dB. This new surface micromachining technology is cost effective and thus capable for mass production. Furthermore, it is not restricted to wavelength around 1550 nm, only. This technology is applicable for tunable VCSEL operating in the range of 800 nm to 2400 nm. Typical applications are optical interconnects, telecommunications, gas spectroscopy and fiber Bragg grating sensing.

8276-25, Session 6

Integrated MEMS-tunable VCSELs for reconfigurable optical interconnects

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An integrated technology for tunable vertical-cavity surface-emitting lasers (VCSELs) is presented. A microelectromechnical system (MEMS) replaces one fixed mirror of the VCSEL and allows changing the air-gap between both components. The devices are intended for reconfigurable optical interconnects, which require the combination of wavelength tuning and high-speed modulation in a compact laser array. The design, fabrication, and experimental results are reported.

The technology is demonstrated for electrically pumped, short-wavelength (850 nm) tunable VCSELs. The GaAs-based 'half-VCSEL' comprises a bottom distributed Bragg reflector (DBR) with high reflectivity, an active region for light amplification, and an oxide aperture for current confinement. The MEMS technology is based on self-aligned reflow process, in which a photoresist droplet is formed on top of the 'half-VCSEL'. The droplet serves as sacrificial layer and preform for the curved, movable micromirror. This DBR is made from dielectric materials (TiO_2/SiO_2), whereby the technology is applicable to a wide range of wavelengths and material systems. The integrated technology allows low-cost fabrication in dense 2-D arrays.

Using a 3-D electromagnetic model, the half-symmetric cavity is designed to select the fundamental transverse mode. Its wavelength is tuned by electro-thermal actuation of the MEMS. Fabricated devices with 10 µm large aperture are singlemode and tunable over 24 nm. An improved high-speed design with reduced parasitic capacitance enables direct modulation with 3dB-bandwidths up to 6 GHz and error-free data transmission at 5 Gbit/s.

8276-26, Session 6

1.55-um high-speed MEMS-tunable VCSEL

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Wide tunable vertical-cavity surface-emitting lasers (VCSEL) in the long wavelength region around 1.55mu are highly attractive for a wide range of applications; especially in wavelength managed optical communication. VCSELs are predestined for high speed data transmission due to their small active region and low threshold currents. In order to achieve high modulation bandwidths for directly modulated VCSELs, both the intrinsic modulation properties and the extrinsic device parasitics have to be considered. The small-signal modulation response and the relative intensity noise measurement method have been used to study intrinsic and parasitic influences on the modulation response of the device. Additional, the static characteristics comprising output power, threshold current, emission spectra and the line width as well as electrical and thermal design of the device are discussed with respect to its high-speed modulation behavior. The presented tunable VCSEL combines an InP-based cavity incorporating 7 InGaAlAs quantum wells, a buried tunnel junction and a concave bulk micro-electro-mechanical system (MEMS) distributed Bragg reflector (DBR) which can be electro-thermally actuated for wavelength tuning. To study the dynamics of the tunable VCSEL the dependence of resonance frequency on bias current and wavelength is investigated. The device shows 3-dB direct modulation frequencies above 6 GHz. The low threshold current of 2.7mA, high side-mode suppuration-ratio of >50dB and maximum output power of >2.5mW as well as the tuning range of >50nm and the line width of 31MHz are presented. All measurements are performed at room temperature (20°C).

8276-27, Session 6

850-nm VCSELs optimized for cryogenic data transmission

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We report on the development of 850-nm high-speed VCSELs optimized for low-power data transmission at cryogenic temperatures near 100K. These VCSELs operate on the n=1 quantum well transition at cryogenic temperatures (near 100K) and on the n=2 transition at room temperature (near 300K), such that cryogenic cooling is not required for initial testing of the optical interconnects at room temperature. Relative to previous work at 980nm, the shorter 850-nm wavelength of these VCSELs makes them compatible with high-speed receivers that employ GaAs photodiodes.

In this talk we will discuss the quantum well design that simultaneously (1) minimizes transmitter energy per bit at cryogenic temperatures, and (2) achieves functional laser properties at two widely spaced operating temperatures (100K and 300K). In particular, high-speed laser characteristics (bandwidth, rise/fall times, and relaxation oscillations) will be discussed for both cryogenic and room-temperature operation.

8276-28, Session 6

Polarization investigation of a widely tunable high speed short-wavelength bulk-micromachined MEMS-VCSEL

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Tunable short wavelength micro-electro-mechanical systems- (MEMS-) vertical-cavity surface-emitting lasers (VCSELs) are interesting sources for optical interconnects. In this report the state of polarization (SOP) of a high-speed widely tunable VCSEL Operating near 850 nm with a mode hop free single mode tuning range of about 20nm and an amplitude modulation bandwidth of about 5 GHz and an electro thermal tuning speed of 700Hz has been investigated. Additionally the effect of applying a sub-wavelength grating (SWG) on polarization behavior has been investigated. The VCSEL mainly consists of a bottom part called half-VCSEL with a plane semiconductor bottom DBR from alternating pairs of AlGaAs layers and AlGaAs/GaAs quantum wells (QW) on GaAs substrate. The movable top mirror membrane is a concave semiconductor DBR from alternating pairs of AlGaAs. The investigation has been done by coupling of the light from the VCSEL in to the Polarization beam splitter equipped with a half-wave plate at the input side and measuring the output power from two outputs of the beam splitter. The VCSEL shows a stable state of polarization with polarization suppression of about 30dB during the tuning.

8276-29, Session 7

VCSEL beam control with collective and self-aligned polymer technologies

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We present recent advances on polymer microlenses integration on Vertical-Cavity Surface-Emitting Lasers (VCSELs) to achieve output beam shaping. We describe the low cost and collective fabrication methods we have developed to allow for a self-alignment of the lens with the laser source. These approaches are based either on surface tension effects or on a self-writing process using novel Near Infra-Red (NIR) photopolymers. Results on beam collimation and focusing at 850nm and 760nm are presented and successfully compared to optical modeling taking into account Gaussian optics propagation. A fully vectorial and three dimensional optical model that takes into account the complete geometry of laser resonator is also implemented to investigate device operation. Potential applications may concern improvement of VCSEL insertion in optical interconnects or sensing systems, as well as fabrication of novel types of optical micro-probes for near-field microscopy. Finally, we discuss considerations to achieve an active beam control by means of an integrated polymer-based MEMS (Micro-Electro-Mechanical System) fabricated using similar low cost methods.

8276-30, Session 7

Impact of photon lifetime on thermal rollover in 850-nm high-speed VCSELs

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We present an empirical thermal model, based on experimental measurements for accurately quantifying the temperature dependence of macroscopic VCSEL parameters such as thermal impedance, internal optical loss, threshold current, internal quantum efficiency. We use it for studying power dissipation mechanisms contributing to thermal rollover in modern VCSELs.

VCSEL parameters are extracted from basic continuous-wave (CW) measurements over a range of ambient temperatures (15-100 C). We apply our model to two, oxide-confined, 850-nm VCSELs, fabricated with a 9-µm inner-aperture diameter and optimized for high-speed operation. The two devices differ in the shallow surface etching applied to the top DBR (0 nm for Device A vs. 55 nm for Device B), which reduces the photon lifetime of the VCSEL cavity.

We demonstrate that for both devices, the power dissipation due to linear heat sources (sum of optical absorption, carrier thermalization, carrier leakage and spontaneous carrier recombination) exceeds power dissipation across the series resistance (quadratic power dissipation) at any ambient temperature and bias current. We further show that while dominant contributors to self-heating for Device A are quadratic power dissipation, internal optical absorption, and carrier leakage, Device B with photon lifetime of less than 2 ps has negligible absorption heating and exhibits better performance due to delayed onset of the thermal rollover. We find that carrier leakage places an ultimate limit on the thermal performance of this entire class of devices. The new thermal model is useful for identifying the mechanisms that limit the thermal performance of VCSELs and to formulate design strategies to ameliorate them.

8276-31, Session 7

Multi-mode to single-mode switching caused by self-heating in bottom-emitting intra-cavity contacted 960 nm VCSELs

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The key component for short reach data and computer communication systems is the vertical cavity surface emitting laser (VCSEL). The high-speed performance of modern multi-mode VCSEL-based optical links is limited by for example the fiber coupling efficiency, mode competition, and modal and chromatic fiber dispersion. Single-mode overcome many of these limitations. We present investigations of anomalous modal behavior in bottom-emitting intra-cavity contacted 960 nm VCSELs. At low currents the broad-aperture VCSELs show multi-mode operation at 945 nm via whispering gallery-like modes. However a subsequent increase of current results in a rapid increase of fundamental mode intensity and a switching to a pure single-mode lasing regime at 960 nm and also to a higher differential output power versus current slope efficiency. As a result we achieve record single-mode output power of 17 mW with a side-mode-suppression-ratio (SMSR) above 20dB. The observed phenomena cannot be explained by oxide-index guiding or changes in current pumping. Our 2D heat transport simulations show a strong temperature gradient inside the microcavity due to the an effective lateral heat-sinking. This creates an effective waveguide and results in lower optical losses for the fundamental mode. According the emission spectra at a fixed current in the pulsed regime, high-order modes dominate the lasing spectra at current pulse widths less than 200 ns. However the subsequent increase of pulse width leads to a rapid rise of optical power for the fundamental mode and an increased SMSR. Thus the self-heating phenomena play a crucial role in our VCSEL's unusual modal behavior.

8276-32, Session 7

Determination of optical loss in photonic crystal VCSELs

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We demonstrate a novel approach for determination of optical loss arising from photonic crystal VCSELs. Through calculations and comparison with experimental results, we also verify that the loss introduced by an etched photonic crystal contributes significantly to the transverse optical confinement and supported modes. The optical loss is examined theoretically using a simple waveguide model from the scalar Helmholtz equation. The modal loss of fabricated lasers is extracted from the observed spectral mode splitting. The effect of modal loss on the slope efficiency and modal behavior is examined. The model is found to be consistent with experimental measurements, and may be generally applicable to VCSELs.

8276-33, Session 7

Implant confined 1850nm VCSELs

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While VCSELs in the 1310-1550 nm range have been long sought sources for telecommunications, operation at even longer wavelengths is becoming increasingly desirable for trace gas detection, spectroscopy, and biomedical sensing. Vixar has recently developed VCSELs at 1850nm, a wavelength of interest for hygrometry and neurostimulation applications. This paper discusses the design and fabrication of these novel new long-wavelength lasers, and reports on the most recent performance results. The VCSELs are based on InP-compatible materials and incorporate highly strained InGaAs quantum wells to achieve 1850nm emission. The longer wavelength allows high index contrast InP/InGaAs DBRs to be used in combination with a dielectric mirror to increase reflectivity and minimize the total thickness of the structure. By including an intracavity tunnel junction, both mirrors are doped n-type for lower optical loss and improved lateral current spreading. Current confinement in the VCSEL is achieved through a novel ion implantation scheme, resulting in a planar fabrication process with only a single epitaxial growth step. The devices exhibit continuous wave lasing for aperture sizes varying from 8 to 50µm diameter with threshold currents in the range of 1-18mA. Peak CW output powers of 0.75mW and 3mW have been achieved for single mode and multimode devices, respectively. The maximum continuous wave operating temperature is 60°C. Pulsed measurements demonstrate differential quantum efficiency up to 45% and output power in excess of 20mW for a single device.

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8277-01, Session 1

Photo-pumped GaAs1-xBix lasing operation with low-temperature-dependent oscillation wavelength

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We will report the photo-pumped lasing operation of GaAs1-xBix with low-temperature-dependent oscillation wavelengths and discuss future prospects for the fabrication of Bi-based lasers. Because our previous study demonstrated that GaAs1-xBix has a low-temperature-dependent band gap, it has received considerable attention as an attractive candidate for the fabrication of laser diodes with temperature-insensitive oscillation wavelengths. However, there were no reports on the lasing behavior of this alloy. Moreover, it is difficult to obtain a high-quality GaAs1-xBix layer sufficient to achieve laser operation, because the alloy must be grown at temperatures as low as 350 °C. In this study, molecular beam epitaxial (MBE) growth of GaAs1-xBix was performed with precise control by adjusting Ga, As, and Bi fluxes and the lasing operation of GaAs1-xBix was achieved. A GaAs0.975Bi0.025/GaAs thin film was grown by MBE on a (100)-oriented GaAs substrate at 350 °C. Lasing oscillation from the GaAs0.975Bi0.025/GaAs thin film with a Fabry-Perot cavity was performed by photo-pumping, and it was revealed that the lasing emission peak energy decreases at a constant ratio of –0.18 meV/K, which is 40% of the temperature coefficient of the GaAs band gap. This result is a major step toward proving our claim that III-V alloy semiconductors consisting of semiconductor and semimetal components should result in new semiconductor lasers with temperature-insensitive oscillation wavelengths. We expect that a smaller temperature coefficient of the lasing emission peak energy can be achieved using a GaAs1-xBix active layer with a larger Bi molar fraction, x.

8277-03, Session 1

Carrier recombination and band alignment of GaAs1-xBix emitters

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The incorporation of Bismuth in GaAs leads to band gaps in the near- and mid-infrared range with potential applications in lasers and optical amplifiers. Furthermore, the large spin-orbit splitting provides an opportunity to suppress non-radiative loss processes. In a first step towards developing lasers, we investigate the carrier recombination processes occurring in GaAs0.986Bi0.014/GaAs p-i-n light emitting diodes (LEDs) via temperature and pressure dependence of the light-current characteristics and an analysis of the electroluminescence spectra. The emission wavelength of the p-i-n structures is measured to be ~936 nm at 260K. The emission wavelength shows a low temperature coefficient of emission peak shift of 0.17 nm/K from 80-260K, which may be attributed to band-anticrossing and/or carrier localization effects. A rapid decrease in emission efficiency with increasing temperature implies that loss processes play a role in these structures. In order to investigate this further, high pressure measurements were utilized. The pressure coefficient of the GaAs0.986Bi0.014 band gap was measured to be 11.8±0.3 meV/kbar compared with 10.7meV/kbar for GaAs. The electroluminescence emission shows that while the overall emission intensity decreases with increasing pressure, the emission in the GaAs barrier region increases as pressure is applied suggesting carrier overflow into the GaAs. This together with a decrease in efficiency with increasing pressure is attributed to electron leakage and subsequent recombination in the GaAs due to a decrease in band offset between GaAsBi and GaAs with increasing pressure. This provides evidence that the GaAsBi/GaAs conduction band offset is type I, highlighting its potential for laser applications.

8277-04, Session 1

Electrically driven photonic crystal nanocavity lasers, LEDs, and modulators

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We demonstrate a lateral p-i-n junction in GaAs photonic crystal cavities formed by ion implantation. Our fabrication has been optimized to allow precise control of the doping layout using electron-beam lithography with position accuracy under 30 nm. The lateral junction allows for efficient electrical injection into the nanocavity region with minimal heating effects. Lasing is observed with world record low thresholds of 181 nA and 287 nA at 50K and 150K, respectively, from embedded quantum dot emitters. These thresholds are three orders of magnitude lower than previously made electrically pumped photonic crystal lasers and one order of magnitude lower than metal-clad hybrid lasers. At room temperature, our devices do not lase due to the reduced gain of our quantum dots. We believe further refinement of the fabrication and optimizing the material will allow room temperature lasing to be observed. At room temperature, the now single-mode LEDs can be directly modulated at speeds in excess of 10 GHz with sub fJ/bit energy. This demonstrates that our devices are intrinsically fast due to their small cross-sections and can be viable low power sources for optical interconnects. In addition, we have fabricated 1D nanobeam LEDs which show similar properties as their two-dimensional counterparts. Finally, we demonstrate a fiber taper coupled external electro-optic modulator with the lateral junction platform, also operating at sub fJ/bit energy levels. The lateral junction photonic crystal design is an exciting new platform and will enable numerous applications in practical electrically controlled nanophotonic devices.

8277-05, Session 1

Lateral cavity photonic crystal surface emitting laser with ultralow threshold

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Nowadays, the surface emitting lasers have attracted great interest due to the narrow divergence angle and the symmetrical beam spot. The widely studied vertical cavity surface emitting lasers (VCSELs) are based on the complicated epitaxial wafer including dozens of DBRs, which are very difficult to fabricate for infrared long wavelengths. Connie J. Chang-Hasnain and S. Boutami's groups have made effort to reduce the epitaxial thickness of the required VCSEL mirror and increased fabrication tolerance. S. Noda's group has reported photonic crystal (PhC) surface emitting laser (PCSEL), which uses the characteristics of band edge mode to achieve surface emitting laser without DBR. While the non-planar wafer bonding process and the finely designed wafer pair have been adopted to achieve electrically driven laser. Large PhC regions in PCSELs are required to ensure the sufficient in-plane feedback, which increases the fabrication cost. Otherwise, the low threshold current density has always been pursued in the history of semiconductor laser. In this work, we proposed a lateral cavity photonic crystal surface emitting laser (LC-PCSEL) based on the PhC band edge mode lateral resonance and vertical emission to achieve electrically driven surface emitting laser without DBR in the long wavelength optical communication band. Deep etching technique was adopted to realize the LC-PCSEL on the commercial AlGaInAs/InP multi-quantum-well epitaxial wafer. 1553.8 nm surface emitting lasing action was observed under pulsed electrical pumping at room temperature. The threshold current density of 667 A/cm2 is ultralow for the reported surface emitting lasers by now.

8277-69, Session 1

Stacking-layer-number dependence of highly stacked InAs quantum dot laser diodes fabricated using strain-compensation technique

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Semiconductor quantum dots (QDs) grown using self-assembly techniques in the Stranski-Krastanov (S-K) mode are expected to be useful for high-performance optical devices such as QD lasers. A significant amount of research has been carried out on the development of high-performance QD lasers because they offer advantages of 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 QD laser diodes consisting of highly stacked QD layers and investigated the dependence of diode parameters on the stacking layer number. We fabricated QD laser diodes having 5, 10, 15, and 20 QD layers in the active region. All laser diodes operated at around 1.55μm at room temperature, and their threshold currents showed obvious dependence on the stacking layer number. Laser diodes having more than 10 QD layers showed sufficient gain, i.e., the threshold currents decreased with a decrease in the cavity length. On the other hand, for laser diodes having less than 10 QD layers, the threshold currents increased with a decrease in the cavity length.

8277-06, Session 2

High-speed directly modulated buried heterostructure photonic crystal lasers

S. Matsuo, NTT Photonics Labs. (Japan)

A photonic network on a silicon CMOS chip is a desired breakthrough technology for overcoming bandwidth and power consumption limits. This is because over 50% of the total power consumption is used for the interconnects. If we are to construct a photonic network on a CMOS chip, the density requirement is a critical issue. In this context, directly modulated lasers with ultra-low energy costs are needed for constructing a photonic network on a silicon CMOS chip. Thus, we have proposed an ultracompact buried heterostructure photonic crystal (PhC) laser, consisting of an InGaAsP-based active region buried in an InP layer. In this device, there is an InGaAsP-based active region inside the line-defect of the InP-PhC. By employing a buried heterostructure with an InP layer, we can greatly reduce thermal resistivity and effectively confines both the carrier and photon in the cavity. We therefore achieved a low threshold input power of 6.8 uW and a maximum output power in the output waveguide of -10.3 dBm by optical pumping. The output light is effectively coupled to the output waveguide with a high external differential quantum efficiency of 53%. We observed a clear eye opening for a 20-Gbit/s NRZ signal modulation with an absorbed input power of 175.2 uW, resulting in an energy cost of 8.76 fJ/bit. This is the smallest reported energy cost for any type of semiconductor laser.

8277-07, Session 2

Red-emitting diode lasers with internal surface DBR gratings

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Red-emitting diode lasers are used in many applications in medicine, material processing, IT and science, where they provide high optical power, high efficiency, small size and robustness, all at low cost. A large coherence is required for a variety of techniques in applications such as spectroscopy, interferometry and holography. However, for these applications inefficient, bulky helium-neon lasers or diode lasers with external wavelength stabilization are widely used.

By integrating a wavelength stabilization element into ridge waveguide and broad area lasers we demonstrate diode lasers with small spectral linewidth. To this end, we have developed surface distributed Bragg reflector (DBR) gratings in order to achieve a simple, single-epitaxy manufacturing process.

These DBR lasers consist of a 1 mm gain section and a 900 μm grating reflector. The grating was defined by i-line stepper lithography with a period of around 980 nm, corresponding to a grating order of 10. The RIE etching process was controlled so as to manufacture a specific shaped grating trench to achieve a high reflectivity.

DBR lasers from the same gain material, but with four different grating periods show lasing at four lasing wavelengths ranging from 631.8 nm to 637.6 nm at a temperature of 15°C. The characteristics from the test devices driven under pulsed operation (pulse width: 1 μs, duty cycle: 0,5%) will be shown. Unmounted and uncoated 30 μm wide DBR lasers reach an output power of 250 mW at 500 mA. We estimate the reflectivity of the rear grating to exceed 60%.

8277-08, Session 2

Very narrow linewidth and low frequency noise reduction of high power DFB laser diode for Cs pumping

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Currently, atomic clocks need a lot of specificities about optical sources: a high power for atomic cooling or atomic detection, a high spectral purity and a good beam quality. Our DFB laser diodes are Aluminum-free, low losses, active region (GaInAsP compressively strained Quantum Well in a GaInP Large Optical Cavity). The use of Al free materials allows the realization of a diffraction grating, with optimized coupling coefficient, buried in the laser structures, thanks to an epitaxial regrowth, and has shown an excellent reliability..

We obtain a low threshold current at 30°C around 50mA and a high slope efficiency of 1W/A. At this measurement temperature, we have also obtained the D2 line of Cs (852.12nm) for a current of 170mA and so, a high optical intensity of 110mW. The side mode suppression ratio (SMSR) for these operating conditions is higher than 50dB. We also measured by the self-heterodyne method the linewidth of our DFB laser at 30°C. We obtained at the D2 line of Cs a very narrow linewidth of 200 kHz for a white noise approximation (lorentzian fit) and 446 kHz for a low frequency noise approximation (Gaussian fit). Furthermore, we can see the usual decrease of the linewidth with the optical power, without any further increase at high power.

A study for reducing low frequency noise by locking its frequency with saturated absorption is currently in progress. We have demonstrated that the low frequency noise (at 300Hz) has been reduced by a factor of one hundred from 7080 Hz/sqrt(Hz) to 70.03 Hz/sqrt(HZ).

8277-09, Session 2

830nm high power single mode DFB laser for high volume applications

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High power DFB lasers in the AlGaAs/GaAs material system offer the promise of tight wavelength control without the need of a thermoelectric cooler, therefore making them well suited for applications where low cost, compactness and high power is required. DFB lasers with lasing wavelength that fall within the Silicon detection window are not commercially available today because of the inherent difficulties of epitaxial re-growth in the AlGaAs/GaAs material system that result in poor performance as well as insufficient reliability. Here we report an 830nm single mode DFB laser that offers electro-optical performance close to that of a Fabry-Perot laser and is compatible with use in uncooled environments for power levels in the range of 200mW. The laser design is based on a partially corrugated DFB with a short 2nd order grating section. This structure has been selected as it offers more stable and higher slope efficiency as well as higher kink power compared to a classical fully corrugated DFB design. Through careful design and high quality epitaxial re-growth of the etched grating, power as high as 400mW and slope-efficiency in excess of 1.0W/A at 25C have been achieved. High temperature operation with 200mW output power for currents below 350mA at 60C, and wavelength locking in the wide temperature range of 25C to 65C, have been demonstrated with high yield suitable for high volume production. Promising reliability results have been observed with accelerated life tests over 2,000 hours.

8277-10, Session 2

AlGaInAs semi-insulating buried-heterostructure distributed reflector lasers for low-driving-current high-speed direct modulation

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AlGaInAs-based multiple-quantum-well (MQW) semiconductor lasers have been investigated enthusiastically for high speed light sources. The AlGaInAs MQW enables high-speed direct modulation because of its large differential gain which arises from the large conduction band offset. We have been developed AlGaInAs-MQW distributed reflector (DR) lasers with semi-insulating buried-heterostructure (SI-BH) as a suitable candidate for high speed light source for short reach data transmissions. The DR laser has DBR mirrors on both sides of a DFB active region. Owing to the increased optical feedback with these DBR mirrors, we can obtain short-cavity lasers without increasing threshold gain. Combining with AR coatings on both facets, the DR lasers exhibit stable single mode operation avoiding influence of the phase variation of grating at the facets. The small active region of the DR laser, which comes from the combination of the short cavity structure and the SI-BH waveguide, makes driving current lower. The DR lasers have shown excellent characteristics such as high output power, stable single mode operation, and high values of relaxation oscillation frequencies under low driving current in a wide temperature range. We have achieved 25- and 40-Gbps direct modulation with low driving current. Using 1.55-μm wavelength DR laser, we obtained 40-Gbps direct modulation with 5 dB dynamic extinction ratio with the driving current less than 50 mA even at 85 degrees Celsius. Using 1.3-μm wavelength DR laser, 40-Gbps transmission over 10-km single mode fiber under the operation conditions up to 85 degrees Celsius was demonstrated.

8277-11, Session 3

Long-wavelength quantum dot FP and DFB lasers for high temperature applications

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High temperature (>125°C) resistant semiconductor lasers are attractive as light sources in a variety of harsh environments. Long-wavelength lasers including Fabry-Perot (FP) and distributed feedback (DFB) lasers operating under higher temperature combined with silica-based optical fibers can expand application fields of data transmission and optical sensing to severe environments like space or deep underground. Quantum-dot (QD) active layers can drastically reduce temperature dependence of the threshold current of a semiconductor laser owing to 3-dimensional confinement. Here, we report extremely high temperature continuous-wave (CW) operation of QD lasers on GaAs substrate emitted at 1300-nm-range by enhancing gain and increasing the quantized-energy separation of the QD active layers. The key factor to enhance gain is to overcome the trade-off between QD sheet density and inhomogeneous broadening. We found that a suppression of the In out-diffusion during MBE from self-assembled InAs QDs significantly reduced inhomogeneous broadening with high QD sheet density maintained. Eight stacked QD layers, in which each layer has high QD sheet density of 6e10 cm-2, showed narrow photoluminescence FWHM of 24 meV at room temperature, resulting in that our QD lasers could have sufficient modal net gain even at elevated temperatures. QD-FP laser exhibited record high CW-lasing temperature for long-wavelength laser of 220°C with a high characteristic temperature T0 (25-125°C) of 170K. QD-DFB laser also exhibited high CW-lasing temperature of 150°C with a wide single-mode operation range of temperature from 25 to 150°C owing to high gain QD active media. Further optimization of threshold gain will increase QD-DFB lasing temperature.

8277-12, Session 3

InAs/InP quantum dot based lasers and effect of optical feedback

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The effect of controlled optical feedback has been investigated for InAs/InP laser structures operating in the 1.55 µm fiber window. Mode locked lasers in particular show extremely small phase noise when subjected to optical feedback, implying a very low timing jitter which is of interest for many applications.

Owing to growth optimisation, p-type doped directly modulated DFB lasers have also been shown to exhibit a robustness to optical feedback that complies with 10 Gb/s isolator free operation.

8277-13, Session 3

Generation of picosecond pulses and optical frequency combs with multi-section 1065nm ridge waveguide diode lasers

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Mode-locked diode lasers generate reliably picosecond or even sub-picosecond optical pulses. Especially, colliding pulse mode-locked (CPM) lasers are promising sources for short optical pulses with high repetition frequency.

We present experimental results to the generation of stable ps optical pulses with multi-section ridge waveguide CPM lasers. The lasers with a central emission wavelength of 1065nm consist of an odd number of 100µm long electrically separated sections. CPM operation is achieved by a reverse DC biasing of the central section which acts as a saturable absorber and forward DC biasing of the other (gain) sections.

For a cavity length of 1.9mm, passive mode-locking is achieved for a reverse bias of -2.0V applied to the central section. The repetition frequency is about 43GHz and the pulse length is 3.3ps assuming a sech2 pulse shape. For an injection current of 250mA a pulse peak power of ~1W is achieved. By changing the input current to the gain sections higher harmonics of up to 130GHz are observed with pulse length ~1.1ps. The time-averaged optical spectra exhibit a large number of discrete frequencies. For the 1.9mm long lasers the frequency comb spans 6nm assuming a dynamical range of 20dB with a frequency spacing of about 21GHz. At a cavity length of 0.9mm a frequency comb with more than 175 single frequencies over 12nm with a spacing of 45GHz is obtained. Detailed investigations of the optical pulse and frequency comb generation in dependence on laser length, reverse absorber voltage and DC bias current will be presented.

8277-14, Session 3

Mode-locked tapered multi-section quantum-dot laser for high peak power and sub-picosecond pulse generation

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We present high peak power and ultra short pulse generation from quantum-dot multi-section tapered lasers at 1269nm. In this device the quantum-dot structure was grown on GaAs substrate using Molecular Beam Epitaxy. The active region contains 10 layers of InGaAs quantum dots separated by GaAs barriers and embedded in a GaAs waveguide. The device presents one straight gain section of 700 µm, one straight absorber section of 700 µm and a tapered gain section of 1.6 mm with a flared angle of 2°. The corresponding total length is 3mm and the absorber to gain section-length ratio is 30.4%. With a fully gain guided quantum-dot multi-section tapered laser diode we demonstrate high peak power and sub-picosecond pulses under passive mode-locking. Using the intermediate section as an absorber with a reverse bias of 6V and connecting the other straight section and the tapered section together under 825 mA and 20°C we obtain the highest peak power under mode-locking regime. This value corresponds to 8.03 W with a pulse width of 640 fs. At this operation point an average power of 68.9 mW and 5.1 pJ pulse was also observed. With the same configuration and a gain current of 800 mA and 20°C we obtain the lowest pulse width generation under mode-locking regime. This value corresponds to 616 fs with a corresponding peak power of 7.88 W.

8277-15, Session 4

Sub-300 nm AlGaN lasers on bulk AlN substrates

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We describe recent progress on the development of sub-300 nm lasers at the Palo Alto Research Center (PARC). We successfully explored the feasibility of using high quality bulk AlN substrates for the epitaxial growth of UV laser structures. The substrates were grown by physical vapor transport. They feature excellent crystalline quality with typical dislocation densities < 10-3 cm-2, x-ray diffraction rocking curve values of about 20 arc sec for the (002)-reflection and a rms surface roughness of 0.1 nm. The AlxGa1−xN/AlyGa1−yN hetero-structures were grown by metal-organic vapor phase epitaxy. The laser structures included AlN/AlGaN transition layers, AlGaN cladding layers and AlGaN waveguides. The whole layer stack below the MQW region was designed towards laser diodes emitting at 250 nm. Various active zones with emission wavelengths between 267 and 291 nm were tested by time-resolved photoluminescence (PL) studies and optically pumping laser experiments. Long PL decay times at room temperature of 900 ps from the multiple quantum well emission were determined. This is a direct confirmation the high structural quality of the devices. Lasing was achieved for all test structures by optically pumping with a KrF excimer laser at an emission wavelength of 248 nm. The lasing threshold pump power density for the shortest emission wavelength (267 nm) was as low as 126 kW/cm2, which is comparable to blue-violet devices. The polarization of the emitted laser light was found to be TE polarized for all test structures. Concepts for realizing the p-side of the UV laser diodes will also be discussed.

8277-16, Session 4

(Al,In)GaN laser diodes with optimized ridge structures

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At present, III-nitride based LDs are commercially available efficient laser light sources with output powers ranging from few mW to several hundreds of mW. While their wavelengths extend from near UV to green, the majority of commercial devices are designed for data storage applications at 405 nm and laser projection with wavelengths of about 450 nm and 520 nm. The performance of such lasers strongly depends both on epitaxial design of a diode structure and on the geometry of the laser.

We develop (Al,In)GaN ridge waveguide laser diodes in the violet-blue spectral region. Varying the indium content of the InGaN quantum wells we tailor the emission wavelength of our devices for specific applications in the range from 390 nm to 425 nm. Critical steps towards an efficient laser diode involve minimizing the internal optical losses as well as reaching a current injection efficiency close to 100%. By comparing different free standing GaN substrates (Lumilog, Sumitomo) we adjust the epitaxial structure and simultaneously optimize the processing sequence. In particular we focus on the ridge formation. The width and geometry of the laser ridge directly influences the device parameters - electrical (threshold currents) and optical (smaller widths provide better beam quality and better stability). We compare different planarization methods which involve the use of SiOx and BCB to obtain devices with ridge widths around 2 microns. So far, we have achieved threshold currents around 60 mA and slope efficiencies greater than 0.7 W/A.

8277-17, Session 4

Recent development of green and blue InGaN-based laser diodes on nonpolar/semipolar substrates

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We present new advances in green and blue InGaN-based laser diodes fabricated on nonpolar/semipolar GaN substrates. These alternative growth planes have enabled new heterostructure designs and a new epitaxial growth parameter space which together have led to world class demonstrations of both green and blue laser diodes. For green wavelengths, we report on continuous wave single-mode lasing with more than 100 mW of output power and over 4% wall-plug-efficiency. In the blue regime, we present single-mode lasers operating with over 23% wall-plug-efficiency and output powers greater than 700 mW. Furthermore, we demonstrate high power blue emitters operating with over 1.4 W of output power and bar-type emitters exhibiting over 4.6 W of output power. The rapid rate of progress on the nonpolar/semipolar platform is validation of the predicted theoretical advantages. The continued improvements in green and high power blue laser diode performance will soon lead to the commercialization of this InGaN-based semipolar/nonpolar technology and will enable a variety of new applications in defense, biomedicine, and consumer projection displays.

8277-18, Session 4

Engineering of AlGaN-Delta-GaN quantum wells gain media for mid- and deep-ultraviolet lasers

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Mid- and deep-ultraviolet (UV) lasers have applications for biochemical agent identification, free space communication, and water purification. Though large TM-polarized gain is expected for AlGaN quantum well (QW) emitting in 220-230 nm, relatively low optical gain is expected for conventional AlGaN QW emitting in the 240-300 nm. Attributing to the strong valence subbands mixing from the insertion of ultra-thin delta-GaN layer in the center of high Al-content AlGaN QW, our recent work revealed the use of AlGaN-delta-GaN QW resulted in large TE-polarized gain applicable for lasers emitting in the ~240-300 nm spectral regime.

Here, we present a comprehensive optimization study on the gain characteristics of AlGaN-delta-GaN QWs with various delta-GaN positions and Al-content AlGaN QW compositions for optimizing the material gain in the mid- and deep-UV spectral regime. The comparison of the gain characteristics for both symmetric and asymmetric AlGaN-delta-QWs was also performed. From our finding, the use of AlGaN-delta-GaN QW resulted in ~ 7-times increase in material gain, in comparison to that of conventional AlGaN QW, for gain media emitting at 240 nm. By optimizing the GaN delta layer position in the AlGaN QW, the optical gain of the active region can be further enhanced by ~10%. By employing asymmetric AlGaN-delta-GaN QW with different Al-content, the optical gain is enhanced further by ~ 15%. Therefore, optimized optical gain in excess of 4000 cm-1 can be achievable by engineering the delta position and AlGaN composition of the AlGaN-delta-GaN QWs with realistic design applicable for deep and mid UV lasers.

8277-77, Session 4

Beyond blue pico laser: development of high power blue and low power direct green

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InGaN lasers are interesting light sources for laser projection. Blue InGaN laser diodes for 10 and 20lm pico projection are already commercially available. The development of direct green lasers is one of the most challenging areas of InGaN material science. We present direct green lasers for pico projection operating above 515nm with good power conversion efficiencies and lifetimes above 1000h. Projectors of 1000lm brightness need 1W-class blue lasers. The mayor challenge for this power level is a high power conversion efficiency which is necessary (1) to prevent from thermal roll-over and (2) to achieve long lifetimes.

8277-20, Session 5

Quantum cascade lasers as mid-IR frequency combs

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Broadband quantum cascade lasers driven in continuous wave are now providing hundreds of miliwatts of continuous wave operation on a peltier cooler while achieving operation over 300cm-1 bandwidth.

Using a combination of fast QWIP detector, and interferometric non-linear detection, the coherence properties of the laser in multimode operation are studied.

In particular, locking of the beatnote to an external RF modulator is demonstrated. These results are promising to the development of electrically injected, mid-infrared optical combs.

8277-21, Session 5

Terahertz quantum cascade lasers based on symmetric InGaAs/GaAsSb active regions

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Terahertz quantum cascade lasers (THz QCLs) are predominantly realized in the GaAs/AlGaAs material system mainly because of the flexible conduction band offset. However, with stagnating, yet cryogenic, operating temperatures since many years now, strategies to improve this figure of merit have shifted from active region optimizations to novel injection schemes, other material combinations and the exploration of three-dimensional confinement techniques.

Our group recently demonstrated a THz QCL in the Al-free, low effective electron mass InGaAs/GaAsSb material system which is lattice-matched to an InP substrate. The favorable properties of this material system in a nutshell: the low effective mass of InGaAs provides a gain advantage and the barrier is more penetrable than standard InAlAs due to a lower effective mass, a lower conduction band offset and a type II alignment. Therefore it can be kept at reasonable thickness values and the resulting band structure is not as sensitive to growth fluctuations.

A three-well active region in this material combination has been designed and processed in a double-metal waveguide. Up to now, the highest operating temperature is 135 K for those devices. Additionally, we have also designed a symmetric active region to study the influence of the growth direction. These bidirectional THz QCLs show a dramatically asymmetric electrical as well as optical behavior when operated under both bias polarities. Although the active region is nominally symmetric, the threshold current densities differ by up to 36 % and maximum operating temperatures are 90 and 125 K, respectively.

8277-22, Session 5

Terahertz intersubband polariton electroluminescence at room temperature

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The technologically interesting Terahertz spectral region is devoid of cheap, electrically pumped room-temperature sources. A new approach exploits the high radiative efficiency of polaritonic states associated with high Rabi frequencies in intersubband polaritons.

We observe intersubband polaritonic electroluminescence up to room temperature in the THz regime for the first time. We employ electronic feedback type microcavities, allowing strong subwavelength confinement and couple them to modulation doped digitally graded in GaAs/Al0.15Ga0.85As parabolic quantum wells with a designed intersubband transition frequency of ωISB=3.7THz. The electron gas inside the quantum wells is nonresonantly excited, avoiding coupling effects to an injectior reservoir. Using a parabolic potential allows room temperature operation due to the insensitivity to thermal electron redistribution. Moreover, in accordance with Kohn's theorem, no depolarization blueshift is observed, maximizing the coupling compared to the intersubband transition energy.

Electroluminescence from samples with different cavity resonance frequencies is observed at low temperatures (T=10K). Two emission peaks are visible in each spectrum corresponding to the coupled eigenstates of cavity mode and intersubband transition. The emission lines tune with the microcavity resonance frequency and a strong anticrossing is observed. The Rabi frequency is 720GHz, corresponding to 3.0meV. The resulting ratio ΩR/ωISB = 0.2 puts the sample in the ultra strong coupling regime, where new phenomena like the emission of correlated photon pairs are predicted. Electroluminescence is seen up to room temperature at decreased power, but still at the same coupling strength as for cryogenic temperatures.

8277-23, Session 5

Emergence of free carrier absorption in heterostructure devices

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Free carrier absorption is an important mechanism for the THz response of bulk semiconductor. It is shown how free carrier absorption naturally arises in semiconductor heterostructure devices in the limit of small barriers from a combination of intersubband transitions and the differential conductivity. The implications for the correct modeling of the gain spectrum in quantum cascade lasers are discussed.

8277-24, Session 6

Multi-wavelength operation of quantum cascade lasers using gratings with an aperiodic basis

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We demonstrate simultaneous lasing of mid-infrared quantum cascade lasers on multiple single-modes, each one having a side-mode suppression ratio of about 20dB. This is achieved by using a new class of distributed feedback gratings having multiple peaks in Fourier-space. Their design relies on the use of small aperiodic grating sequences as unit cells whose repetition forms a superlattice. The superlattice provides well-defined Fourier components while the choice of the unit cell structure enables selection, modulation or suppression of certain Fourier components.

8277-25, Session 6

Quantum cascade laser external cavity tuning solution for 1660 to 720 wavenumbers operation with only three gain blocks

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A broad gain QC laser covering a frequency range of almost 400cm -1 is demonstrated. This device operates CW at room temperature unlike earlier pulsed results[1] with larger tuning range. The active region is composed of three different cascade designs based on the bound-to-continuum structure [2]. Special care has been taken in the design in order to obtain a flat modal gain over the emission range. The growth of an InP buffer, the InAlAs/GaInAs active region and InP top cladding, as well as Fe-doped lateral regrowth for making BH waveguides are done by MOVPE. The widths of the processed ridges are between 6 and 12µm. The processed devices are mounted epi-layer up on copper and measured using a thermopile detector and FTIR for power- and spectrum measurements, respectively.

A 4.5mm-long, 8µm-wide, HR coated device in CW exhibits more than 120mW of output power at -30C with a threshold current of 530mA, corresponding to a threshold current density of 1.47 kA/cm 2. CW operation is observed up to 15C. The Fabry-Pérot free running spectrum is broader than 100cm -1 in continuous operation and enlarges to more than 350cm -1 in pulsed operation. A 12µm-wide device showed emission over a range of almost 400cm-1.

Together with two existing devices from Alpes Lasers, this laser covers the range from 6 to 12.9µm.

[1] A. Hugi, et al. “External cavity quantum cascade laser tunable from 7.6 to 11.4mm”, Appl. Phys. Lett. 95,

061103 (2009).

[2] J. Faist, et al. “Quantum-cascade lasers based on a bound-to-continuum transition”, Appl. Phys. Lett. 78, 147 (2001).

8277-32, Session 6

Dual-wavelength homogeneous mid-infrared quantum cascade laser

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We demonstrate a dual wavelength mid-infrared Quantum Cascade Laser (QCL) utilizing a single active region to emit at 5µm and 9µm. The novelty of our device consists in the large energy difference between the two lasing energies and is achieved through simultaneous injection into the top 2 levels of a 4-level cascade. The gain and losses at both wavelengths were measured by two different methods, the Hakki-Paoli method and the cut-back method, and were compared with theoretical predictions. The gain measurements by the two techniques are consistent with each other and in agreement with the calculated value for the 5µm laser. However, the gain of the long wavelength laser is considerably lower than expected while the mid-infrared losses are much larger than expected. A possible practical application of the devices is spectroscopy for trace gas sensing. We are also investigating these devices for their potential application of quantum coherence to achieve lasing without inversion. The intense fields generated by the 9µm laser are expected to partially eliminate the resonant absorption on the transition of interest at an energy corresponding to the difference between the energies of the two lasers. Under suitable conditions positive gain is achieved and lasing is predicted to occur without population inversion at the third energy. Our results on the dual wavelength QCL provide insights in the detail charge transport and optical properties of this design concept and opens up the possibility for future optimization of inversionless lasers.

8277-78, Session 6

Continuous wave operation of distributed feedback quantum cascade lasers with low threshold voltage and small divergent angle for CO2 isotope sensor

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We demonstrated room temperature continuous wave (CW) operation of distributed feedback quantum cascade lasers around 2300 cm-1. Single mode operation under CW operation is demonstrated up to 70deg C, with a side mode suppression ratio (SMSR) of 30 dB. The lasers were designed for distributed CO2 sensing networks with a low threshold voltage of less than 8 V for battery operation and a small divergent angle of 28 by 33 degrees at FWHM for easy collimation.

OPTO
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8277-28, Session 7

Key design-concepts for mid-infrared and THz quantum-cascade lasers: dual upper-states and indirect pumping

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Striking features such as ultra-broad-band gain (delta-lamda/lamda~40 %) and high mode-stability, of dual upper-state mid-infrared InGaAs/InAlAs quantum-cascade lasers are interpreted consistently in terms of very fast (100 fs) elastic (alloy disorder and interface roughness) scatterings between anti-crossed upper-subbands, showing possible lasing due to localized-k-state (~2.5×10^6 1/cm) electrons in the lower subband among upper ones at room temperature. For further improvement of device performance of indirectly pumped THz InGaAs/InAlAs quantum-cascade lasers with a low threshold-current-density of 340 A/cm2 at 6 K, we discuss significances of quantum-structure design based on generalized condition for complete thermalization.

8277-29, Session 7

Room-temperature watt-level emission at 3.3um in Sb-free InGaAs-AlAs quantum-cascade lasers

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Recently, the need for compact sensors, capable of real-time concentration monitoring, has become crucial. In particular the 3-μm spectral region is relevant since the fundamental C-H, N-H and O-H stretching modes have strong resonances in this region(e.g. Methane, Formaldehyde). The unique possibility offered by quantum cascade lasers(QCLs) to tailor the emission frequency, makes them ideal as sources for these applications. Unfortunately for wavelengths smaller than 4μm, the realization of QCLs is challenging using the standard material systems, due to the large conduction band discontinuity needed.

In this work we present for the first time a Sb-free QCL design based on the InGaAs/AlInAs-AlAs on InP material system emitting at ~3.3μm. Two step barriers (AlInAs-AlAs) are used in the active region design in order to limit the material strain introduced by AlAs.

Lasers show room temperature, Watt-level emission. Maximum operation temperature above 350K was observed [1]. Previously, no QCL with emission wavelength smaller than 3.6μm was demonstrated in this material system in a temperature accessible by thermoelectric cooling[2]. The use of this material system is necessary since it is the only one Sb-free and it is fully compatible with the high-performance QCL fabrication processes for continuous wave emission, i.e. buried heterostructure process(BH). The use of first-order grating for spectral control will also be exploited.

[1] A.Bismuto,M.Beck,J.Faist Appl.Phys.Lett.98,191104(2011).

[2] J.Faist,F.Capasso,D.Sivco,A.Hutchinson,S.Chu, A.Cho Appl.Phys. Lett.72,680(1998).

8277-30, Session 7

Broadband continuous-wave tuning of external cavity anticrossed dual-upper-state quantum-cascade lasers

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Broadband wavelength tuning of external cavity quantum cascade lasers (EC-QCLs) has been demonstrated to realize a versatile mid-infrared light source for absorption spectroscopy. In the spectroscopic applications, stable single mode tuning of EC-QCLs with continuous wave (cw) operation is required because its narrow linewidth is crucially important for high-accuracy measurements. In this decade, broadband tuning of EC-QCLs employing multiple-stacks of bound-to-continuum active regions has been reported. However, multiple-stack BTC-QCLs reported so far, exhibit relatively high threshold current densities at room temperature as well as inhomogeneous spectral behavior. The former creates difficulty in achieving cw operation above room temperature and the latter gives rise to unstable single mode lasing without extremely low-reflectivity antireflection coating.

On the other hands, in identical-stack QCLs based on the dual-upper-state to multiple-lower-state (DAU/MS) design, depression of electron population in an upper subband, induced by stimulated emissions can be compensated quickly by relaxation from other subbands. Thus, gain spectra of identical-stack DAU-QCLs would be regarded to be spectrally homogeneous one, and simultaneously, the threshold current density is decreased by the adoption of the DAU/MS design. From this reason, by the use of the identical stack active region, the broadband wavelength tuning in cw operation is achieved with single mode. In the results, we present a broadband wavelength tuning in cw operation at room temperature with an EC-QCL using a gain medium based on the DAU/MS design. The tuning range around 6.8 μm reaches 321cm-1 in pulsed, and 248cm-1 in cw operation at room temperature.

8277-31, Session 7

Tapered active-region mid-infrared quantum cascade lasers for complete suppression of carrier-leakage currents

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Conventional quantum-cascade lasers (QCLs) emitting in the 4.5-5.5 μm range suffer from significant carrier leakage from their active regions, as evidenced by low values (i.e., ~ 140 K) for the characteristic temperatures T(0) and T(1) of their threshold current and slope efficiency, respectively. By taking advantage of the flexibility of the MOCVD crystal-growth method to easily grow quantum wells (QWs) and barriers of multiple alloy compositions, we have implemented the deep-well concept for carrier-leakage suppression, and obtained virtual doubling of the T(0) and T(1) values. Recently we implemented the tapered-active (TA) concept and obtained T(1) values as high as 454 K.

The TA design causes a significant increase in the energy difference between the upper laser level and the next higher energy level E(54); thus results in further carrier-leakage suppression. This high E(54) value is determined by two factors: the energy separation between the first excited states of a pair of coupled QWs (CQWs) is larger when the CQWs are asymmetric than when they are symmetric; and, the Stark shifts of the first excited states are quite different for asymmetric CQWs compared to symmetric CQWs. Then, we achieved an optimized TA QCL design for which E(54) values as high as 97 meV are obtained, while insuring good carrier depopulation of the lower laser level [i.e., $\tau(3) = 0.24$ ps] via the double-phonon-resonance scheme. As a result the relative carrier leakage decreases to values ≤ 1%. At 300 K, front-facet, CW wallplug-efficiency values as high as 25 % are estimated.

8277-33, Session 8

1300-nm InAs/GaAs quantum-dot lasers monolithically grown on Ge and Si substrates for Si photonics

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1300-nm InAs/GaAs quantum-dot laser structures were fabricated by Molecular Beam Epitaxy. The new techniques of III-V buffer layers directly grown on Ge and Si substrates were developed to suppress the formation of threading dislocations and antiphase boundaries. Strong photoluminescence around 1300-nm with linewidth of about 30 meV has been demonstrated for InAs/GaAs QDs grown on both Si and Ge substrates. QD laser structures were optimized on both Si and Ge substrate. For InAs/GaAs QD laser grown on a Si (100) substrate, the first room-temperature electrically-pumped operation at 1302 nm was demonstrated with threshold current density of 725 A/cm2 and output power of ~26 mW for broad-area lasers with as-cleaved facets under pulsed operation. The Si-based InAs/GaAs QD laser has a 42 oC maximum lasing temperature with a characteristic temperature T0 of 44 K. For InAs/GaAs QD laser epitaxially grown on a Ge (100) substrate, lasing at a wavelength of 1.305 μm with the low threshold current density of 55.2 A/cm2 was observed under continuous-wave current drive at room temperature. This is the first III-V QD laser demonstrated on Ge substrate. The QD laser on Ge has a 60 oC maximum lasing temperature with a characteristic temperature, T0, of ~40 K between 20 oC and 60 oC.

8277-34, Session 8

Molecular beam epitaxy grown GaInAsSbBi alloys on GaSb substrates for mid-infrared laser diode applications

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Recently, mid-infrared semiconductor lasers have drawn increasing attentions for various applications. So far, high power room temperature (RT) continuous-wave (CW) operation of semiconductor lasers within the spectral region of 3-4 μm remains challenging. GaSb-based laser diodes with type-I compressively strained GaInAsSb quantum wells (QWs) have achieved RT CW operation above 3 μm. However, besides a relatively low characteristic temperature, these devices have difficulties to further extend the lasing wavelength beyond 3.4 μm. It has been reported that adding Bi into GaAs reduces the bandgap energy significantly, as much as 60-80 meV per percent Bi. Also GaAs-based GaAsBi light emitting diodes and optical pumped lasers have been demonstrated successfully. Accordingly, it is expected that the incorporation of Bi into GaInAsSb will also shrink the bandgap energy of GaInAsSb to further extend the radiation wavelength. Moreover, Ga(In)AsSbBi can be an attractive active material to achieve 3-4 μm radiation with better performance due to higher hole confinement, lower conduction band discontinuity, and lower internal loss in the QW. Currently, there is little work reported for the material growth and characterization of GaAsSbBi alloys. In this work, we will present our initial study on the incorporation of Bi into GaSb and the properties of GaAsSbBi alloys. At lower growth temperature and lower growth rate than the conventional GaSb material growth conditions, Bi can be incorporated into GaSb using Molecular Beam Epitaxy with composition as high as 10%, which was evidenced by XRD and RBS measurement. Surface morphology and photoluminescence will also be discussed.

8277-35, Session 8

Temperature dependence of 2.3um and 2.6um GaInAsSb based BTJ-VCSELs and edge emitting lasers

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There is a growing interest in electrically pumped lasers that emit in the 2-3μm wavelength region for applications such as gas sensing, pollution monitoring and medical diagnosis. GaSb based type-I quantum well edge-emitting lasers (EELs) provide room temperature continuous wave operation but are limited by Auger recombination and inter-valence band absorption. For most applications, Vertical Cavity Surface-Emitting Lasers (VCSELs) are a preferred option because of lower power consumption, cheaper fabrication and improved beam quality. However, self-heating and the presence of fundamental loss processes necessitate careful design to provide gain peak - cavity mode alignment at a particular temperature and wavelength for optimum performance. In this study we have investigated 2.3μm and 2.6μm VCSELs. Edge-emitting lasers with nominally identical active regions were used to look at the effects of non-radiative recombination and to extract information about the gain peak which was then used to analyse the VCSEL behaviour. A combination of high hydrostatic pressure and temperature dependence techniques were used to investigate the wavelength dependence of non-radiative processes and cavity mode - gain peak detuning. From these measurements we find that 85% (97 %) of the threshold current of 2.3μm (2.6μm) edge-emitting lasers is due to non-radiative recombination. Our results suggest that temperature insensitive VCSEL operation around room temperature could be achieved with a larger gain - cavity de-tuning, offsetting the effect of increasing non-radiative recombination with increasing temperature, as shall be discussed in further detail.

8277-36, Session 8

Recent progress in lattice-matched Ga(NAsP)-based laser structures monolithically integrated on (001) Si substrate

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In recent years the class of dilute nitride III/V-semiconductors and corresponding heterostructures are gaining increasing interest both from fundamental as well as applied point of view. This is caused by their unique optoelectronic properties and in particular by the novel conduction band formation process leading to an extreme band gap bowing with increasing N-content in the crystal.

The novel material system Ga(NAsP) can be grown lattice-matched to (001) Si-substrate. The incorporation of N in the Ga(NAsP)-material allows for a significant reduction in the lattice constant, which leads on one side to a dislocation free deposition. On the other side the specific conduction band formation process in these materials is used to realize a direct band gap semiconductor. Ga(NAsP)/(BGa)(AsP)-MQWH were grown on exact oriented (001) Si substrates embedded in thick (BGa)P separate confinement hetero-layers by metalorganic vapour phase epitaxy (MOVPE). The incorporation of B into GaP and Ga(AsP) allows for a precise strain management of the whole III/V laser stack towards the lattice constant of Si. The optoelectronic properties and electric injection lasing characteristics of Ga(NAsP)-MQWH on (001) Si-substrate will be presented and discussed. These results form the basis for a unique realization of monolithic integration of III/V-based optoelectronic and Si-microelectronic functionalities in the near future.

8277-37, Session 8

Strained confinement layers in InP quantum dot lasers

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Self assembled InP quantum dots (QD) offer a range of emission wavelengths from 645-750nm making them useful for laser applications in photodynamic therapies and bio-photonic sensing. We have demonstrated broad area InP/AlGaInP QD lasers grown by MOVPE with 300K threshold current density (Jth) as low as 150Acm-2 for 2mm long lasers with as-cleaved facets and emitting between 700-750nm. However, at elevated temperatures Jth increases rapidly with temperature. To address this issue here we revisit the design of layers around the dots. We examine samples with five layers of dots, each grown on a lower confining layer (LCL) of (Al0.30Ga0.70)InP lattice matched to GaAs, formed from 3 mono-layers of InP and with a GaxIn(1-x)P upper confining quantum well layer (UCL). Samples with different UCL compositions with x between 0.43 and 0.58 are studied. The waveguide cladding consisted of (Al0.70Ga0.30)0.51In0.49P. A further set of structures (x=0.51-0.58) were grown with AlInP claddings. The QD properties are strongly influenced by the UCL, with the measured dot absorption and lasing energies increasing with Ga percentage in the UCL, changing at the same rate as the measured and calculated UCL transition energies. The magnitude of the absorption varied across the composition range, with the strongest and most well defined absorption occurring for an UCL with x=0.54 (lightly tensile strained with respect to GaAs). This composition also gave the lowest 300K threshold current density for 2mm long lasers with uncoated facets of 180 Acm-2 but more importantly had significantly improved high temperature performance.

8277-38, Session 9

Broadband modeless cw semiconductor laser: design and coherence properties

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We demonstrate a cw broadband (THz) modeless external-cavity semiconductor diode laser taking advantage of the broadband inhomogeneous gain behavior of quantum-dots. The laser cavity is formed by a L=54cm long arm, an AOM with AOM =110MHz and 85% 1st ordrer diffraction efficiency, a geltech aspheric lens and two cylindrical lenses to collimate the diode beam. The gain chip is a 2mm long single transverse mode InAs/GaAs quantum-dot diode amplifier emitting at 1060nm, with a 100mW at 300mA injection at 300K. The threshold was 30 mA. In contrary to the narrow cw spectrum without AOM, the cw modeless laser optical spectrum is broadband with a bandwidth up to 1THz. Residual Fabry-Perot modulations appear at the gain chip FSR (=22GHz), due to imperfect AR coating of the intracavity facet. No fine spectral structure appears at the FSR when the output is lunched through a confocal scanning Fabry-Perot interferometer. Thus the laser is modeless. The free running laser output was studied in terms of Relative Intensity Noise. The rms intensity fluctuations are <0.5%. In order to study the coherence of such laser, we recorded the RF spectrum of homodyne-detected signal through a Michelson. The resulting beat signal at 26MHz shows a linewidth of 500kHz. The coherence time of this laser is thus ~1µs.

8277-39, Session 9

All semiconductor high power fs laser system with variable repetition rate

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Laser diodes offer an interesting alternative to commercially available light sources for the generation of ultrashort pulses. They have the unique feature that they can be directly electrically pumped and that the emission wavelength can be controlled over a huge spectral range by changing the composition of the laser material. Hence they have the potential of being a highly flexible, compact and cost effective light source. However there is a considerable chirp of the pulses generated by a diode laser as a consequence of the strong coupling of real and imaginary part of the susceptibility in the semiconductor. This problem is solved by using an external cavity with intracavity dispersion management. By applying this technique we are able to generate pulse durations with less then 200 fs if an additional external pulse compressor is used. By using such a cavity in a master oscillator power amplifier setup the peak power can be increased up to 6.5 kW. This enables a huge field of possible applications like time domain terahertz spectroscopy or material processing. Anyway for some applications like fluorescence lifetime imaging even the repetition rate of an external cavity laser is too high. To solve this problem an ultrafast semiconductor pulse picking element is implemented to reduce the repetition rate into the kHz region. In conclusion we will demonstrate a compact all semiconductor laser system which is capable to generate sub ps pulses with a high peak power and a variable repetition rate at central wavelength of approximately 840 nm.

8277-40, Session 9

Continuously current-tunable narrow line-width miniaturized external cavity diode laser at 633 nm

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Red emitting diode lasers with a narrow spectral line-width and a continuous tuning range are requested as light sources for interferometric measurements with nm-accuracy. For this purpose tuning ranges of about 25 GHz together with a spectral line-width below 10 MHz are necessary.

The manufacturing of internal gratings in red emitting laser diodes is extremely challenging. Therefore, external cavity diode lasers (ECDL) are typically used. The tuning is performed by turning gratings applied. In this work another concept is used. The external cavity laser resonator is formed by the front facet of a diode laser and a reflection Bragg grating (RBG). The RBG has a high reflectivity and a small spectral width, which is approximately equal to the targeted tuning range. The length of the resonator is selected so short, that the distance between the laser modes is larger than the tuning range. Herewith, single mode operation should be guaranteed.

The ECDL was mounted on an aluminum nitride bench with a footprint of 5 x 10 mm2. The laser diode on a submount was soldered directly on a miniaturized Peltier cooler. A GRIN-lens collimated the light from the laser to the grating. The ECDL emitted at a wavelength of 633 nm and reached a maximal output power of 10 mW. The mode-hop free tuning range was 34 pm, i.e. 25 GHz. The measured emission line-width was smaller than 10 MHz. The emitted beam was approximately diffraction limited with a M2 » 1.1 in both directions.

8277-41, Session 9

High power single mode InGaAsP/InP laser diode for pulse operation

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There is a need for high power narrow linewidth eye safe (>1.5um) semiconductor lasers which can be used in various systems such as optical time domain reflectometer (OTDR), seed laser for high power fiber lasers, and rangefinding applications. Recent development efforts have focused on the demonstration of fiber coupled narrow linewidth ridge waveguide (RWG) InGaAsP/InP laser diodes.

In this paper we report results of our studies of narrow linewidth RWG laser diodes utilizing an external cavity configuration. The external cavity was formed by a Fiber Brag Grating (FBG) located close to the front facet of the laser diode chip. Laser diodes within 1.5um -1.65um spectral range were used for the design. Benefits and limitations of external cavity design were investigated including the spectral dynamics of lasers with different spectral width FBG's. The optical power characteristics of lasers under 2ns-10us pulse excitation were measured.

The demonstrated performance shows that fiber coupled RWG laser diodes in external cavity configuration is a good replacement of more complicated and expensive fiber coupled MOPA lasers in eye-safe wavelengths. We demonstrated >1W of peak power and low spectral linewidth (<0.3nm) in a SM fiber under 2ns pulse excitation.

8277-42, Session 9

Single transverse mode wide stripe grating coupled surface emitting laser diodes with external volume Bragg grating cavity

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We proposed a new approach for high-brightness, narrow line semiconductor lasers that is based on using a wide stripe grating coupled surface emitting laser (GCSEL) with a detuned grating output coupler. In this case, an external cavity with feedback provided by a volume Bragg grating (VBG) produced selection of longitudinal (spectral) and transverse (spatial) modes. Extremely low reflectivity of an internal output coupling grating in GCSELs gives an opportunity for complete control of lasing by an external cavity with a VBG. A GCSEL with a 200 µm stripe and a single reflecting VBG as an external output coupler emitted 4 W CW or 25 W pulse power at 976 nm. The measured slope efficiency was more than 0.9 W/A. Spectral width was less than 15 GHz FWHM compared to ~1000 GHz in the original extended-cavity GCSEL. Divergence of an external cavity GCSEL was the same as for the original one because angular selectivity of a reflecting VBG too wide to produce selection of transverse modes in such geometry. It was found that a combination of transmitting and reflecting VBGs provides extremely sharp angularly selective feedback. Using such an element we produced several GCSELs with stripe width of 200 µm and waveguide lengths from 3 to 4 mm placed in an external cavity. Near diffraction limited emission at pumping current up to 5 thresholds was observed. However, further increase of pumping resulted in multimode emission. Nature of this multimode regime and ways of its suppression will be discussed.

8277-43, Session 10

Deformed microcavity for whispering gallery mode lasers with directional emissions

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Optical microcavity lasers can be designed to take advantage of total internal reflection, supporting whispering-gallery modes (WGMs) with a high quality factor (Q-factor). One of the crucial problems, however, is that their emission is non-directional, in addition to their inefficient power output coupling. To solve the problem, one approach is to use deformed optical microcavities. However, deformed microcavities have the general problem that the Q-factor degrades significantly as the deformation increases. We report Limaçon-shaped resonator and elliptical resonator with a wavelength-size notch at the boundary, both of which support in-plane directional laser emissions from whispering gallery modes.

8277-44, Session 10

Quantum cascade lasers with active photonic crystal structure for high-average-power operation in a single spatial mode

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Conventional Quantum Cascade Lasers (QCLs) with Active Photonic Crystal (APC) structure involve diffraction gratings for lateral spatial-mode control. However, since the built-in index step is quite small (5-8 x10^-3), the devices have provided near diffraction-limited beams only under very low (≤ 1 %) duty-cycle operation; and, for 100 µm-aperture devices, to only relatively modest peak pulsed powers (≤ 0.5W).

We present here an APC QCL with a built-in index step (~ 8 x10^-2) an order of magnitude larger than in conventional APC QCLs, for which gain is preferentially enhanced in the low-index APC sites (i.e., in the phase-locked array elements). The elements are basically made of QCL material, while the high-index interelement regions, to be formed by etch and regrowth, contain part of the QCL material and a transverse waveguide with an InGaAs core layer. The APC-QCL structure has been analyzed by using the COMSOL software package. For 8.0 µm-emitting structures of 15 µm-wide element regions, the lateral resonance (for global coupling in the array) is found to occur when the interelement width, s, is ~ 6.0 µm. Single, in-phase-mode operation is assured over an ~ 1.2 µm-wide variation in s, around resonance; thus, providing for large fabrication tolerances. Thermal analysis for a 5-element structure emitting 5 W average power shows that the thermally induced index variations are only ~ 6.5 x10^-3; thus, ensuring that thermal gradients will not affect array operation. Etch and regrowth tests have confirmed the feasibility of the proposed structure.

8277-45, Session 10

Mode locking and phase coherence in quantum cascade lasers

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We present our recent theoretical and experimental results on mode locking, short pulse operation, and generation of frequency combs in mid-infrared quantum cascade lasers.

8277-46, Session 10

Analysis of multiple lateral mode emission of quantum cascade lasers based on near field intensity profiles

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Quantum cascade (QC) lasers have been established as high power coherent light sources in the mid-infrared of the electromagnetic spectrum with attractive features such as freely designable emission wavelength, continuous wave and high temperature operation.

Almost all sensing applications employing QC lasers as illuminating light source require a stable far field intensity distribution in order to realize a high signal-to-noise ratio during the measurement. However, it has been shown that QC lasers are likely to show lateral multi-mode emission in particular when operated at higher output power, with resulting far-field beam instabilities and beam steering effects upon variation of operating current or temperature. These effects complicate effective coupling of the QC laser output beam into a optical system thus deteriorate signal-to-noise ratio and prevent e.g. high-precision spectroscopic sensing measurements.

We established an experimental setup for direct observation of the near-field intensity at the facet of the QC Laser. The setup comprises an IR imager in combination with a microscope lens. Although the optics are operated close to the diffraction limit very consistent results could be achieved. Propagation of the near-field intensities into the far-field distribution show an excellent matching with far-field profile measurements performed on the same devices. Based on time resolved measurements of the near field the mode dynamics of various laser devices emitting at λ=8µm have been measured. Effects due to coherent coupling of different laser modes will be analyzed and their effects on pointing stability and far field distribution of QC lasers will be discussed.

8277-47, Session 11

Room-temperature type-I GaSb-based lasers in the 3.0 - 3.7um wavelength range

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GaSb-based type-I quantum-well lasers, emitting in the spectral range from 2 to 4 µm, are attractive light sources for various trace gas sensing applications by means of tunable diode laser absorption spectroscopy (TDLAS). Excellent device performance has been achieved so far in the spectral range from 2 to 3 µm, however, room-temperature operation above 3 µm is much more difficult to achieve. In this work we demonstrate the extension of room-temperature operation wavelength of GaSb-based type-I lasers up to 3.6 µm by implementation of high-quality quinternary AlGaInAsSb heterostructures.

8277-48, Session 11

Optically pumped type-II Mid-IR tunable DFB laser

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A new approach to tunable middle infrared lasers, an optically pumped type-II InGaSb/InAs gain medium with chirped distributed feedback grating, was developed. A chirped grating is patterned using an interferometric lithography (IL) technique with spherical waves and etched into the top clad of slab waveguide structure. Because the period of grating increases gradually laterally from one end to the other across a 4 mm distance, wavelength tuning is implemented by shifting pump stripe to different positions on the device with different grating periods. Since grating is made 6 degrees tilted with respect to facets and pump stripe is adjusted to be normal to the grating, Fabry-Perot modes are successfully suppressed. In addition, a thin layer of nickel is deposited into the grooves of grating as loss which breaks the DFB mode degeneracy so that single longitudinal mode operation is achieved.

Continuous tuning of 30 nm at about 3.1 µm with 400 mW single facet output power at 80K and 1.5nm line width is reported. Benefiting from the fact that type-II GaSb based of laser covers ~ 2.3- to 12-micrometers range by varying the thickness of InAs layers, different lasing wavelengths and tunable ranges could be achieved across the entire molecular fingerprint infrared.

We focus on controlling the lasing wavelength of this type of lasers in the 3- to 4-µm range which fits in one of the low loss atmospheric transmission windows and covers an important region of molecular vibration spectra, especially the hydrocarbon C-H stretch. This makes this type of laser very suitable for atmospheric pressure remote gas sensing of industrially important small molecules such as methane, hydrogen chloride and ammonia.

8277-49, Session 11

Mid-IR interband cascade lasers operating at very low input powers

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Mid-IR interband cascade lasers incorporating a new generation of design innovations display continuous wave (cw) operating temperature up to 109 °C, output power up to 158 mW and wallplug efficiency up to 13.5% for cw operation at room temperature (RT = 25 °C), and cw lasing to 50 °C at 5.7 microns. Threshold input powers for RT cw operation are as low as 29 mW, as compared to 830 mW for the lowest quantum cascade laser result reported to date.

8277-50, Session 11

High performance interband cascade lasers at 3.8 microns

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An interband cascade laser design, provided by the Naval Research Laboratory (NRL), has been grown by molecular beam epitaxy and fabricated into both broad area and narrow ridge devices, with cavity lengths ranging between 1 mm and 4 mm. Initial data on the broad area devices is very promising; at 300K, under low duty cycle pulsed conditions, threshold current densities are as low as 395 A/cm2 with optical emission centered at a wavelength of 3.8 microns. Continuous wave performance of the narrow ridge devices will be presented at and above 300K. We will describe laser performance results on these narrow ridge devices along with derived estimates of their waveguide losses and internal quantum efficiencies as a function of device ridge width.

8277-51, Session 11

Intersubband photoluminescence in InAs quantum wells

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We conducted a photoluminescence (PL) study on a series of InAs quantum wells with asymmetric barriers designed to generate emission from intersubband transitions (ISBT) near 4 um wavelength. Our goal is to explore a path to an optically pumped laser based on ISBTs. The asymmetric structures incorporated an InAs electron well adjacent to an In0.4Ga0.6Sb hole well. These two layers are flanked by In0.25Ga0.75AsySb1-y quaternary alloy barriers. Due to the broken-gap type-II band alignment the electrons are predominantly confined in the InAs layers, while the holes are confined in the InGaSb layers. The intent of the design is to achieve efficient intersubband E2-E1 PL. Also, by creating a quasi-semi-metallic transition between E1-H1, we can potentially provide a rapid electron-drain for the lower E1 level; this could lead to a population inversion and gain.

PL analysis of a series of epitaxial structures where the InAs electron well layer thickness was varied from 11-19 monolayers revealed emission from both interband and intersubband transitions. The origin of the latter, a transition from the upper trapped conduction state (E2) to the lower trapped conduction state (E1) in the InAs was confirmed by its TM polarization, its improved thermal characteristics and its transition energy which was in good agreement with the Superlattice Empirical Pseudopotential Model (SEPM) theory. We report on our initial PL studies as well as on attempts to generate gain on the ISBT transition by pumping the structures with a high power 2.1 um passively-Q-switched Ho:YAG laser.

8277-68, Poster Session

Optically pumped mid-infrared in-plane DBR laser

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We describe edge-emitting optically-pumped gain-guided mid-IR lasers exhibiting Watt-level output in the mid-infrared, that feature a distributed Bragg reflector (DBR) grating that partially occupies the pump surface. The goal is to achieve high output power with narrow spectral linewidth in the mid-infrared.

The surface DBR near the back facet will enhance modes within the stopband and thus provide spectral selectivity. However, the laser design and the DBR geometry must be carefully chosen so that emission from the facet is limited to DBR-enhanced modes.

The surface DBR grating was fabricated in the top clad layer using interferometric lithography (IL). Devices with a variety of coupling coefficients (κ) and a range of DBR grating lengths, L, resulting in kL ranging from 1.4 to 7 were studied. Observations show that a small range of parameter space exists where the front facet emission is contained in a narrow spectral range.

The best performance so far comes from a device with an estimated κ of ~47 cm-1, κL of ~2.3, and DBR peak 30 nm away from gain peak. Compared to the broad spectrum from the FP cavity emission, a single narrow peak centered at 3596 nm was observed in the front facet spectrum from the in-plane-DBR structure. This peak has a full width at half-maximum value of 2.8 nm, and >95% of the output power is contained within a 6nm range. An output power of ~2.8 W is measured.

8277-71, Poster Session

Modeling Distributed-Feedback GaAs-Based and InP-Based Lasers for Computing Coupling Coefficients

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This modified mathematical waveguide model is constructed to compute the backward coupling coefficients that are important to the performance of lasers. Two types of semiconductor-based quantum-well lasers, GaAs/AlGaAs/metal and InGaAsP/InP/metal, are discussed and compared. Numerical results demonstrate how the geometries and materials of metal-gratings, the layer thickness and materials of semiconductor layers, and wavelengths can affect coupling coefficients. The results show the limitation of increasing the coupling coefficient by reducing the layer thickness. The optimal design of the layer thickness is discussed. Further physical interpretations can support the above results and provide insights into such optoelectronic devices.

8277-72, Poster Session

Direct intensity modulation of three-guide coupled rectangular ring laser having bidirectional lasing characteristics

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Microring lasers are very desirable sources for photonic integrated circuit (PIC) applications due to their compact feature and manifold functionality. They do not require cleaved facets and are easily attached to optical waveguides. In circular geometries the device area is mainly determined by the radius of curvature of the cavity. However, increased radiation loss becomes an issue as radius of curvature decreases. Device area can be reduced significantly by folding the cavity using total internal reflection (TIR) mirrors. Such mirrors can be combined with regular optical waveguides and can reduce the size of PIC drastically. The rectangular laser cavity consists of four low loss total internal reflection mirrors and an output coupler made out of three passive coupled waveguides. Coupling is done laterally. Active and passive materials are integrated within the folded cavity. The fabrication process is exactly the same as for other active and passive devices except for one deep etch step for TIR mirror fabrication. Two different lasers having active section lengths of 250 µm and 350 µm and total cavity lengths of 580 µm and 780 µm are fabricated. For both the clockwise and counterclockwise circulating directions, the lasing threshold currents of around 38 mA are obtained at room temperature under continuous wave operation. Here, the direct intensity modulation of a three-guide coupled rectangular ring laser having bidirectional lasing characteristics is demonstrated. A 3-dB modulation bandwidth over 3 GHz is observed in both circulating directions for both lasers. More detailed results will be presented.

8277-73, Poster Session

Measurement of differential carrier lifetime of undoped and modulation p-doped quantum dot lasers

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Quantum dot lasers are currently being commercialized for 1300nm fibre-to-the-X (FTTX) applications, relying upon a lack of temperature sensitivity of the threshold current and efficiency. However, the origin of this temperature sensitivity has been attributed to a wide range of possible factors. Auger recombination is a critical factor in determining laser threshold and a reduction in the Auger coefficient with increasing temperature has been attributed to the constant threshold current in modulation p-doped QDs. This was previously deduced by fitting modeled radiative currents in the QDs, barrier, and wetting layer and non-radiative recombination attributed to Auger recombination alone.

In this paper we present differential carrier lifetime measurements of un-doped and modulation p-doped (18 acceptors/QD) dot-in-well lasers operating at 1310nm. We spectrally resolve the emission from the QD device in order to observe the excited state (ES) and ground-state (GS) emission independently. For the current densities and temperatures studied (around room temperature), we find that for the un-doped device the GS and ES differential carrier lifetimes are equivalent and essentially constant with temperature. However, for the modulation p-doped device the GS and ES differential carrier lifetime is significantly lower that that of the un-doped sample and increases with increasing temperature, in agreement with a reducing Auger rate. In addition, the ES differential carrier lifetime is observed to increase with increasing temperature, suggesting that inter-level carrier scattering is also reduced with increasing temperature and that the recombination rate in the excited state is long compared to all other lifetimes in the system.

8277-76, Poster Session

Antireflection coatings in semiconductor lasers: effects on power emission and external cavity lasing

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Parameters controlling light generation and emission in Fabry-Perot (FP) and distributed feedback (DFB) semiconductor lasers are analyzed through a mathematical model. Effects of facet reflectivity on laser emission and the overall power dissipation are studied. Five-fold increase of wall-plug efficiency is estimated for an AR coated structure with reflectivity of 10-5 compared to a FP laser with cleaved/cleaved configuration. It is also shown with typical values that, optimized conditions of facet coating can reduce the laser power dissipation by several hundred milliwatts for optical output levels of the order of 10 mw. External cavity lasing (ECL) through selective feedback of light into the FP gain medium is analyzed by the model. Effects of threshold shift and changes in slope efficiency for ECL operation as reported in literature are explained. Our model also explains reported observations of residual Fabry-Perot modes of oscillation in ECL operations. It is shown that AR coating plays the most significant role in decreasing the threshold current in ECL mode compared to that of FP lasing. It is estimated that coating reflectivity of 10-5 with external grating efficiency of 50% can result in a shift of threshold current by more than 50 mA. Effects of grating efficiency and facet reflectivity on increasing the window of feasible ECL operation with reduced competition from residual modes is studied.

8277-19, Session 12

High-power operation of wide-striped InGaN laser diode array

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InGaN-based laser diodes (LDs) which are operational at an optical power of several hundred mW have been commercially available for the Blu-ray Disc system. However, watt-class optical power operation has been required for new applications such as projection displays and laser annealing. Although wide-striped LDs are candidates to realize the high-power operation because of high catastrophic optical damage (COD) level, high-quality epitaxial layers have been required for highly efficient wide-striped LD. Another approach to high-power light source is an array structure which consists of multi-emitters. Key issues of the LD array are high uniformities in crystalline quality and thermal properties. Thus, we describe characteristics of highly efficient wide-striped LDs using state-of-the-art epitaxial growth technique and a thermally optimized layout design of a high-power LD array using the efficient emitters.

The layer structure which was designed for a lasing at wavelength of 405nm was grown by metal-organic chemical vapor deposition (MOCVD) under precise controlled condition to maximize a non-radiative recombination lifetime in the active layer. The wide-striped single-emitter InGaN LDs using the high-quality epitaxial layers were successfully operated at optical power over 2W. Wall-plug efficiencies were measured to be over 30%. Using the high-quality wide-striped emitters, we designed LD array layout to minimize heat generation. Based on the design, a 1-mm-wide LD array which has five 6-μm-wide ridge-stripe waveguides was fabricated and mounted on a TO-type 9-mm-diameter package. An extremely high-power of 6.3W continuous wave (CW) operation of the wide-striped LD array was realized at a case temperature Tc=25°C. The array is capable to be operated with a power of 4.8W even at Tc=60°C.

8277-52, Session 12

Numerical studies of thermal lensing effects on high-CW-power single-spatial-mode diode lasers

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Three-dimensional (3-D) above-threshold analyses have been performed on laterally antiguided laser structures operating in leaky modes, and on twin-waveguide structures operating in guided modes, and designed for generating watt-range CW powers in a single, stable spatial mode. The 3-D numerical code takes into account carrier diffusion in the quantum well, thermo-optic effects as well as edge radiation losses. Additionally, modal gains for three to five higher-order optical modes, on a 'frozen background' provided by the fundamental-mode operation, are computed by the Arnoldi algorithm. Due to the combination of the thermal lensing and gain spatial hole burning effects, the modal gains for higher-order modes increase with drive current while the fundamental mode gain is kept equal to the threshold value. Approaching the threshold for a competing higher-order mode places a limit on the range of stable, single-mode operation. The modal structure and stability for both device types are studied over a wide range in the variation of the active core width and widths of the buried waveguides, s, bordering the low-index device core. The results of the numerical analyses indicate an essential role of thermal lensing in transforming the optical-modes' shapes and in insuring single-mode stability to high drive levels above threshold CW operation in a stable, single spatial mode to powers as high as 2 W is predicted for 2-mm-long lasers operated in leaky modes. The maximum CW power in a single-guided-mode is predicted to be 2.46 W for 2-mm-long and 3.4 W for 3-mm-long devices.

8277-53, Session 12

Near-field evolution in strongly pumped broad area diode lasers

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Many applications such as pumping of solid state lasers or ignition of explosives require high optical output powers during a short period. Pulsed operated diode lasers meet these requirements. They can be driven at elevated power levels, well above the power specified for continuous wave (cw) operation. The optical near-field intensity of a diode laser in this operation regime is a key parameter since it determines the beam properties of the device.

We analyze a set of gain-guided AlGaAs/GaAs quantum well broad area diode lasers emitting at 808 nm. They are subjected to single pulse step tests carried out up to and beyond their ultimate operation power limits. The near-field emission is monitored by a streak-camera, while the bulk temperature is determined spectroscopically.

In the final phase of the step tests, the power limit for pulsed operation for the diodes is identified as the catastrophic optical damage (COD) effect occurring at ~50 times threshold current. The near-field before and during COD was resolved on a picosecond time scale. It shows a clear change from a gain to a thermally induced index guided regime at elevated pumping levels. A higher optical load at the facet due to a narrower near-field at constant output power level supports initiation of the COD. The growth of the COD defect site is monitored and a velocity of 30 µm/µs is determined. The final width of the damage is verified by opening the device and taking a micro-photoluminescence map of the active layer. Insight into the physics behind COD is gathered by making up the energy balance.

The experimental data with picosecond time resolution allow a deeper understanding of the near-field evolution at extreme pumping levels and the kinetics of the COD.

8277-54, Session 12

100,000 h estimated lifetime of 100-um-stripe width 650 nm broad area lasers at an output power of 1.2 W

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Compared to longer wavelength devices, the development of reliable red-emitting diode lasers is more challenging due to the applicable semiconductors and the limited stability of the laser facets. Reliable operation over 1,000 h is sufficient for the pumping of fs-Cr:LiSAF lasers or in photodynamic therapy, but laser display technology requires more than 10,000 h.

Reliability tests for 650 nm broad area (BA) lasers based on a GaInP single quantum well embedded in AlGaInP waveguide layers will be presented. The structure has a transparency current density of 220 A/cm2, an internal efficiency of 0.83, and internal losses of 1.0 cm-1. 100 µm stripe width BA lasers (length 1.5 mm) were fabricated as low mesa structures and facet coated including a facet passivation procedure. Mounted on diamond heat sinks and standard C-mounts at 15°C the devices had threshold currents of 550 mA, slope efficiencies of 1.2 W/A, and conversion efficiencies of 0.33.

Four broad area lasers were tested over 20,000 h, firstly at an output power of 1.1 W over 10,000 h and secondly at 1.2 W. No failure occurred. Aging rates at both power levels below 3x10-6 h-1 were determined. Assuming a 30% current increase as failure criteria, a lifetime of 100,000 h can be estimated. Over the 20,000 h the changes in the threshold current are below 30 mA. The slope efficiencies decrease by 0.1 W/A. The beam properties remained constant.

These data proof that the material is well suited for the fabrication of high-brightness diode lasers for laser display technology.

8277-55, Session 12

Performance limitation and mitigation of longitudinal spatial hole burning in high-power diode lasers

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Facets of high-power broad area diode lasers are typically coated with one high-reflecting and one partially reflecting layer to improve slope efficiency and maximize output power. The typical cavity lengths of commercial devices have also been progressively increasing, mainly to reduce temperature rise at the active region and improve laser performance and reliability. The asymmetric reflectivities and long cavity length, however, result in a highly inhomogeneous longitudinal profile of the photon density, which induces a spatially non-uniform carrier distribution, so-called longitudinal spatial hole burning (LSHB). A more uniform longitudinal photon and carrier distribution is believed to improve the overall gain of the cavity and reduce gain saturation, although further study is required to understand the impact of LSHB to power efficiency and its implication in laser design optimization to achieve higher peak powers. We present a phenomenological model that incorporates LSHB to describe longitudinal photon and carrier density inhomogeneity, as well as light-current characteristics of a diode laser. The impact of LSHB on the power efficiency is demonstrated through numerical calculation and can be significant under high-power operations. This presents new guidelines for high-power diode laser designs, in which LSHB imposes limits on reducing facet reflectivity and/or increasing cavity length, beyond which performance deteriorates. Alternatively, effects of LSHB can be mitigated through longitudinal patterning of the waveguide or contact to achieve high-power and high-efficiency diode lasers. We propose specially designed longitudinal patterning of electrical contact to mitigate LSHB. Ongoing device implementation will be used to demonstrate performance benefits.

8277-56, Session 13

Wavelength tunable high-power single-mode 1060-nm DBR Lasers

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The wavelength tunable 1060-nm distributed Bragg reflector (DBR) laser chip consists of three sections: a gain section for lasing, and phase and DBR sections for wavelength control. A micro-heater is lithographically integrated on the top of the DBR section to tune the emission wavelength. The phase section is designed with either a top heater or by current injection to provide fine tuning of the wavelength. The wavelength tuning efficiency of our DBR laser is approximately 9.4 nm/W at 25C. Single-mode output powers of 686 mW and 605 mW were obtained at a CW gain drive current of 1.25 A and heat sink temperatures of 25C and 60C, respectively. Gain-switching by applying 1.1 GHz sinusoidal signal mixed with 600 mA DC injection current produced approximately 58 ps long optical pulses with 3.04 W peak power and 228 mW average power. The average power increased to 267 mW and pulse width broadened to 70 ps with DC bias of 700 mA.

The light emitted from the 1060-nm DBR laser chip was coupled into a single-mode periodically poled lithium niobate (PPLN) crystal waveguide. A telecentric optical design is employed to maximize the alignment tolerances between the laser chip and PPLN waveguide in a compact package. A mirror mounted on a micro-electro-mechanical system (MEMS) actuator steers the beam to maintain high optical coupling over the operating conditions and life of the package. Up to 350 mW optical power at 530 nm with the wall-plug efficiency of up to 15% was demonstrated.

8277-57, Session 13

High efficiency laser sources usable for single mode fiber coupling and frequency doubling

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Semiconductor laser diodes with a tapered gain region provide a beam quality near to the diffraction limit combined with high output power. They can be configured as lasers with a high-reflectivity coating on the rear facet and a high antireflection coating on the front facet. Additionally as amplifier with an antireflection coating on both facets they can be used in MOPA configuration together with a seed laser. Today amplifiers are commercially established with an optical output-power of 1-2W in a wide range of applications such as Raman spectroscopy or frequency doubling.

With a new class of tapered lasers and amplifiers based on improved vertical and lateral designs, the output power for both types can be enlarged significantly. Taper design consists of an overall resonator length of 5mm and a taper angle of 4° providing a small lateral far-field angle <12° (95% power included). Tapered lasers emitting at 976nm have demonstrated 16W at 20A operation current with a wall-plug efficiency of 60% at 8.5W and 59% at 10W. Slope efficiency was 1.05W/A. These values are comparable to 100µm wide broad-area lasers with 5mm resonator length. The long-term stability has been tested by lifetime tests at 10W.

The dependence of the beam quality on different parameters has been investigated especially for the high-current regime up to 15A. Whereas for lower power levels no changes have been found, slightly changes occurred at 10W after 1000 hours. Best beam quality was M2<1.8 at 8W for tapered lasers as well as for tapered amplifiers.

8277-58, Session 13

Short pulse generation by Q-switching two section tapered lasers

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High power two-section tapered lasers are promising candidates to generate short optical pulses by Q-switching. The main advantage of these devices is that high peak optical power can be generated by using a low excitation current in the ridge-waveguide section. In this work we analyze the Q-switching dynamics of two-section tapered lasers by means of a simplified three-rate-equation model. The goal is to improve the understanding of the underlying physics and to optimize the device geometry and driving conditions to improve the device performance. Quasi-3D static simulations are also performed and compared to cw experiments to determine the dynamic model parameters. The numerical results indicate that optical pulses with peak power higher than 10 W and duration lower than 100 ps can be generated by a proper choice of the driving conditions. The simulations are compared with initial experimental results on two section 1060 nm DBR-tapered lasers.

8277-59, Session 13

Laser diodes with distributed feedback for application as subnanosecond fiber laser seeder

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Semiconductor lasers with fast wavelength locking at ~1060 nm and short time response are desirable as fiber laser seeders. Seed lasers modulated with pulses of 1.5 mm but with relatively small grating strength ~10 1/cm. Our DFB lasers with 3.6 mm long cavity emitted light at ~1062 nm at room temperature and reached >700 mW of kink free CW power and >1 W of peak power under pulse conditions, with linear dependence up to maximum tested current of 2 A. DFB lasers were optimized for operation with <1ns long pulses. We investigated the spectral evolution in pulse mode and high frequency modulation of these DFB lasers. Under the pulse conditions DFB lasers maintain single spectral line which is red-shifted during the pulse. The small-signal modulation measurements demonstrated that our lasers have frequency response of ~5 GHz. Finally, DFB lasers were assembled into the 'butterfly' modules with single mode fiber pigtail and integrated into laser fiber system. We will present our results on performances of such fiber laser where DFB laser is modulated with pulses of few hundred of picoseconds long.

8277-60, Session 14

Manufacture of high performance quantum cascade lasers with highly strained materials on InP

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Most recent results of our quantum cascade lasers (QCL) with high performances will be reported. Fabricated QCL structures with strains larger than compressive/tensile 1%, uniform alloy composition or optimized multiple alloy compositions will be discussed. Strain and wavelength limitations of QCLs grown with MOCVD will be explored. Challenges in the manufacture of QCLs will be examined.

8277-61, Session 14

Low-dissipation continuous-wave mid-infrared emitting DFB quantum cascade lasers

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Quantum-cascade (QC) lasers are interesting light sources for various applications in the mid-infrared spectral region (3-20 µm) including spectroscopy of greenhouse gases or optical free-space communication. Tremendous progress concerning Watt-level optical output power at room-temperature, continuous-wave (CW) operation (T>400K), high wallplug-efficiencies (>20%) or large spectral tuning (>400 cm-1) has been demonstrated. But there is still a lack of devices suitable for various applications where extremely low electrical dissipation is needed.

Typical high-power QC laser devices show electrical power consumptions around 10 W. This power is too much for compact systems. In a first study we were able to reduce the electrical dissipation significantly. Therefore, and also to obtain single-mode emission, strong first-order DFB-gratings were incorporated. In addition the dimensions of the devices were strongly reduced to widths of 4-6 µm and lengths of 1.5 mm. Typical epi-side up mounted DFB QC lasers emitting single-mode at 4.3 µm in CW at 293K show electrical power consumptions of approximately 2 W for 2 mW of optical output power. Moreover very recent results show that by optimizing the laser fabrication process and the active-region layer structure the dissipation could further be reduced also for other wavelengths: 1.7 W (lambda ~ 4.5 µm, 3-mm length, same driving conditions) which is below reported values at higher wavelengths [1]. Extrapolating the results from the first study very short devices with high-reflectivity back-facet coating and additional epi-side down mounting can result in values below 1 W.

[1] S. Blaser et al., Electron. Lett., vol. 43(22), 2007

8277-62, Session 14

High-power quantum-cascade-laser tapered oscillators at 9.6 microns

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Quantum-cascade-lasers (QCLs) with tapered amplifier sections are of great interest for achieving high peak power under pulsed conditions. We present the characteristics of QCLs with tapered gain sections that are configured to operate as Fabry-Perot oscillators. The 9.6-micron QCL material was grown using organo-metallic vapor-phase epitaxy (OMVPE). The tapered oscillators have a cavity length of 3 mm and consist of a straight section with uniform ridge-width of 15 microns and a tapered section with taper half-angles of either 1° or 2°. Seven different geometries were characterized in terms of output power and beam quality. For a device with 2.5-mm-long 1° taper and uncoated facets, the single-facet output is >5 W (1 kHz, 200 nsec, 300 K). At high drive currents, this device becomes multimode and is found to lase on two lateral modes. In contrast, devices with a 2° taper were found to lase predominantly on a single spatial mode for all drive currents. Devices with a 2-mm-long 2° taper and uncoated facets generate a single-facet power of >4 W. By applying a high-reflectivity coating to the back facet, the single-facet output power is increased. We will present a summary of measurements for devices both with and without facet coatings.

8277-63, Session 14

Watt-level power from quantum cascade lasers in the second atmospheric window of 8-12 microns

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In the last few years there has been significant progress made in the development of high power and high efficiency quantum cascade (QC) lasers in the wavelength range of 4 to 5 microns, while QC lasers in the second atmospheric window have been experiencing performance development at a slower pace. Now, similar improvements in the QCL design and growth used for the mid-wave IR can be applied to the long-wave IR, with some important differences and adaptations to the challenges presented by the operation at longer wavelengths, which include among others, a smaller optical confinement, a stronger sensitivity to background doping, and thicker waveguides. In addition, by comparing several long wavelength laser designs and their characteristics we identify that leakage from the upper lasing and injector states to the second downstream mini-band is expected to be a limiting factor to laser performance in the long-wave IR as well.

Our current results from long-wave IR QC lasers include watt-level powers at wavelengths in the spectral range of 8-10 µm, where several applications can benefit from improved laser output powers and conversion efficiencies. Room temperature continuous wave operation of QC lasers has been demonstrated at wavelengths as long as 11.5um. Powers as high as P~1W and conversion efficiencies of about 5% have been recorded at selected wavelengths in the LWIR spectrum.

Selective strain designs are expected to yield even better performances with improved lasing characteristics for band structures that significantly suppress electron leakage to the high energy subbands.

8277-64, Session 15

32 emitters quantum cascade laser phased array

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We demonstrate a monolithic Quantum Cascade Laser array. We show phase-locking and single-mode emission at λ=8.4µm. It consists of narrow ridges buried into InP:Fe. Phase-locking is provided by evanescent coupling between adjacent ridges. This µ-structuration is simultaneously an answer to the excessive heating and poor beam quality of broad area lasers. First, it increases the surface of exchange between the multi-layer active region and the InP:Fe, which presents a higher thermal conductivity. Secondly, by choosing carefully the width of emitters and the distance between them, we insure phase locking and control of the supermode emission.

We have investigated 2µm wide emitters. In order to study the behavior of evanescent coupling, we have chosen spacing from 1 to 8 microns. The number of emitters ranges from 1 to 64. Technological feasibility was demonstrated up to 64 emitters, and lasing operation up to 32 emitters.

We have obtained a pure dual-lobe farfield pattern as expected from an anti-symmetrical supermode.

The width of each lobes narrows with an increasing array size as expected from the diffraction theory. The beam quality is insensitive to the injective current. The optical power scales linearly with the number of emitters. We show thermal resistance improvement compared to standard single ridge lasers QCL.

Finally we show some work on innovative design to force the array to lase on its fundamental super-mode.

8277-65, Session 15

Passive coherent beam combining of quantum-cascade lasers with a Dammann grating

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Powerful sources in the mid-IR with a good beam quality are required for applications such as optical countermeasures. The quantum cascade laser (QCL) is an interesting solution but the maximum optical power in CW regime is currently limited. The coherent beam combining (CBC) of several QCL could lead to higher output power while keeping the beam quality of a single emitter. Thus, CBC is an interesting way to address the power scaling issue of QCL. This paper presents the first demonstration of coherent beam addition of five QCL in an external cavity in continuous regime.

The QCL used, emitting at 4.6 µm, have their output facets anti-reflection coated to facilitate the phase locking in external cavity. The combining of these five emitters is achieved by a Dammann grating (DG) able to separate an incident beam into five beams of equal intensities with a 75% efficiency. A combining efficiency of ~ 66% is measured corresponding to an output power of ~ 0.5 W in continuous regime at room temperature along with an output beam quality close to the one of an individual QCL. Thus, the output beam of the external cavity has an increased spatial brightness compared to a single emitter. The current power limitation of this method is mainly due to the simple-pass loss of 25% introduced by the DG. More power should be obtained using a more efficient beamsplitter such as multilevel phase gratings or continuous phase gratings.

8277-66, Session 15

Ultra-low beam divergence and improved efficiency in optically pumped mid-IR lasers

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Optically pumped edge-emitting GaSb-based lasers that employ type-II quantum wells have been demonstrated to generate multi-Watt qcw power levels at wavelengths ranging from 2.5-9 µm. In this work, we present two recent innovations that further improve the mid-infrared optically pumped semiconductor laser (OPSL) device characteristics.

Devices emitting near 3.7µm wavelength have been engineered to have an ultra-low confinement of the transverse optical mode in which the mode extends ~100µm into the substrate. As a result, a fast-axis divergence of only ~4 degrees FWHM is measured. In addition, the very small mode overlap with the gain region results in the suppression of filamentation in broad area OPSLs. A lateral divergence of only ~3.5 degrees is observed, providing a nearly circular beam with high brightness. Results show that devices must be carefully designed to avoid higher-order transverse modes that can be accommodated in the low-doped GaSb substrates with low loss.

The baseline type-II quantum well design was modified to give an improved electron-hole wavefunction overlap. The "W-quantum well", which consists of the barrier/InAs/InGaSb/InAs/barrier sequence, has two coupled electron wells (InAs) that surround the hole well (InGaSb) to achieve a high e-h wavefunction overlap. We have re-designed this sequence by adding additional stages to increase the wavefunction overlap by ~20%. In addition, we have introduced the concept of tailoring the thickness of the outer layers to concentrate the electron and hole wavefunctions at the center to further enhance recombination. As a result, improved efficiency in the OPSLs is observed.

8277-67, Session 15

28-dB gain mid-infrared optical amplification using resonant quantum cascade laser optical amplifier

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We report in this work using quantum cascade lasers (QCLs) for resonant amplifications of mid-infrared signals as well as a photodetector under both photovoltaic and photoconductive modes. Experiments are done using two QCLs with identical QC structure and same lasing wavelength, where one works as transmitter and the other as receiver. When the QCL receiver is biased at low voltage or without bias, it works as a photoconductive or photovoltaic detector. Detailed detection characteristics are studied. When the QCL receiver is biased near threshold, it operates as a tunable resonant amplifying detector. The modulated signal of QCL transmitter is coupled into the receiver's waveguide and reflected back into FTIR through a beam splitter. The receiver is biased with DC current through a bias-T and the AC electrical signal output is taken out to a spectrum analyzer. The AC signal detected by the receiver increases as the increase of the receiver's bias current until it gets to its threshold. The signal power reaches its maximum when the receiver is biased right below its threshold. The detected signal power is more than 28 dB higher compared with the case of no bias. Further increasing the bias current, the receiver not only starts to lase but also its gain peak moves away from the input signal and the detected signal drops. We monitor the reflected optical intensity on FTIR at various bias currents of the receiver. The optical intensity reflected from the receiver's waveguide presents the same phenomena as the AC electrical signal.

Conference 8278: Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting XVI

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8278-01, Session 1

Spectral design flexibility of LED brings better life

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Light-emitting diodes (LEDs) are penetrating into the huge market of general lighting because they are energy saving and environment friendly. The big advantage of LED light sources, compared to traditional incandescent lamps and fluorescent light tubes, is the flexible spectral design to make white light using color mixing schemes. The spectral design flexibility of white LED light sources will promote them for novel applications to improve the life quality of human beings. As an initial exploration to make use of the spectral design flexibility, we will present 3 examples: 'no blue' white LED light source for photolithography room illumination, 'no blue' white LED light source for sufferers of disease Porphyria, and optimized spectra for good light quality and health. For 'no blue' white LED light source to be used in photolithography room, the spectrum has been designed after the investigation of the photosensitivity of the resists existing in the cleanroom. The prototype has been made and tested in the cleanroom and compared with the currently used yellow fluorescent light tube in terms of color rendering and distance to planckian locus. For the sufferer of Porphyria, a LED light source, made of high brightness colored LEDs applying an optical filter, is being tested by a patient suffering Porphyria. Preliminary results have shown that the sufferer could withstand the light source for much longer time than the standard light source. For the light and health, optimized spectra have been designed with high color rendering index. The good health is ensured by the spectrum optimized so that vital hormones (melatonin and serotonin) are produced during times when they support human daily rhythm. At last future perspectives on spectral design flexibility of LED light sources improving human being's life will be discussed.

8278-02, Session 1

Opportunities and risks with blue enhanced light sources

D. Lang, OSRAM GmbH (Germany)

Natural daylight is characterized by high proportions of blue light. By proof of a third type of photoreceptor in the human eye which is only sensitive in this spectral region and by subsequent studies it has become obvious that these blue proportions are essential for human health and well being. In various studies beneficial effects of indoor lighting with higher blue spectral proportions have been proven.

On the other hand with increasing use of light sources having enhanced blue light for indoor illumination questions are arising about potential health risks attributed to blue light. Especially LED are showing distinct emission characteristics in the blue. Recently the French agency for food, environmental and occupational health & safety ANSES have raised the question on health issues related to LED light sources and have claimed to avoid use of LED for lighting in schools.

In my paper parameters which are relevant for potential health risks will be shown and their contribution to risk factors will quantitatively be discussed. It will be shown how to differentiate between photometric parameters for assessment of beneficial as well as hazardous effects.

The paper will discuss guidelines how blue enhanced light sources can be used in applications to optimally support human health and well being and simultaneously avoid any risks attributed to blue light by a proper design of lighting parameters.

In the conclusion it will be shown that no inherent health risks are related to LED lighting with a proper lighting design.

8278-03, Session 1

Smart dimming circuit used in solid-state lightings suitable for skygazer

K. Sakai, Kochi Univ. of Technology (Japan)

A skygazer is an astronomical visual observer who uses telescopes in a field; they are people who attend a star party for example.

The lighting is important for them, the requirements are solid-state for toughness, light weight for handling, flicker-less for stress-free, and dimming controls corresponding to photopic, mesopic and scotopic vision.

Especially, the lighting never spoils a dark adaptation at moonless night, because the dark adaptation consumes several dozen of minutes.

However, bright light is used to prepare the equipment at twilight.

To satisfy their requirements, at first, we clearly define the range of illuminance and its wave length based on an earlier study, and then we propose a smart dimming circuit.

The proposed lighting consists of several LEDs, an ordinal dry-battery, a boost-converter, 8-bit MCU, and several small components.

The main idea is the dimming scheme using PAM to reduce flicker, MCU controls feed-back voltage of the converter corresponding to LED current.

Thereby, LEDs are simply connected to the converter through a shunt resister, MCU can share the converter output with LEDs because the forward voltage range of LED is close to the working range of MCU.

The next idea is efficient use of built-in components in MCU.

MCU is not large of course; necessary built-in components are ADC and 32-tap resister divider network.

The resister divider network is a digital potentiometer, it resembles DAC without amplifier.

Finally we show the dimming algorithm implemented in MCU and the evaluation result.

8278-04, Session 1

Secondary optical design for safety light curtains

Y. Hsu, Y. Chen, J. A. Whang, National Taiwan Univ. of Science and Technology (Taiwan)

The rapid development of LED (Light Emitter Diode) industry in recent years, LED has many advantages that will gradually replace traditional light sources. It not only has small volume, quick reaction time, high color rendering index, and low power consumption, but also has high directivity and high color purity. The factors are suitable for illumination and light signal transmission.

In this article, we design a convergence lens and use a LED light source with ± 30° half-power angle. The lens can convergence light source and make it become parallel light. The goal to achieve high directivity can be applied to wireless sensors.

According to the simulation results, compared to the LED with dome lens that has ± 0.6° half-power angle, the LED use our design's lens has ± 0.34° half-power angle that significantly reduce the divergence degree. In the same transmission distance, the LED with our design's lens has more than 200 times received energy.

8278-05, Session 2

High efficient semipolar LEDs with a small droop

S. Nakamura, D. F. Feezell, Univ. of California, Santa Barbara (United States)

No abstract available

8278-06, Session 2

Towards general lighting with GaN-on-Si

A. J. Krost, Otto-von-Guericke-Univ. Magdeburg (Germany)

GaN-on-Si heteroepitaxy has become a serious alternative to established growth of group-III-nitrides on sapphire or SiC because of its low price, large diameter wafers, and thermally well conducting properties. Most of the work and published device results have been for GaN growth on (111) silicon substrates. Recently, we have demonstrated thick, crack-free layers exceeding 14 µm in thickness. Meanwhile, companies as Samsung(1) and Bridgelux(2) have announced breakthroughs in GaN-on-Si-based high-power LEDs aimed for general lighting. For such application thick, high-quality structures with highly conducting n-type layers are required which is a major challenge because of tensile thermal stress leading to cracks in the GaN/Si system during cooling down. In addition to thermal stress doping with Si is a major source of tensile stress. The latter can be overcome by Ge-doping instead of Si-doping3. We show ways to control stresses and strains in GaN heteroepitaxy to achieve crack-free, device-relevant GaN layers on Si with thicknesses up to >14 µm. An emerging new field is the growth of semipolar GaN on high-index Si(h11) substrates. Recent results will be presented.

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8278-07, Session 2

High performance ThinGaN(R) LED with buried n-contact epitaxially grown on Si(111) substrate

P. Stauss, P. Rode, P. Drechsel, W. Bergbauer, U. Steegmueller, OSRAM Opto Semiconductors GmbH (Germany); S. Fritze, A. Dadgar, A. J. Krost, J. Christen, Otto-von-Guericke-Univ. Magdeburg (Germany); T. Markurt, T. Schulz, M. Albrecht, Leibniz-Institut für Kristallzüchtung (Germany)

In order to make SSL more attractive, it will be necessary to reduce the costs for the InGaN/GaN LEDs further. One step forward might be the use of Silicon substrates for the epitaxial growth of the InGaN/GaN LED layers. This will enable the use of even larger substrates and the adoption of the major technologies used in the silicon industry.

However, the majority of the results published for InGaN LEDs grown on silicon substrates so far, still show a gap in performance compared to sapphire based LEDs.

In this talk we will present our latest results for InGaN-LEDs grown on Si, which give rise to the assumptions, that in the future GaNonSi might gain on GaN grown on traditional substrates. The InGaN-layers have been grown in commercial multi-wafer MOVPE reactors with Si-substrates sizes up to 200mm. The 1mm2 dies have been processed applying our superior UX:3 technology and assembled in OS-Golden Dragon LEDs.

8278-08, Session 2

Spontaneous emission characteristics of InGaN quantum wells light-emitting diodes on Ternary InGaN substrates

J. Zhang, N. Tansu, Lehigh Univ. (United States)

The growths of visible LEDs employ InGaN quantum wells (QWs) grown on GaN templates, which lead to the existence of large compressive strain in the QWs. The compressive strain in the InGaN QW leads to 1) the existence of piezoelectric polarization, and 2) the bandgap enlargement in the QW. The existence of piezoelectric polarization leads to the optical matrix element reduction. The strain-induced band gap increase leads to additional challenge in pushing the emission wavelength to the green up to red spectral regimes. Recent works have revealed successful growths of InGaN template, which can be employed as substrate for LED epitaxy. The use of InGaN substrate has the potential for enabling the growth of InGaN QW with significantly-modified strain in the QW.

In this work, we present a comprehensive analysis on the spontaneous emission characteristics of InGaN QWs on ternary InGaN substrates emitting in green up to red spectral regimes. Specifically, the spontaneous emission rates of the InGaN QWs on ternary InGaN (with 15 % In-content) substrates emitting are compared with those of conventional InGaN QWs on GaN templates. For InGaN QWs / InGaN substrates emitting in the 540-580 nm, the spontaneous emission rates were found as 1.5-2.1 times higher than those of conventional InGaN QWs / GaN substrates. The use of InGaN substrate is expected to lead to InGaN QWs with enhanced spontaneous emission rates, as well as reduction in compressive strain in the QW, for green and yellow LED applications.

8278-09, Session 2

New MOCVD production platforms for white lighting

B. Dlugosch, C. Sommerhalter, AIXTRON, Inc. (United States); B. Schineller, M. Heuken, AIXTRON SE (Germany)

To satisfy future productivity requirements for GaN based LED manufacturing, the CRIUS® II and AIX G5 HT Planetary Reactor® were developed. Both reactors are based on the IC 2 platform design, allowing easy maintenance and high uptime. In reactor design special focus was laid on an increase of GaN-buffer growth rate and a low variance of the process results to hardware changes while maintaining high standards for uniformity and yield.

For the CRIUS® II the optimization of the showerhead and chamber exhaust design resulted in flow uniformities even superior to the smaller tools. This was demonstrated by typical 55x2" GaN thickness std. dev. 30 µm/hr at 400 mbar. This demonstrates that parasitic gas phase nucleation is limited.

The AIX G5HT Planetary Reactor® chamber was improved with respect to gas inlet, outlet, heater and reactor ceiling. In the 56x2" configuration several runs with hardware changes were made to assess the process stability of the tool. At an average wavelength of 467.1 nm a total wavelength spread of ±1.2 nm was found for all wafers. For the GaN-buffers growth rates exceeding 31 µm/h were achieved.

Additional results and developments will be presented.

8278-10, Session 3

High performace LED phosphors for the BLU, automobile, and lighting applications

C. Yoon, SAMSUNG Electronics Co., Ltd. (Korea, Republic of)

No abstract available

8278-11, Session 3

Development and optimization of new phosphors for LED-based lighting

A. A. Setlur, GE Global Research (United States)

In this presentation, we describe some of our progress in the development of new LED phosphors within fluoride, oxyfluoride, and nitride systems. We discuss how phosphor composition and processing can affect phosphor efficiency at room and high temperatures as well as phosphor reliability. For example, it is known that at high activator concentrations, concentration quenching can occur at room and elevated temperature. In some Ce^{3+}-doped materials, there are low energy Ce^{3+} centers that have lower quantum efficiency versus the main Ce^{3+} centers. Consequently, concentration quenching can be assigned to energy migration between the main Ce^{3+} centers with energy transfer to the lower energy Ce^{3+} centers with lower quantum efficiency. This places fundamental limits on the maximum concentration for specific phosphor systems. In addition, there are potential concerns with the high temperature, high humidity (HTHH) stability of fluoride and oxyfluoride phosphors. We will describe processing methods that can significantly improve HTHH phosphor stability. Using these materials, we finally discuss the performance of these phosphors in LED-systems with warm white color temperatures and 90+ CRI.

8278-12, Session 3

Cluster LEDs mixing optimization by lens design techniques

M. Chien, C. Tien, S. Chiang, National Chiao Tung Univ. (Taiwan)

This paper presents a novel procedure analogous to general lens design rule to step-by-step optimize the spectral power distribution of a white-light LEDs cluster with possibly highest color rendering performance and efficiency in a defined range of color temperature.

The challenge in the design of a LED-based cluster is how to adjust the spectral power distribution (SPD) in an underdetermined condition, thus enabling us to manipulate strategically the chromaticity point, light quality, and system efficiency according to different operational purposes. For example, we are able to enhance the fidelity appearance in high-color-quality mode or to employ higher efficiency at a sacrifice of color rendering in an unoccupied area.

The algorithm enables the users to determine easily the optimal LED setup to meet requirements such as light efficiency, color quality, or other figures of merit over a wide range of color temperatures. The procedure includes six steps: (1) initial system, (2) define boundary condition, (3) optimization, (4) merit analysis, (5) judgment, and (6) tolerance analysis, and each step has been considered and validated in detail by an experimental platform.

The design example of an R/G/A/CW cluster can extend the operation window to 2600 K < TCC < 8500 K for the requirements of CQSm = 80 points and LEm = 60 lm/W. Due to its simplicity and versatility, the proposed technique certainly has a promising impact on rapid prototyping and other specialized features for lighting applications.

8278-13, Session 3

Infrared excited Yb: Er: Y2O2S phosphors with intense emission for lighting applications

G. A. Kumar, M. Pokhrel, D. K. Sardar, The Univ. of Texas at San Antonio (United States)

In this work we are presenting the detailed spectroscopic properties of hexagonal Yb and Er-doped Y_2O_2S phosphor synthesized by solid state flux fusion method. The detailed optical characterizations such as absorption, emission, and fluorescence decay will be performed to explore the emission processes in the UV-VIS-NIR as well as to quantitatively estimate the fluorescence quantum yield. Our preliminary study shows that upconversion efficiency in this material is so high that even with less than a 15 µW of 980 nm excitation one could see the green upconversion with naked eye. The low power excitation upconversion mechanism in this material offers several potential applications such as solar energy conversion and low threshold upconversion lasers. The high fluorescence efficiency as well as power dependent color tenability enables the present material to find possible application in infrared excited LED, lasers, displays etc.

8278-14, Session 4

Understanding the relationship between IQE and defects in nitride-based LEDs

H. Amano, Nagoya Univ. (Japan)

No abstract available

8278-15, Session 4

First-principles studies of the causes of droop

C. G. Van de Walle, Univ. of California, Santa Barbara (United States); E. Kioupakis, Univ. of Michigan (United States)

The efficiency of nitride LEDs decreases dramatically when operating at the high powers needed for lighting, a fact that is reflected in the higher cost of present LED light bulbs. The origin of this efficiency droop problem is still an issue of active research. The two leading hypotheses are carrier leakage and Auger recombination. Experimentally, it is exceedingly difficult to pinpoint the microscopic origins of the losses. Using quantum-mechanical first-principles calculations, we have found that indirect Auger recombination, a process assisted by carrier scattering due to lattice vibrations and the random distribution of the alloy atoms, can explain the experimentally measured droop data. Approaches to mitigate the effect of this intrinsic loss mechanism will be discussed.

8278-16, Session 4

Comparative study of efficiency droop in (Al,In)GaN LEDs and laser diodes

U. Schwarz, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

No abstract available

8278-17, Session 4

Effects of polarization-field tuning in GaInN light-emitting diodes

J. Xu, M. F. Schubert, D. Zhu, J. Cho, E. F. Schubert, Rensselaer Polytechnic Institute (United States); H. Shim, C. Sone, Samsung Electro-Mechanics (Korea, Republic of)

III-V nitrides form the backbone of light-emitting diode (LED) technology. However, the relevance of the very strong polarization fields in III-V nitride LEDs remains unclear. Here, we demonstrate the tuning of polarization fields via external mechanical force and directly measure the effects on carrier recombination and transport in the same GaInN LED. With this design of experiment, we have excluded the sample-to-sample and wafer-to-wafer variation, which has not been achieved in previous studies of the polarization field. The tuning the polarization field (i.e. compressive strain in a GaInN LED epitaxial layer) is experimentally confirmed by the red-shift of the emission spectrum at low current level, which is a well-known consequence of QCSE in GaInN LEDs. Tuning the polarization field reduces peak efficiency, but enhances high current efficiency, and thus reduces efficiency droop in GaInN LEDs. Simulation and experiments show excellent agreement with respect to these trends. Our results show that the polarization field has clear impact on carrier transport and recombination, and suggest that the electron leakage out of the active region and lack of hole injection plays an active role in the efficiency droop of GaInN-based LEDs.

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8278-18, Session 4

Effect of dislocation density on efficiency curves in InGaN/GaN multiple quantum well light-emitting diodes

Y. Harada, T. Hikosaka, S. Kimura, M. Sugai, H. Nago, K. Tachibana, N. Sugiyama, S. Nunoue, Toshiba Corp. (Japan)

In InGaN/GaN Blue LED devices, the mechanism of optical property enhancement by the improvement of crystal quality is still under discussion. In this paper, we discuss the contribution of the reduction of threading dislocation density (TDD) on the optical property. The external quantum efficiency (EQE) curves depending on the TDD are discussed comparing with the rate equation (ABC) model.

Blue InGaN/GaN MQW LEDs were grown on sapphire substrates by metal-organic chemical vapor deposition. TDD was controlled by changing the growth condition of the GaN buffer layer on sapphire. TDD was estimated from the X-ray rocking curve measured on the plural crystal planes.

At the current density <20A/cm2, the EQE increases with decreasing the edge-type TDD from 5e8cm-2 to 2e8cm-2. The current density at the maximum EQE shifts to lower value as the TDD decreases, while the EQE presents no remarkable difference in the higher current range irrespective of TDD. According to the ABC model, the peak shift reflects the Shockley-Read-Hall process (A coefficient). In fact, the non-radiative recombination lifetime evaluated from the time-resolved photoluminescence measurements increases from 30nsec to 40nsec with decreasing the TDD from 5e8cm-2 to 2e8cm-2. On the other hand, B and C coefficient, which represent the radiative and Auger recombination respectively, are independent of the TDD. It is revealed that the reduction of TDD contributes the enhancement of EQE at lower current density by the reduction of non-radiative recombination center, and it brings little contribution on the efficiency droop.

8278-19, Session 4

Quantum efficiency characterizations of staggered InGaN quantum wells light-emitting diodes by temperature-dependent electroluminescence measurement

G. Liu, J. D. Poplawsky, J. Zhang, V. Dierolf, Lehigh Univ. (United States); H. Zhao, Case Western Reserve Univ. (United States); N. Tansu, Lehigh Univ. (United States)

Nitride-based light-emitting diodes (LEDs) play important roles for solid state lighting. The polarization fields in III-nitrides lead to severe reduction in electron-hole wavefunction overlap, which reduces the internal quantum efficiency (IQE) of LEDs. Recent approach by employing staggered InGaN quantum wells (QWs) to improve the LED IQE has shown radiative recombination rate increase for both 2-layer and 3-layer staggered InGaN QWs as compared to that of the conventional QW. The 520-525 nm emitting LEDs employing 3-layer staggered InGaN QWs exhibited ~2.5-3.5 times increase in output power.

Here, we performed comprehensive characterizations of the radiative recombination rates and IQE of the staggered InGaN QW LEDs. The characterizations were carried out by employing time-resolved photoluminescence (TRPL) and temperature-dependent electroluminescence (TDEL) measurements, and these measurements were carried out on both the 2-layer and 3-layer staggered InGaN QWs LEDs. Both the 2-layer and 3-layer staggered InGaN QWs were grown by metalorganic chemical vapor deposition using the graded growth temperature method. The monomolecular and Auger recombination rates

in staggered InGaN QWs were measured. By extracting the data from the TRPL, the green-emitting 3-layer staggered InGaN QWs LEDs exhibited 2.12 times enhancement in the radiative recombination rate over that of conventional InGaN QWs. By employing the TDEL measurement in temperature range of 40 K up to 300 K, the IQE of the green-emitting 3-layer staggered LEDs was obtained as ~ 1.5-times higher in comparison to that measured from the 2-layer staggered LEDs. Further characterizations on the linearly-shaped staggered InGaN QWs LEDs will be performed.

8278-20, Session 5

Deep UV LEDs with high IQE based on AlGaN alloys with strong band structure potential fluctuations

T. D. Moustakas, The Boston Univ. Photonics Ctr. (United States)

No abstract available

8278-21, Session 5

Influence of QW composition on the efficiency of AlGaN-based LEDs emitting at 350 nm

T. Passow, R. Gutt, M. Kunzer, W. Pletschen, L. Kirste, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); K. Forghani, F. Scholz, Univ. Ulm (Germany); K. Köhler, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

AlGaN-based UV-LEDs grown on sapphire typically suffer from a high dislocation density leading to a low internal quantum efficiency. It is widely accepted that the internal quantum efficiency is improved for In-containing quantum wells (QWs) due to carrier localization effects and hence screening of non-radiative recombination centers. Here, we investigate the effect of In incorporation into the QW active region of AlGaN-based LEDs emitting at 350 nm. Single QW test structures with GaN and low In content (<1%) GaInN QW active regions were grown by MOVPE on sapphire substrates. The carrier localization in the QWs was investigated by temperature dependent photoluminescence spectroscopy. A clear "S-shape" behavior of the PL peak position was observed for the GaInN QW, which indicates an enhanced carrier localization in the GaInN QW despite the very low In content in the sub-percent range. Since the growth conditions of GaInN are significantly different to that typically used for the growth of GaN, we will discuss the effect of these modified growth conditions in comparison to the direct effect of In incorporation on carrier localization.

Mesa-LEDs of AlGaN-based LED structures based on the above discussed GaN and GaInN QWs were fabricated. The light output power at 40 mA is 8.2 mW for the LED with GaInN QW active region, which corresponds to an increase by a factor of 4 compared to the LED with GaN QW. The output power increases to 19 mW at a current of 100 mA.

8278-22, Session 5

Toward blue emission in ZnO based LED

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ZnO nanowire light emitting diodes (LEDs) have drawn large interest recently. 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.

After integration of the heterostructure in a LED device, a rectifying behaviour has been found with a forward current onset at 3 V. The diodes emitted a unique UV-light peak centered at about 397 nm for either as-prepared or annealed samples. The emission turn-on voltage was as low as 3.9 V for the hydrothermal and 4.2 V for the electrodeposition.

We have shown that the emission wavelength could be tuned and shift toward the violet-blue region by up to 40 nm by doping with Cu or Cd [1, 2]. The bandgap engineering of doped-ZnO nanowires is of utmost importance for tunable light emitting diode (LED) applications. Combined experimental and DFT computational study of ZnO doping by substituting Zn by Cu or Cd atoms have been done in the oxide crystal lattice.

Zn1-xCuxO nanowires have been epitaxially grown on magnesium-doped p-GaN by electrochemical deposition. The heterojunction was integrated in a LED structure. Efficient charge injection and radiative recombination in the Cu-doped ZnO nanowires are demonstrated showing the high quality of the ZnO-NWs/p-GaN interface. Emission shifted from ultraviolet to violet-blue spectral region compared to pure ZnO LEDs. Observed electroluminescence is peaking at about 437 nm in case of 1.8 at. % doped ZnO and 397 nm for the undoped ZnO. Demonstration of such devices for new generation of LED is proposed.

8278-23, Session 6

GaN-based microcavity polariton light emitting diodes

T. Lu, S. Wang, National Chiao Tung Univ. (Taiwan); Y. Yamamoto, Stanford Univ. (United States)

Due to the larger exciton binding energy and oscillator strength compared to GaAs and CdTe system, GaN becomes a very promising material for the room temperature (RT) polariton-based optoelectronic devices. So far, the RT polariton lasing in GaN-based microcavities (MCs) has been achieved with optical pumping, but the electrical polariton device is still underdeveloped in GaN MCs. Here we report the first realization of an electrically pumped GaN-based exciton-polariton light emitting diode (LED) in a microcavity. The GaN-based microcavity consists of a 29-pair AlN/GaN bottom DBR, a 5λ-thick optical cavity layer composed of an n-type GaN, 10 pairs of InGaN/GaN MQWs and a p-type GaN layer, and an 8-pair Ta2O5/SiO2 dielectric top DBR. The strong coupling and the anticrossing behaviour of the excitons and microcavity photons are verified with temperature-dependent electroluminescence and angle-resolved electroluminescence (AREL). In temperature-dependent electroluminescence measurement, an anticrossing dispersion is clearly observed at 300K, while the corresponding simulation results reveal that the condition of zero exciton-photon detuning at zero angle is reached at a temperature of 280 K and the normal mode splitting is about 7.4 meV. In AREL measurement, a zero detuning is realized at 7.4 degree with normal mode splitting about 8.3 meV. These measurement results confirm the microcavity system is operated in the strong coupling regime.

8278-24, Session 6

3D nanostructures for enhanced light extraction in vertical light-emitting diodes

J. H. Son, J. Lee, Pohang Univ. of Science and Technology (Korea, Republic of)

GaN-based light-emitting diodes (LEDs) are attracting great interest as candidates for next-generation solid-state lighting. However, the external quantum efficiency of LEDs, determined by the internal quantum efficiency (IQE) and the light extraction efficiency (LEE), must be further increased. Although an internal quantum efficiency of nearby 70 % has been achieved, there are much room for enhancement of light extraction efficiency, because the most of the generated photons from the active layer remain inside LEDs due to the total internal reflection (TIR) at GaN-air interface.

Here, we demonstrate the fabrication of novel cone shape nanostructure with controllable side wall angle to maximize the light extraction efficiency of vertical LEDs. The SiO2 nanosphere lithograpgy (NSL) was used as an etching mask to control the side wall angle of cone shape nanostructure. The side wall angles of cone shape nanostructure were varied from 24.1o to 42.6o with inductively coupled plasma (ICP) etching time. The vertical LEDs with cone shape nanostructures of 24.1o side wall angle provide about 6% higher light output power compared to that with hexagonal pyramids nanostructure formed by photochemical etching (PCE). This achievement is attributed to effective elimination of TIR by angle-controllable nanostructures. The 3-dimensional finite-difference time-domain (FDTD) method with perfectively matched layer (PML) was used to theoritically calculte the light extraction efficiency of vertical LEDs with various side wall angle. The simulation results clearly show that the enhancement ratio of light extraction efficeicny was maximum at side wall angle equal to critical angle for TIR at GaN-air interface.

Acknowledgements

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8278-25, Session 6

Optical mode pattern study of GaN LEDs with and without top nano-gratings

G. Chavoor, D. Cattarusa, X. Jin, California Polytechnic State Univ., San Luis Obispo (United States); X. Fu, X. Kang, B. Zhang, G. Zhang, Peking Univ. (China)

This study analyzes optical confinement factor and light emitting mode order for three different GaN LEDs: a conventional LED, thin Film LED, and thin Film LED with a photonic crystal (PhC) grating. For the first structure, we increase the thickness of AlxGa1-xN from 0 to 600nm, alter the x composition in AlxGa1-xN from 0.05 to 0.2 in steps of 0.05, and adjust the p-GaN and n-GaN thicknesses each from 0 to 200nm. For the second structure, we alter the n-GaN substrate thickness from 300-1000nm in steps of 100nm and 1000-4000nm in steps of 1000nm. These simulations show that increasing the substrate thickness causes the light emitting mode order to increase. The higher the mode, the more current is needed to make the device emit light. Higher current leads to shorter device lifetime. The last structure contains a photonic crystal grating with a period T = 100nm, 230nm, 460nm, 690nm, 920nm, 1500nm, 2000nm, 3000nm and 50% duty cycle. For each grating period, we display the effects on optical confinement factor and optical field intensity. The results show that changing the grating period does not affect the mode order, but does affect the optical field intensity. A larger grating period corresponds to lower optical field intensity. Maximizing optical field intensity increases the brightness of the device. The simulation method above can be used to improve the efficiency, brightness, and lifetime of GaN LEDs by reducing the effects of transverse mode coupling and maximizing the optical field intensity.

8278-26, Session 6

Light-emitting diodes with surface gratings of different periods for light extraction

C. Liao, C. Lin, H. Chen, C. Chen, C. Hsieh, P. Chang, Y. Kiang, C. Yang, National Taiwan Univ. (Taiwan)

Surface grating on a light-emitting diode (LED) has been shown to be an effective structure for enhancing the light extraction of the LED. It has been shown that through the diffraction of the grating structures and the scattering of the sub-grating-period rough surface structures, the light extraction efficiency can be enhanced by more than 70 %. In this paper, we compare the light extraction efficiencies of LEDs with surface gratings of different grating periods to understand the optimized grating periods. The surface gratings are fabricated with holography lithography and photoelectrochemical (PEC) wet etching. The holography is implemented with two-beam interference with the fringe period varying from a few hundred nanometers through a few microns. The etching rate of PEC wet etching is almost linearly proportional to the illuminated light intensity on semiconductor. It leads to selected-area etching for producing surface grating structures. Such surface gratings will be fabricated on both conventional and vertical LEDs. In a conventional LED, the surface gratings are fabricated on a second mesa level of n-GaN. In a vertical LED, the surface gratings are fabricated on the N-polarity n-type surface. Their results will be compared. After we have the information about the optimized grating period, we will use phase mask to produce interference fringe for mass production.

8278-27, Session 6

Power enhancement of 380 nm UV-LED with hexagonal pyramid structures by AlN sacrificial layer

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In this study, we propose to enhance an output power for 380 nm UV-LED with a hexagonal pyramid structures (HPS) on the interface of sidewall between AlGaN and AlN layers. The HPS are formed by inserting a 50 nm AlN as a sacrificial layer in n-AlGaN than using a selective wet etching process in KOH solution at 90 °C for 60 min. From the scanning electron microscope (SEM) image, the HPS can be clearly seen on the interface of AlGaN, the facet angles and the average of structure height of pyramid are 58°and 0.5-μm, respectively. According to the ray tracing results, 15% enhancement of the light extraction efficiency can be expected in the UV-LED with HPS. Furthermore, we measured the output power at 20 mA between the UV-LED with and without HPS are 2.69 mW and 3.01 mW, respectively. As a result, the light extraction efficiency can be improved by this approach because of changing the routes of light reflection around the sidewall.

8278-28, Session 7

Steps toward understanding the growth and physics of visible group III-N LEDs

D. D. Koleske, Sandia National Labs. (United States)

No abstract available

8278-29, Session 7

Emission efficiency dependence on the overgrown p-GaN thickness in a high-indium InGaN/GaN quantum-well light-emitting diode

H. Chen, C. Chen, C. Liao, K. Chen, W. Chang, J. Huang, Y. Yao, Y. Kiang, C. Yang, National Taiwan Univ. (Taiwan)

It has been demonstrated that post-growth thermal annealing of an InGaN/GaN quantum well (QW) at a high temperature could cause the changes of indium composition fluctuation and indium-rich cluster structures and hence alter the emission behaviors. Such changes are particularly prominent when the average indium content in the QW is high. In this regard, the high-temperature growths of the p-AlGaN electron blocking layer and the p-GaN hole transport layer have been supposed to be detrimental to the emission efficiencies of the pre-grown InGaN/GaN QWs in a light-emitting diode (LED), particularly an LED in the green or longer-wavelength range. Research efforts have been made to reduce the growth temperatures of the p-type layers for minimizing the detrimental thermal annealing effect. P-InGaN of low indium content has been used to replace p-GaN for decreasing the growth temperature down to <900 oC. In this paper, we demonstrate an unexpected result regarding the thermal annealing effects of the overgrown p-type layers on the InGaN/GaN QW emission behaviors in high-indium-content LEDs. By overgrowing p-GaN layers of different thicknesses in a series of LED samples, we observe that the internal quantum efficiency (IQE) of the QWs first increases with increasing p-GaN thickness, i.e., with increasing thermal annealing time, and then decreases with thicker p-GaN. The measurement results of temperature-dependent photoluminescence and cathodoluminescence are used for interpreting the emission behavior variations with the p-GaN thickness. Also, the fabricated LEDs show the consistent variations of electroluminescence result and electrical property.

8278-30, Session 7

Glass encapsulation in LED module

J. Wang, S. Huang, W. Cheng, W. Cheng, National Sun Yat-Sen Univ. (Taiwan)

Thermal degradation is a well-known standing issue in LED module, particularly in the areas where large thermal-expansion-coefficient mismatch or low temperature material presents. For instance, silicone whose Tg is about 150   was found to be problematic above Tg for over thousand hours. How to maintaining optical performances of LED, i.e. lumen, chromaticity, and correlated color temperature (CCT), at higher operating temperature still remains as a challenging issue. In this study, glass encapsulation instead of conventional silicone is explored toward the potential and challenge of developing high performance LED module.

Our glass encapsulation development, ranging from material, optics design, packaging, to reliability test, will be presented.

1. Glass-encapsulation material development and selection.
2. Packaging consideration of glass-encapsulation LED module.
3. Optics design of glass encapsulation.
4. MTTF predication of optical performances in LED module.
5. Potential of glass-encapsulation LED module.

At particular, the areas of new opportunity and challenge of adopting glass encapsulation in LED modules will be emphasized.

8278-32, Session 7

Innovative methodology for testing the reliability of LED based systems

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With this work we present an innovative strategy for the evaluation of the performance and reliability of advanced LED devices and solid state systems. The strategy is based on the extensive analysis of the degradation mechanisms that take place during LED lifetime, in particular as a function of temperature and current.

With a detailed thermal characterization of the devices it is possible to perform iso-current reliability tests where different devices are subjected to fixed current stress while other parameters (temperature, humidity) are changing, or vice versa iso-thermal stress where the junction temperature is kept constant during lifetime. This method allows an high confidentiality prediction of lifetime, and modeling of the degradation kinetics at different operating conditions. It is also possible to separately evaluate how the different components of an LED structure degrade over stress time, with focus on: i) LED chip, ii) electrical and thermal contacts, iii) package and lenses, iv) phosphors (in the case of white LEDs).

Based on this strategy we propose also a method to carefully study the effects of degradation in multichip/multi-LED system (es: RGB or cool-white/amber). These solid state light sources are able to achieve high color rendering index and adjustable color temperature, but suffer from a limited chromatic stability during lifetime, caused by the use of LED sources with different degradation kinetics. With our approach is possible to estimate the degradation of the single LEDs and therefore design a model to compensate the operating condition, thus ensuring stable color point operation.

8278-50, Session 7

GaN epilayer transferring to Cu substrate from sapphire substrate using Ga2O3 sacrificial layer

R. Horng, D. Wuu, S. Ou, H. Hsueh, National Chung Hsing Univ. (Taiwan)

GaN epilayer can be grown on sapphire substrate with a Ga2O3 sacrificial layer. It was employed for the epilayer transferring from sapphire substrate to Cu substrate using the chemical lift-off process application. The (-201) b-oriented Ga2O3 thin film was first deposited on the c-plane sapphire substrate, followed by the GaN growth via metalorganic vapor phase epitaxy under N2 and H2 environment in sequence. From the measurement of transmission-electron- microscopy, the orientation relationship between GaN and b-Ga2O3 was identified as GaN[11-20]||Ga2O3[010]. A GaN epilayer with an electroplated copper substrate was demonstrated using a chemical lift-off process where the Ga2O3 sacrificial layer can be laterally etched out with a hydrofluoric solution. It is worthy to mention that the separated sapphire substrate can be cleaned and reused for LED epitaxial growth next time. It is benefit the cost down for the LED fabrication and Green Photonics Development.

8278-64, Session 7

V-doped AZO thin films and its application on GaN-based LEDs

Y. S. Wei, Y. Liu, C. Liu, National Central Univ. (Taiwan)

In this study, the electrical properties of the V-doped AZO TCLs (transparent conductive layer) were investigated. Using the co-sputtering system, V-doped AZO thin films with different V doping contents were prepared. The doping concentration of V in the AZO thin films ranges from 1 wt.% to 10 wt.%. The resistivity of the as-deposited V: AZO (10 wt.%) thin films can reach a fairly good resistivity of 3.37 × 10-2 Ω-cm, which is much lower than the resistivity (3.15 Ω-cm) of the as-deposited AZO thin film. The resistivity of the V: AZO thin film can be further reduced by annealing. The lowest resistivity (1.56 × 10-3 Ω-cm) of V: AZO thin film occurred at 10 wt.% doping after 400 °C annealing for 30 minutes. Using Hall measurement, the carrier mobility and carrier concentration were measured. We found that the carrier concentration does not increase monotonically with the V doping concentration. The maximum carrier concentration occurred at the V doping concentration at 5 wt.%. As for the carrier mobility, we notice that it can be improved with V-doping concentration. Also, the V: AZO thin films were processed on the GaN high-power LED as TCL (transparent conducting layer). Finally, the optical and electrical characteristics of the GaN LED with V-doped AZO TCL will be discussed and reported in this talk.

8278-52, Poster Session

Spectroscopic study and white-light simulation in praseodymium-doped fluorogermanate glass as single-phosphor for white LEDs

A. S. Gouveia-Neto, N. P. Rios, L. A. Bueno, Univ. Federal Rural de Pernambuco (Brazil)

Solid-state light sources for lighting purposes are of great scientific and technogical interest owing to their wide variety of benefits over daily used incandescent and fluorescent illuminant systems. The advantages range from energy consumption to environmental issues. Essentially, there exist two approaches to produce white-light employing LEDs. The first is by color addition using LEDs producing the three primary colors, or a combination of complementary colors light. The second is by blending visible light emission from a UV-blue excited rare-earth doped phosphor. White LEDs produced by means of a combination involving a UV-blue LED and a yellow emitting phosphor, has attracted much interest recently, owing to the low cost, easy fabrication process, and high brightness emission. However, the approach suffers from low CRI due to two color mixing, and the generated white-light changes either with excitation power or temperature. To overcome these problems, a white LED fabricated via a UV-blue excited red, green, and blue emitting phosphors is required. Thus, novel phosphors capable of producing high downconversion efficiencies and suitable combinations of activators to diversify the emission wavelengths are desired. Praseodymium-doped fluorogermanate 75GeO3:25PbF2 nano-structured phosphors were synthesized by thermal treatment of precursor glasses. Luminescence features of praseodymium ions incorporated into low-phonon-energy PbF2 nanocrystals dispersed in the fluorogermanate glass matrix was evaluated. The luminescence spectra exhibited emission signals peaked at 490, 525, 613, 643 nm. White-light emission was observed in praeodymium single-doped phosphor excited using a LED at 460 nm. The dependence of the luminescence emisson intensity upon annealing temperature, and rare-earth concentration was also evaluated. The results indicated the existence of optimum annealing temperature and activator ion concentration to obtain intense emission light with CIE chromaticity coordinates within the white-light boundary region. Results suggest that the novel nanocomposite glass material herein reported is a promissing phosphor for white-light LED applications

8278-53, Poster Session

Characterization of four-color multi-package white light-emitting diodes combined with various green monochromatic phosphor-converted light-emitting diodes

J. H. Oh, K. N. Lee, Y. R. Do, Kookmin Univ. (Korea, Republic of)

In this study, several combinations of multi-package white light-emitting diodes (LEDs), which combine an InGaN blue LED with green, amber, and red phosphor-converted LEDs (pc-LEDs), were characterized by changing the peak wavelength of green pc-LEDs between 515nm and 560nm (515, 521, 530, 540, 550, 560nm) in color temperature of 6500K and 3500K. Various green monochromatic pc-LEDs were fabricated by capping a long-wave pass-filter (LWPF) on top of pc-LEDs to improve luminous efficacy and color purity. LWPF-capped green monochromatic pc-LED can address the drawback of green semiconductor-type III-V LEDs, such as low luminous efficacy in the region of green gap wavelength. Luminous efficacy and color rendering index (CRI) of multi-package white LEDs are compared with changing the driving current of individual LED in various multi-package white LEDs. This study provides a best combination of four-color multi-package white LEDs which has high luminous efficacy and good CRI.

8278-54, Poster Session

Effects of 2D SiO2 and SiNx photonic crystal on extracted light from Y3Al5O12:Ce3+ ceramic plate phosphor

H. K. Park, J. R. Oh, Y. R. Do, Kookmin Univ. (Korea, Republic of)

We reports the optical effects of a two-dimensional (2D) SiO2 and SiNx photonic crystal layer (PCL) on Y3Al5O12:Ce3+ (YAG:Ce) yellow ceramic plate phosphor (CPP) to achieve enhanced extraction efficiency of YAG:Ce CPP on top of a blue InGaN light-emitting diode (LED) cup. The low external efficiency of YAG:Ce CPP is due to low light extraction efficiency by the total internal reflection (TIR) and waveguide effect occurring in film-type phosphor. To reduce the TIR and the waveguide effect on YAG:Ce CPP, 2D triangular-lattice air-hole nanoarrays of SiO2 and SiNx with various lattice constant (330, 420, 580, and 720nm) as PCL were fabricated on the YAG:Ce CPP by nanosphere lithography (NSL). The optimum properties on light extraction efficiency of YAG:Ce CPP are realized by adding the 2D SiNx PCL with a 580nm lattice constant. The structural, morphological and optical properties of 2D SiO2 and SiNx PCL-assisted YAG:Ce CPPs with various lattice constant on top of a blue LED cup were investigated by performing scanning electron microscopy (SEM), atomic force microscopy (AFM) and photoluminescence (PL) measurements.

8278-55, Poster Session

Blue excitability of green Zn2SiO4:Mn2+ phosphor and its LED application

H. S. Lim, Pukyong National Univ. (Korea, Republic of)

We have been synthesized blue-excitable and green-emissive Zn2SiO4:Mn2+ phosphors through a solid state reaction above a conventional sintering temperature of 1200 oC and subsequently a rapid thermal quenching [1]. The high-temperature-sintered Zn2SiO4:Mn2+ phosphors showed a drastic enhancement of 4A1(4E)-6A1 and 4T2-6A1 forbidden excitation bands peaking at 420 nm and 440 nm of Mn2+ ion, respectively, compared with the conventional green Zn2SiO4:Mn2+ phosphor. It showed a 5 nm-redshifted and 5 nm-broadened green emission band with 530 nm peak and 40 nm half width due to the forbidden 4T1-6A1 transition of Mn2+ ion, compared with the conventional phosphor. The temperature-dependent photoluminescence behaviors were similar with that of a conventional Y3Al5O12:Ce3+ phosphor: the quenching temperature, at which the initial emission intensity is halved, 150 oC [2]. It indicates that our Zn2SiO4:Mn2+ phosphor can be excited by the InGaN-based blue light-emitting diode as an alternative to a well-known β-SiAlON:Eu2+ green phosphor with difficulty in high-temperature and high-pressure process and patent issue.

8278-56, Poster Session

Yellow Y-Ca2SiO4:Ce3+ phosphor for white-light-emitting diode

J. H. Kim, Pukyong National Univ. (Korea, Republic of)

White-light generation was achieved by yellow-emitting ϒ-Ca2-xSiO4:xCe3+ phosphor excited by InGaN-based blue light. The powder phosphor was obtained through β→ϒ phase transition of phosphor caused by rapid thermal cooling around 400 °C. The ϒ-Ca2-xSiO4:xCe3+ phosphor showed the broad yellow emission with 560 nm peak and 120 nm half width, which was attributed to f-d transition of Ce3+ ion. Its absorption spectrum showed two bands peaking at 370 nm and 450 nm due to 2F5/2 and 2F7/2 splitting of 4f1 ground state of Ce3+ ion, respectively [1]. The temperature-dependent photoluminescence behaviors were similar with that of a conventional Y3Al5O12:Ce3+ phosphor: the quenching temperature, at which the initial emission intensity is halved, 150 °C [2]. It is indicated that our yellow phosphor can be a new alternative as yellow phosphor for white-light-emitting-diode.

8278-57, Poster Session

Abnormal red-emission EuSi2O2N2 phosphors for white-light-emitting diode

J. Lan, Pukyong National Univ. (Korea, Republic of)

This paper concentrates on a red-emitting EuSi2O2N2 phosphor excited by a blue light. The red-emitting EuSi2O2N2 phosphor was synthesized by a solid-state reaction of Eu2O3 and α-Si3N4 at 1300 °C under a nitrogen atmosphere, and it photoluminescence property was observed to microstructure and energy transfer mechanism. The EuSi2O2N2 phosphor is indexed on a monoclinic unit cell [1]. It can be efficiently excited in the blue light-emitting InGaN diodes (460nm), and shows a abnormal red emission peaking at around 680 nm corresponding to 4f65d1→ 4f7 transition of Eu2+ ion. It is suggested that this red phosphor will be useful for white-light-emitting diodes [2].

8278-58, Poster Session

Museum lighting for golden artifacts, with low correlated color temperature, high color uniformity and high color rendering index, using diffusing color mixing of red, cyan, and white-light-emitting diodes

A. Thorseth, D. D. Corell, P. B. Poulsen, S. S. Hansen, C. Dam-Hansen, Technical Univ. of Denmark (Denmark)

Museum lighting present challenges due to the demand for a high color rendering index (CRI), color uniformity and the damaging effects of both visible and invisible radiation. Golden objects are furthermore normally displayed with illumination which has a correlated color temperature (CCT) of 2200 K, a CCT that is not commercially available as single LEDs. An LED system that conforms with these requirements has been developed and implemented at The Royal Danish Collection at Rosenborg Castle. Color mixing of commercial LEDs (red, cyan, and white) was employed to achieve the spectral power distribution needed for the CCT and a CRI above 90, for all CRI test color samples. Replacing the traditional low voltage incandescent lighting has shown energy saving above 70%. Harmful IR radiation was reduced by 99%. Temperature fluctuations in the display cases were reduced from several degrees Celsius to below one, despite the fact that the lighting units where placed within the display case. Spatial color uniformity of the illumination and uniformly colored shadows was achieved by use of a highly diffusing reflector dish which avoids direct illumination from the LEDs.

8278-59, Poster Session

Optimization of light quality from color mixing light-emitting diode systems for general lighting

A. Thorseth, Technical Univ. of Denmark (Denmark)

Given the problem of metamerisms inherent in color mixing light-emitting diode systems with more then 3 distinct colors, a method for optimizing the spectral output of multicolor LED system with regards to standardized light quality parameters has been developed. The composite spectral power distribution from the LEDs are simulated using spectral radiometric measurements of single commercially available LEDs for varying input power, to account for the efficiency droop and other non-linear effects in electrical power vs. light output. The method uses electrical input powers as input parameters in a randomized steepest decent optimization. The resulting spectral power distributions are evaluated with regard to the light quality using the standard characteristics: CIE color rendering index, correlated color temperature and chromaticity distance. The results indicate Pareto optimal boundaries for each system, mapping the capabilities of the simulated lighting systems with regard to the light quality characteristics.

8278-60, Poster Session

Light emitting diode in stationary transportation applications: wavelength response to varying temperature

G. Schirripa Spagnolo, D. Papalillo, A. Martocchia, Univ. degli Studi di Roma Tre (Italy)

In recent times, the transportation industry has generated a number of developments involving new technology in signaling. Important developments have involved the production of light by means of light emitting diode (LED). The optical proprieties of LEDs depended on junction temperature. Since the heat from the junction must be dissipated into the ambient somehow, changing the ambient temperature affects the junction temperature and hence the emitted light. When the LEDs have been used in the railway or traffic signals, the optical proprieties of these have to maintain more rigorous color specifications. Besides, the limits imposed must be respected in ample range of variation of the ambient temperature (typically 248÷348 k). The peak wavelength of LED shifts proportionally to changes in junction temperature. Therefore, to respect color specifications with signals using LED as light source, it is not simple. In this paper, we describe problems of the temperature dependent changes of colorimetrical parameters of LEDs. Besides we will introduce a method through which to build a correct signal with feedback that, according to the measured temperature, it reacts so that to correct the optic characteristics of signal.

8278-61, Poster Session

Fabrication of random nanostructures for light extraction of organic light-emitting diodes

J. Shin, D. Cho, J. Moon, S. Choi, J. Han, C. W. Joo, J. W. Huh, J. Hwang, Electronics and Telecommunications Research Institute (Korea, Republic of); Y. W. Park, T. H. Park, B. Ju, Korea Univ. (Korea, Republic of); H. Y. Chu, J. Lee, Electronics and Telecommunications Research Institute (Korea, Republic of)

In this presentation, as an effort to improve the internal light extraction efficiency of bottom emission OLEDs as well as transparent OLEDs, we have reshaped the surface of the glass substrate to have a scattering layer of random texture using selective etching with irregularly patterned Ag mask. SiO_2 layer and Ag thin film was consecutively deposited on an glass, and thermal annealing was carried out between 300 and 600°C to fabricate irregularly patterned Ag masks. During the thermal annealing, Ag thin films was agglomerated and formed nano-sized particles on the SiO_2 layer via solid state dewetting. To optimize Ag mask, we have deposited Ag thin films of various thicknesses from 10 to 50 nm. As a result of these experiments, the fabrication process of the Ag mask was optimized with 30 - 40 nm of Ag film and 500°C of dewetting temperature. To form the scattering layer, SiO_2 layer beneath the Ag mask was selectively etched away. The buffer layer with high refractive index was coated on the scattering layer for planarization to prevent the high leakage current. To evaluate the light extraction efficiency of the scattering layer, bottom emission orange OLEDs with scattering layers were fabricated. Measurements showed that incorporation of the scattering layer improved the external quantum efficiency by over 40% compared to those of the OLEDs without the scattering layer. In this presentation, the detailed results on OLEDs with the scattering layer will be disclosed and furthermore, transparent OLEDs with the scattering layer will be also discussed.

8278-62, Poster Session

Electrical and optical properties of vertical GaN light-emitting diodes with deep-pillar nanostructures

K. S. Shin, J. I. Sim, H. An, Korea Univ. (Korea, Republic of); S. Oh, M. Yoo, Verticle Corp. (Korea, Republic of); T. G. Kim, Korea Univ. (Korea, Republic of)

Recently, high-power GaN-based light emitting diodes (LEDs) have attracted considerable interest in the various applications, such as traffic signals, mobile phone handset keypad, LCD backlighting, and indoor illuminators. However, further improvements on the light extraction efficiency are required for their practical use in these applications.

In this work, we report the fabrication method for deep-pillar structures using double-layer polymer coating methods and its application to honeycomb-type vertical GaN LEDs (VLEDs). For this study, polystyrene (PS) sphere of 500 nm size prepared with 10 wt% concentration is diluted in a solution of surfactant Triton X-100/methanol(1:400 by volume) before the spin-coating process. Double layered PS spheres were coated onto the n-GaN layer by a simple spin-coating method. Ni metal was then deposited using e-beam evaporator and PS beads are removed using an ultrasonic cleaner to form Ni dot array mask. Then the ICP-RIE was applied to make pillar patterns. The etching time was set at 4 min for 1.0 mm-depth and 6 min in 1.5 mm-depth.

As a result, two VLEDs with 1.0 mm and 1.5 mm pillar-patterns showed an increase in the optical output power by 3.09 times and 3.2 times at 350 mA, respectively, as compared to the VLED with flat-surface. On the other hand, the operation voltage of the reference VLED was 3.23 V while those of the VLEDs with pillar-patterns were measured to be 3.28 and 3.34 V, respectively. This might be due to the reduced contact area and the increase of the sheet resistance via plasma damages.

8278-63, Poster Session

Efficiency-droop mechanism in vertical red light-emitting diodes using electrical-to-optical impulse responses

J. Shi, F. M. Kuo, C. Lin, W. Chen, National Central Univ. (Taiwan); M. Lee, Southern Taiwan Univ. of Technology (Taiwan); L. J. Yan, J. Sheu, National Cheng Kung Univ. (Taiwan)

Recently, a lot of work has been done, demonstrating both experimental results and theoretical models, to explain the efficiency-droop mechanism in III-nitride based LEDs and to try to improve their performance. However, up to now, the efficiency-droop mechanism in AlGaInP-based LEDs, which plays an important role in generating a visible white-light spectrum with a high color rendering index, has rarely been discussed. In this paper, we utilize a dynamic measurement technique to investigate the droop mechanism of an AlGaInP-based LED with a vertical structure on a host Si substrate. Short electrical pulses (~100ps) are pumped into this device and the output optical pulses probed using high-speed photo-receiver circuits. From this, the internal carrier dynamic inside the device can be investigated by use of the measured electrical-to-optical (E-O) impulse responses. Results show that the E-O responses measured under different bias currents are all invariant from room temperature to ~100°C. This is contrary to most results reported for AlGaInP-based red LEDs, which usually exhibit a shortening in the response time and degradation in output power with the increase of ambient temperature. The temperature dependent dynamic measurement results for an AlGaInP-based red LED show that device-heating induced carrier leakage is not likely the dominant mechanism responsible for the efficiency droop. According to the extracted fall-time constants of the E-O impulse responses, defect recombination and saturation of spontaneous recombination may be the dominant causes of the efficiency droop under low and high bias currents, respectively.

8278-65, Poster Session

Dependence of efficiency-droop effect on the location of high indium layer in staggered InGaN quantum wells

Y. Yao, Y. Chen, Y. Lee, National Taiwan Normal Univ. (Taiwan)

Staggered quantum wells (QWs) structures are numerically studied to reduce the influence of the efficiency-droop effect on the InGaN-based green light-emitting diode (LED). The location of high In-content InGaN layer in staggered QWs considerably affects the distribution of the electrostatic-field of an LED. When the high In-content InGaN layer is suitably located in the staggered QWs, the localized electrostatic-field with high intensity increases the transport efficiency of injected holes across the active region, improving the overall radiative efficiency of the LED. Most importantly, as accumulation of injected holes in the last QW is relieved, the Auger recombination process is quenched, suppressing the efficiency-droop in the LED. Theoretically, the incorporation of the staggered InGaN QWs in the green LED (λ=530nm) can ensure an extremely low efficiency droop of 11.3%.

8278-33, Session 8

Colloidal quantum dots in lighting and LEDs

V. Bulovic, Massachusetts Institute of Technology (United States)

No abstract available

8278-34, Session 8

Quantum dot color converting LED for back light applications

E. Jang, Samsung Advanced Institute of Technology (Korea, Republic of)

No abstract available

8278-35, Session 8

Power conversion and luminous efficiency performance of nanophosphor quantum dots on color-conversion LEDs for high-quality general lighting

T. Erdem, S. Nizamoglu, H. V. Demir, Bilkent Univ. (Turkey)

High-quality general lighting requires good photometric performance along with high electrical power conversion efficiency. Among the photometric performance criteria important for general lighting are the luminous efficacy of optical radiation (LER), color rendering index (CRI) and correlated color temperature (CCT). LER≥380lm/Wopt, CRI≥90 and CCT≤4000K are desired. Phosphor-based color-conversion LEDs cannot simultaneously satisfy these requirements all at once, whereas it has been shown that white LEDs integrated with nanophosphors of quantum dots (QD-WLED) can. However, to date power conversion efficiency (PCE) and luminous efficiency (LE in lm/Welect) of such photometrically efficient QD-WLEDs have not been investigated and their potential for ultra-efficiency high-quality lighting has not been evaluated. In this work, to address these points, we studied power conversion and luminous efficiency performance of QD nanophosphors in different architectures. Using four-color mixing of green, yellow and red QDs on blue LEDs, we studied QD-WLEDs that posses LER≥380lm/Wopt, CRI≥90 and 1500K≤CCT≤4000K. Our analyses showed that Stoke's shift causes a fundamental loss of >15% in the optical power. As a result, the maximum feasible LE is 326.6lm/Welect, corresponding to an overall PCE of 85% for the integrated chip. However, considering a state-of-the-art blue LED with a PCE of 81.3%, this level decreases to 265.5lm/Welect, corresponding to an overall PCE of 69%. To achieve 100, 150 and 200lm/Welect, the required minimum quantum efficiency is 39, 58 and 79% for the layered QD color-conversion films, respectively. These results indicate that QD-WLEDs offer the potential to surpass the performance of phosphor-based WLEDs.

8278-36, Session 8

Enhanced photoluminescence using photonic crystal phosphors

K. Min, Y. Choi, H. Jeon, Seoul National Univ. (Korea, Republic of)

The importance of phosphor can never be overemphasized nowadays, especially when phosphor-capped white light-emitting diodes (LEDs) are considered that have a direct and high impact on the global general lighting market. There has been a great deal of effort to develop efficient phosphors with tailored optical properties. Here we suggest one-dimensional (1D) photonic crystal (PC) as a simple phosphor structure from which phosphorescence can be largely enhanced in comparison with its bulk counterpart. The 1D PC structure considered in this study is a distributed Bragg reflector (DBR) consisting of multiple layers in which binary materials with different refractive indices are stacked alternately. For theoretical assessment of the PC phosphor, we utilized the transfer-matrix (TM) method and the plane-wave expansion (PWE) method. Various properties of the 1D PC phosphors such as field distributions of pump photons and the enhancement factor in phosphorescence were investigated for different pump photon wavelengths. Using a specific quantum-dot-embedded 1D PC phosphor structure model, we estimated efficiency higher up to 7 times in pumping phosphor when a monochromatic pump wavelength is tuned exactly to the photonic band-edge (PBE). When switched to a LED-like pump source with a broad bandwidth, on the other hand, tolerance in the wavelength tuning between pump source and the PBE of PC phosphor is greatly relaxed, while pump efficiency is still 2.2 times higher than that of bulk.

8278-37, Session 9

Near-infrared (1.46 um) operation of In-rich InGaN-based nanocolumn LEDs

K. Kishino, J. Kamimura, K. Kamiyama, A. Kikuchi, T. Suzuki, Sophia Univ. (Japan)

Room temperature operation of near-infrared In-rich InGaN nanocolumn LEDs was demonstrated. The In-rich InGaN alloys are environmentally-friendly semiconductor materials to be applicable to optical communication light emitters, but the surface electron accumulation in the p-type In-rich InGaN hinders the operation of the InGaN-based pn-junction near-infrared emitters.

In this study, p-type Ga-rich InGaN were employed for p-side cladding layers of the In-rich InGaN active layers; both were grown on underlying high crystalline-quality n-type GaN nanocolumns. In the course of experiment, the selective-area growth (SAG) of the GaN nanocolumns with rf-plasma-assisted molecular beam epitaxy (rf-MBE) [1] was employed to fabricate the In-rich InGaN-based nanocolumn LEDs. Prior to the growth, triangular-lattice nanohole patterns were formed on a thin Ti film deposited on the c-plane MOCVD-grown GaN template. The regularly arranged Si-doped n-type GaN nanocolumn arrays were first grown by the SAG, followed by thick In-rich InGaN active layer with In composition over 80 % (80 nm) and Mg-doped p-type InGaN layer (250 nm). Ti/Al/Ti/Au metal N-electrode was formed on the underlying n-type GaN template and ITO transparent circle p-electrode of 65 um in diameter was formed on the p-type InGaN. The nanocolumn-LEDs fabricated were evaluated changing the DC injection current from 1.46 to 17.8 mA at the room temperature. A clear rectification property and the near-infrared 1.46 um emission were observed. This experimental finding provides a great step forward in the development of electrically driven III-V nitride based optical communication devices. References: [1] K. Kishino et. al, J. Cryst. Growth 311 (2009) 2063.

8278-38, Session 9

Nitride-based devices employing nanotechnology for photon management

J. He, National Taiwan Univ. (Taiwan)

No abstract available

8278-39, Session 9

Electrically driven nanoarrow array green LED

J. Chang, S. Chang, National Chiao Tung Univ. (Taiwan); Y. Cheng, Academia Sinica (Taiwan); Y. Chen, Y. Li, K. Sou, H. Kuo, C. Chang, National Chiao Tung Univ. (Taiwan)

Light emitting semiconductor devices in green color has attracted great interest in lighting and display applications. Conventionally, GaN based light emitting diodes are often fabricated on c-plane GaN surface. The emission wavelength is typically in the blue region, where its performance is optimal. For green emission, it requires higher In incorporation in quantum wells (QWs). High In concentration QWs grown on this crystal plane has a significant electric field due to spontaneous and piezoelectric polarization, which can reduce the radiative recombination efficiency. The polarization field can also cause carrier density dependent emission wavelength shift. To overcome these detrimental effects, an attractive approach is to grown quantum wells on semipolar crystal plane, which allows higher In incorporation and lower polarization field. Here, we demonstrated an electrically driven nano-arrow array green light emitting diode (LED), where QWs were grown on nanopyramid semipolar planes.

The nano-arrow arrays were fabricated from a GaN substrate, by patterned top-down nanopillar etching, pillar side wall passivation, and epitaxial regrowth. Hexagonal pyramids were formed on top of nanopillars. QWs were grown on the pyramid semipolar planes, which allows higher In incorporation. The fabricated LED emits at 500 nm under electrical injection. The LED shows enhanced radiative recombination efficiency and less carrier density dependent wavelength shift compared with a reference LED grown on c-plane surface. The performance improvement is attributed to the reduced polarization field in QWs grown on semipolar plane.

8278-40, Session 9

Top-down fabrication of GaN-based nanorod LEDs and lasers

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Although planar heterostructures dominate current optoelectronic architectures, 1D nanowires have distinct and advantageous properties that may enable higher efficiency, longer wavelength, and cheaper devices. We present here a recently-developed “top-down” approach for fabricating ordered arrays of high quality GaN-based nanorods with controllable height, pitch and diameter. The nanorods are formed via a 2-step etch process from c-plane GaN grown by metal-organic chemical vapor deposition. The process combines a lithographic dry etch followed by a selective, wet chemical etch of the nanorod sidewalls, leading to hexagonally-shaped nanorods with nonpolar m-plane sidewalls. By adjusting the wet etch step, nanorods with diameters from several hundred nanometers down to tens of nanometers can be fabricated. Importantly, the wet etch step also removes damage caused by the dry-etch, as shown by photoluminescence measurements. Structural characterization shows that the nanorods become largely dislocation-free as the diameter is reduced. The fabrication, structure, optical properties, and device performance of the nanorods and GaN/InGaN nanorod LEDs, both axial and radial-type, will be discussed in detail. Additionally, we have recently studied the lasing properties of these structures in detail. The nanorods show low lasing thresholds of ~250kW/cm2 and single mode emission with linewidths of less than 0.2 nm. 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.

8278-41, Session 10

The efficiency droop in GaInN light-emitting diodes

E. F. Schubert, J. Cho, Rensselaer Polytechnic Institute (United States)

Lighting technologies based on semiconductor light-emitting diodes (LEDs) offer unprecedented promises that include three major benefits: (i) Gigantic energy savings; (ii) Positive contributions to sustainability; and (iii) The unique controllability of solid-state lighting sources. In this presentation, we will discuss a formidable challenge of GaInN LED technology: The efficiency droop, that is, the decreasing LED efficiency occurring at high current densities. We will discuss the origin of the efficiency droop by analyzing its temperature dependence as well as its polarization-field dependence. We will also present specific innovations in GaInN LED structures that allow for a reduction of the efficiency droop.

8278-42, Session 10

Droop in III-Nitride LEDs: review and recent progress

A. David, Soraa, Inc. (United States)

No abstract available

8278-43, Session 10

Simulation of light-emitting diodes for new physics understanding and device design

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Development of state-of-the-art light-emitting diodes (LEDs) requires detailed optimization of their designs at different levels: epitaxial structure, LED chip, and LED lamp frequently including internal light convertors. Coupled electrical, thermal, and optical processes involved in the LED operation and rather complex 3D device geometry necessitates the use of consecutive simulations of the LEDs at all the levels with the essential data exchange between them. The simulation results obtained in such a way for III-nitride LEDs are reviewed in this paper.

A general figure of merit for the LED structures is proposed on the basis of a simple recombination model. New approach is discussed, implementing quantum corrections to the carrier transport in LED structures with super-thin barrier layers. In particular, promising ways for suppression of the efficiency droop with current are considered by using the approach. Light polarization and emission radiation pattern, as the issues important for light extraction from LED dice, are overviewed for various III-nitride materials and substrate orientations.

Special attention is paid to modeling of light conversion in white-light LEDs. The interplay between thermal, electrical, and optical processes in LED lamps is considered as a factor controlling stability of white light characteristics upon the variation of the LED operation conditions. Effects of phosphor-particles size dispersion and conversion medium configuration on the quality of white light are discussed in the paper as well.

8278-44, Session 10

Efficiency droop alleviation of InGaN/GaN blue LEDs with super-lattice active structure

S. Chang, J. Chang, Y. Chen, K. Sou, National Chiao Tung Univ. (Taiwan); H. Yang, T. Hsu, Epistar Corp. (Taiwan); H. Kuo, C. Chang, National Chiao Tung Univ. (Taiwan)

Nitride-based light emitting diodes (LEDs) suffer from reduction in efficiency at high injection current levels, which is so called efficiency droop. It is imperative to overcome this problem to allow LEDs to produce high lu-minous flux with reasonably high efficiencies under high current densities operation for use in general lighting. Over the past year, several different mechanisms for the effi-ciency droop have been suggested, including carrier lea-kage from the active region, nonuniform distribution of holes [1], Auger recombination, and carrier delocalization under high injection carrier density are currently considered to be the most likely reasons. In this work, we investigate the efficiency behaviors of InGaN/GaN blue LEDs with different thickness of GaN quantum barriers (QBs).

The efficiency droop behaviors of InGaN/GaN blue LEDs with different thickness of GaN QBs were investi-gated in this work. The droop percentage from efficiency peak to 70 A/cm2 is only about 10% as reducing the thick-ness of GaN QBs from 104 Å to 33 Å. Major contribution may due to more uniform distribution of electron and hole carrier in the SL like active region. The crystalline quality does not become worse from the results of v-pits density even thickness of GaN QBs is as low as 33 Å. The SL ac-tive structure could be an effective solution to alleviate the efficiency droop for the application of solid state general lighting.

[1] A. David, M. J. Grundmann, J. F. Kaeding, N. F. Gardner, T. G. Mihopoulos, and M. R. Krmes, Appl. Phys. Lett. 92 (2008), 053502.

8278-45, Session 10

Investigation of efficiency droop for UV LED with N-type AlGaN layer

P. Tu, S. Huang, S. Yang, Y. Lin, T. Hung, C. Hsu, Advanced Optoelectronic Technology, Inc. (Taiwan)

The efficiency droop in InGaN-based 380nm UV light emitting device (LED) with n-GaN and n-AlGaN underlayer grown on sapphire substrate by metal-organic chemical vapor deposition (MOCVD) was investigated. From simulation result of high resolution x-ray diffraction (HRXRD) ω-2θ curve by using dynamical diffraction theory, the Al composition in the n-AlGaN layer was determined to be about 3%. The experimental results of temperature dependent photoluminescence (PL) demon-strated that the internal quantum efficiency (IQE) of n-GaN and n-AlGaN UV-LEDs are 43% and 39%, respectively, which are corresponding to an injected carrier density of 8.5 × 10^17 #/cm3. It could be ex-plained that the crystal quality of n-GaN is better than of n-AlGaN. In addition, the observation of pit density from atomic force microscopy (AFM) surface morphology is consistent with the interpretation. It was well-known that the pits appearing on the surface in the virtue of the threading dislocations. Thus, it means that defects induce the non-radiative centers and deteriorate the IQE of the UV-LED with n-AlGaN underlayer. Therefore, the light output power of n-GaN UV-LED is slightly higher below the forward current of 250 mA. Nevertheless, the output power was enhanced about 22% as the injection current was increased to 600 mA. Furthermore, the external quantum efficiency (EQE) of n-AlGaN UV-LED was nearly retained at the 600 mA (only 20% droop), whereas the UV-LED with n-GaN ex-hibits as high as 33%. We attributed this improvement to the less self-absoption by replacing n-GaN underlayer with n-AlGaN.

8278-46, Session 10

Investigation of optical properties and relative carrier dynamics of various LEDs using time resolved electroluminescence system

Y. Yoo, Y. Cho, KAIST (Korea, Republic of)

Generally nitride-based light-emitting diodes (LEDs) suffer from a reduction of the internal quantum efficiency (IQE) with increasing injection current. We call this phenomenon as 'Efficiency droop', which is the gradual decrease of efficiency as the injection-current density surpasses a low value that is typically between 0.1 and 10 A/cm2, is a unique characteristic of GaN-based LEDs. Although many research groups have studied the mechanism and solution of this droop phenomenon and several explanations such as Auger effect, dislocation and defect, thermal effect, and carrier overflow, field effect for the efficiency droop have been proposed in recent years. Despite many recent research efforts the underlying mechanisms are still controversial. In order to minimizing droop and improving efficiency, we concentrated on the study of mechanism of efficiency droop phenomena using pulsed current source. The pulsed current was applied instead of DC current source since the LEDs were operated in DC current source usually with thermal effect. In this work, the optical property and carrier dynamics of LEDs were studied through the electroluminescence (EL) and time-resolved EL (TREL) experiments. A variety of LEDs (UV, blue, green, and red LEDs) were implemented in this study. The carrier dynamics of LEDs were studied with pulsed current source by TREL system by varying the different current and pulse width.

8278-47, Session 11

Improved light output power of GaN-based vertical LEDs through efficient current injection and spreading

T. Seong, Korea Univ. (Korea, Republic of)

Vertical-configuration LEDs, which are fabricated via the removal of an insulating sapphire substrate, have been widely studied to fabricate high-power and high-efficiency LEDs for general lighting applications. Fabrication of high-performance VLEDs requires the achievement of high external quantum efficiency in LEDs. To achieve the goal, the formation of low-resistance and thermally stable ohmic contacts to N-face n-type GaN is essential. In addition, current crowding and heat dissipation are important technological issues. It is well know that unlike G-polar n-contacts, contacts to N-polar n-GaN (for vertical LEDs) are difficult to form. The different electrical characteristics between contacts to Ga-polar and N-polar n-GaN were attributed to the presence of spontaneous and piezoelectric polarization fields. In this work, we have investigated the electrical and thermal stability of N-polar n-GaN by introducing Ga-containing alloy or diffusion barrier layers. It is shown that such treatments effectively improve the thermal stability of N-polar n-contacts. Furthermore, we have investigated the effect of current blocking regions on the output power of VLEDs, which were formed by plasma treatments. The results are compared to those of VLEDs with and without SiO2 current blocking layers. It is shown that the optimized plasma treatment could represent an effective processing tool for the fabrication of efficient high-power GaN-based VLEDs.

8278-48, Session 11

GaN-based LEDs with air voids prepared by laser scribing and chemical etching

S. Chang, National Cheng Kung Univ. (Taiwan)

The authors report the formation of air voids at GaN/corn-shape pattern sapphire substrate (CSPSS) interface by laser scribing and lateral etching with one-step growth. After the epitaxial growth, a 2000-nm-thick SiO2 layer was deposited onto the samples. A diode pump solid state laser was then used to scribe the wafers. The scribed wafers were subsequently wet etched in a mixture of H3PO4 and H2SO4 solution at 220oC. For the fabrication of LEDs, an inductively coupled plasma etcher was then used to partially etch the sample surface until the n-type GaN was exposed. A 245-nm-thick indium-tin-oxide layer was subsequently deposited to serve as the current spreading layer. Cr/Au was then deposited to serve as n- and p-pad electrodes. With 5 and 20 min lateral etching, it was found that pyramid-like air voids were formed with an average height of 0.98 and 1.9 μm, respectively, on top of each cone of the substrate. It was also found that we can enhance LED output power by 11.5% by etching the wafers for 20 min. It was also found that the simulated results agree well with the experimentally observed data.

8278-49, Session 11

Photoelectrochemical liftoff of patterned sapphire substrate

C. Hsieh, C. Liao, C. Lin, H. Chen, C. Chen, C. Yang, National Taiwan Univ. (Taiwan)

Because of certain fundamental drawbacks of the laser liftoff technique, the yield of sapphire substrate liftoff based on this technique for fabricating vertical light-emitting diode (LED) is quite low. Recently, it was shown that photoelectrochemical (PEC) wet etching can be a better approach for sapphire substrate liftoff. By using the technique of epitaxial lateral overgrowth (ELOG) to grow GaN on sapphire, micron-scale air voids are formed above the silicon dioxide mask for the chemical electrolyte to flow into the central part of a sample for accelerating the PEC etching. Based on this approach, sapphire substrate can be lifted off and high quality vertical LED has been fabricated. However, the two-step growth in using the ELOG technique will increase the cost. In this paper, we demonstrate a simpler approach by using the growth of patterned sapphire for effective PEC liftoff. An appropriate design of one-dimensional trenches on sapphire can lead to the formation of air voids between GaN and sapphire for electrolyte to approach the center of a sample. Based on such a structure, PEC liftoff of sapphire substrate with the assistance of ultrasound vibration can be accomplished within one hour when a Xenon lamp is used. By using a stronger light source, the required liftoff time can be shortened. The characteristics of vertical LEDs fabricated based on such a sapphire substrate liftoff technique will also be discussed.

8278-51, Session 11

Cu-electroplating substrate for fabrication of vertical thin-GaN LED structure

Y. Lin, C. Liu, National Central Univ. (Taiwan)

One of typical vertical LED structures is built on transferring the GaN LED epi-layers onto the Cu-electroplating substrate by Cu plating process and Laser-Lift-Off (LLO) technique. How do the physical properties of the Cu-electroplating substrate affect the electrical and optical performance of the LED is an importance issue. Our preliminary study shows that with a lower and higher current density, the Cu substrate is found to have a (220) prefer-orientation and (111) prefer-orientation, respectively. Using the Vicker hardness tests, the hardness of the Cu substrate with the (111) prefer-orientation is larger than that of the Cu substrate with the (220) prefer-orientation by 7 %. After removing the initial sapphire substrate, we found that the finished GaN/Cu wafer warps. The warpage should be caused by the residual compressive stress in the GaN epi-layers. Also, we found that the warpage degree of the Cu substrate plated with the (220) prefer-orientation is smaller than that of the Cu substrate plated with the (111) prefer-orientation. This result implies that the harder electro-plated Cu substrate, the lesser warpage of the GaN/Cu wafer would be resulted. Using the peak position of the E2-high mode in Raman spectrum, the stress level of the GaN epi-layers can be determined. We found that the compressive stress of the GaN epi-layers on the Cu substrate plated with a higher current density is reduced to be 435.5 MPa from the initial stress-level of 1148 MPa on the sapphire substrate. The detail mechanism of the stress relief of the GaN epi-layers by the Cu-electroplating substrate will be discussed in this talk.

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8279-01, Session 1

Electro-optics and optical latching in the SmAPf banana phase

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The discovery fifteen years ago of chiral antiferroelectric smectic liquid crystals (LCs) composed of achiral "bent-core" mesogens, forced a re-evaluation of the interplay between chirality and polarity in smectics, and provided the first example of spontaneous macroscopic reflection symmetry breaking in a fluid phase. However, the first theoretical discussions of the "banana phases," dating from 1992, and the first modern experimental work in the field, focused on a proposed achiral phase with C2V symmetry, composed of a ferroelectric stacking of untilted SmAP layers (the SmAPF phase).

Ironically, proof of the existence of such a phase had not to date appeared in the literature, with the exception of an interesting but very slow-switching polymeric system. Driven by exciting potential applications for fast phase-only modulation, we embarked upon a program of directed design and synthesis of low molar mass SmAPF mesogens, the first example having recently appeared in the literature [Reddy et al., Science 2011, 332, 72-77.]

More recently, a new SmAPf material possessing very high ferroelectric polarization (~900 nC/cm^2), and nearly ideal "electrostatic V-shaped switching" and optical latching has been characterized. The design of the SmAPF materials, and electrooptics of the new analog, will be described.

8279-02, Session 1

Pre-organized liquid crystals: biaxial nature of laterally connected dimer

I. Nishiyama, DIC Corp. (Japan); Y. Tabe, Waseda Univ. (Japan); J. Yamamoto, Y. Takanishi, Y. Ishii, Kyoto Univ. (Japan); H. Yokoyama, Kent State Univ. (United States)

Biaxial nematic liquid crystals have attracted much attention from both fundamental and application points of view. The usual nematic phase is uniaxial, in which molecular axes of constituting molecules are oriented along the director n, whereas the biaxial nematic phase possesses an additional order, called minor director m, which is perpendicular to the director n. If the anisotropic nature on the basis of the minor director m can be controlled by the applied electric voltage, the fast response should be achieved. This is because the rotation around the molecular long axis is much faster than the orientation change of the usual director n. So far, different molecular designs have been proposed for the emergence of the biaxial nematic phase. Among that, we have been interested in applying "pre-organization" concept on generating the biaxiality. Dimeric liquid crystal compounds have been prepared in line with this concept in which two mesogenic parts are linked by the biphenyl connecting group. One of the pre-organized dimmers shows an anomalous textural change, for vertically-aligned and free-standing film samples, at the SmC-N phase transition, in which the Schlieren texture of the SmC changes into the other Schlieren texture of the N phase. There are two possible explanations for this textural change, i.e., the occurrence of the director change at the SmC-N phase transition or the emergence of biaxiality in the N phase. Electro-optical properties have also been measured in detail for investigating the biaxial nature of the sample.

8279-03, Session 1

High birefringent nematic liquid crystals: compounds and mixtures

P. Kula, R. S. Dabrowski, J. Dziaduszek, K. Garbat, Military Univ. of Technology (Poland)

High birefringent liquid crystals are necessary for many photonic applications in visible and infrared spectral regions such as light shutters, shifters, attenuators, filters, electronic lenses and for laser beam steering devices. Recently they also gained increasing interest as materials for GHz and THz working devices (phase shifters, antennas, varactors and filters).

Liquid crystals in with rigid core is designed to obtain extended conjugated pi electron systems show high birefringence. The compounds from the families of tolanes, phenyltolanes, biphenyltolanes, terphenyls, quaterphenyls with terminal isothiocyanato group and laterally substituted by one or a few substituents in chosen rings were the object of our main research activity during last years. Mesogenic properties (nematic range) and physical properties such as optical indices, electric permittivity constants, viscosity were investigated. Founded rules about optimal numbers of lateral substituents and their optimal position in molecular core and their shape and length will be presented

From the presented families of compounds, the most convenient ones were selected and mixtures with broad temperature range of nematic phase with positive dielectric anisotropy (Dn=0.3-0.5 for @589 nm) or negative dielectric anisotropy (Dn=0.2-0.35) as well as mixtures changing sign of dielectric anisotropy from the value De>0 to value De<0 (Dn=0.2-0.4) upon changing of frequency were formulated. Many other examples with low medium or high dielectric anisotropy will be presented.

8279-04, Session 1

Lyotropic chromonic liquid crystals under confinement: monodomain formation and defect dynamics

M. Srinivasarao, X. Yao, J. O. Park, Georgia Institute of Technology (United States); A. D. Rey, McGill Univ. (Canada)

Lyotropic chromonic liquid crystals(LCLCs) are a relatively new class of liquid crystals that consists of dyes molecules with a plank-like or disc-like hydrophobic core with hydrophilic groups at the periphery. When dissolved in water, the dyes aggregate into elongated superstructures whose length is reversible and the aggregration is thought to be isodesmic. Chromonic liquid crystalline phases consist of many dyes, drugs and nucleotides. In order to study this liquid crystalline phase and its physical properties, it is essential to obtain a well aligned sample or a monodomain. Lyotropic liquid crsytals are inherently difficult to align, and hence we have studied the process of monodomain formation and the associated defect dynmaics of an anionic azo dye - Sunset Yellow FCF (SSY) under the confinement of a flat capillary. Sunset yellow solutions were filled into the flat capillary by capillary action and upon cooling from isotropic phase, SSY solutions displayed growth of small uniform domains that were separated from the rest of the solution by line defects. At the center of capillary, a single line disclination (S=+1) split into two lines(S=+1/2) close to the edge of the capillary. At the same time, the two uniform domains linked by the center disclination line were growing/expanding towards each other. The branch points were found to move at a constant velocity and was found to be 0.11 μm/s, which matches quite well with the theoretical estimate of 10-1μm/s The part of the lines (S=+1/2) starting from branch point to the line close the edge had an exponential-shape, from which the ratio of the tension to bending stiffness was deduced. When the center disclination line was close to vanishing leading to a merging of the two uniform domains, the lines pincjed-off and relaxed to the edge of the capillary. The relaxing line had a sine-wave shape and obeyed the Cahn-Hilliard equation for filament buckling. From the relaxation kinetics, the ratio of tension to friction coefficient, about 0.8x10-1μm/s, was obtained. Finally, it formed a planar aligned monodomain throughout the entire capillary with the director normal to the long axis of the capillary. The alignment of the optic axis was characterized by polarized optical microscopy, polarized Raman microscopy and x-ray diffractometry. By using the monodomain, the temperature and concentration dependence of order parameters, both and , were measured by polarized Raman microscopy.

8279-05, Session 2

Optofluidic tuning of photonic crystal lasers

A. Kristensen, T. Buss, M. B. Christiansen, C. Smith, N. A. Mortensen, Technical Univ. of Denmark (Denmark)

The integration and interplay between optical and fluidic functionalities on a chip defines the emerging field of Optofluidics. Microfluidics enables new types of adaptive optics, where the optical properties of a device can be controlled by a fluid. We apply this principle to realize tunable photonic crystal band-edge lasers. Two examples are discussed: (1) Dye doped polymer photonic crystal band-edge laser devices are frequency tuned by exchanging a liquid cladding layer. (2) A dye-doped liquid crystal is used as liquid cladding in a photonic crystal cavity. An applied electric field to the liquid crystal provides wavelength tunability. The photonic crystal enhances resonant interaction with the gain medium.

8279-06, Session 2

Natural photonic crystals: formation, structure, function

M. H. Bartl, The Univ. of Utah (United States)

In biological systems, structurally complex architectures with feature sizes covering several lengths scales are engineered under rather simple environmental conditions and with limited resources-strategies still largely unmatched by our synthetic abilities. Prime examples are found in the amazingly colorful world of insects, which is in large part the result of structural colors, arising from a delicate interplay of light with periodically organized dielectric lattices with feature sizes of a few hundreds of nanometers. Such structural colors have recently gained tremendous interest for the use as photonic crystals with promising potential for energy and information technology applications. In this talk, I will present several photonic nanostructures “engineered” by various beetles with architectures that are still far from our synthetic reach. For example, we discovered recently that the brilliant coloration of several beetles is the result of photonic structures with a diamond-based lattice-the so-called champion of photonic structures. I will also discuss some of our recently gained insights into formation mechanisms of these unique biological architectures. In addition, I will introduce our sol-gel biotemplating route for fabricating highdielectric three-dimensional photonic crystals. Using this approach, we create high-dielectric photonic crystals with a variety of lattice geometries and bandgaps at visible frequencies. In order to evaluate the properties of these novel photonic architectures, we apply a range of structural and optical characterization tools, including multi-directional optical reflectance microspectroscopy, optical and electron microscopy as well as theoretical modeling and photonic band structure calculations.

8279-07, Session 2

Liquid crystalline structures for transformation optics

O. D. Lavrentovich, J. Xiang, H. Park, S. V. Shiyanovskii, Kent State Univ. (United States); Y. A. Nastishin, Institute of Physical Optics (Ukraine)

In transformation optics, one explores metamaterials with properties that vary from point to point in space and time, suitable for applications in devices such as an “optical cloak” and an “optical black hole”. Spatially distorted liquid crystals with variable direction of optic axis and refractive indices represent a promising direction for manufacturing of reconfigurable three-dimensional metamaterials. We describe spatially varying and switchable metamaterials based on arrays of nanorods assembled by dielectrophoretic effect into birefringent liquid crystalline structures. The electric field controls the orientation and concentration of Au NRs and thus modulates the optical properties. We also explore configurations in which the metal nanorods are aligned in a liquid crystalline matrix rather than in an isotropic fluid. The work was supported by AFOSR grants MURI FA95550-06-1-0337 and FA9550-10-1-0527.

8279-08, Session 2

Preparation of porous polymer materials for bulky liquid crystal devices

T. Nose, T. Ito, R. Ito, M. Honma, Akita Prefectural Univ. (Japan); T. Watanabe, K. Ito, S. Yanagihara, Yurikogyo Co., Ltd. (Japan)

Millimeter wave and THz wave regions are attractive as a new application field of liquid crystal control devices. Since the wave length in this frequency region is extremely longer than that of visible rays, extremely large size of LC devices are necessary to attain any control devices by upsizing the optic devices.

In this work, we focus on PDLC type cell structures to attain extremely large size of LC layer. It is known that the PMMA porous materials (PMMA monolith) is easy to fabricate by cooling the simple PMMA ethanol/water solution, and we try to use the monolith as a polymer matrix of the PDLC type structure. It may be possible to make arbitrary structure by preparing suitable container of the initial solution such as Fresnel zone container, grating container and so on, where the thickness of the LC layer becomes several millimeter size.

Big problem is that the PMMA material tends to shrink largely during the preparation process. Then, we investigate first the shrinking phenomena under various preparation conditions of the porous PMMA materials such as cooling ratio, molecular weight of PMMA, mixing ratio, solvent evaporation speed, and so on. Final microscopic porous structure is observed by SEM, and it is confirmed that the fine porous structure with very high porosity can be successfully obtained by the simple solution method.

8279-09, Session 3

Continuous wave mirrorless lasing in cholesteric liquid crystals

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Lasing in liquid crystals has received a great interest from both the laser as well as the liquid crystal community in the past decade. To date, despite numerous efforts, lasing in dye doped cholesteric liquid crystals has only been observed by pumping with pulsed, high power lasers. For the system to become technologically viable, continuous wave (CW) lasing is needed. As such there has been a fury of activity to obtain CW lasing in these systems without success. Here we report, the first observation of lasing in dye doped cholesteric liquid crystals (CLCs) under both coherent (laser) and incoherent (LED) continuous wave (CW) light excitation. The mechanism of lasing is attributed to the unique combination of the dye fluorescence and a polymer stabilized distributed feedback structure of the CLC that exhibits microcavity behavior. We will discuss this findings and present results on possible mechanisms associated with the lasing. This realization of lasing pumped by low power CW excitation opens the possibility of the proliferation of all-organic, compact, wavelength tunable CW mirrorless lasers.

8279-10, Session 3

Electrically and all-optically controllable random lasers based on dye-doped liquid crystal films

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Electrically controllable random lasers below Fréedericksz threshold and all-optically controllable random laser based on thick DDLC cells with adding a photoisomerizable dye are reported. Externally applied voltage below threshold and two-step exposure of UV and green beams on the cell can, respectively, electrically and all-optically control the lasing intensities of the random lasers and thus their energy thresholds. The reasons for the below-threshold electric and all-optical controllabilities of the random lasers are attributable to the effective control of the spatial fluctuation of the orientation of the LC micro-domains and of the dielectric property of the LCs with controlling, respectively, the electric-field-aligned order of LCs below the threshold and via the isothermal nematic↔isotropic phase transitions due to the trans↔cis isomerization; leading to the variations of the scattering strength of the fluorescence in their recurrent multiple scattering. This may cause the variations of the lasing intensity of the random lasers and thus of their energy thresholds.

8279-11, Session 4

Recent applications of liquid crystal spatial light modulators

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This presentation reviews recent application development in Kent Optronics involving liquid crystal spatial light modulators (SLM). Examples discussed are Multispectral Polarized Scene Projector (MPSP), Multi-Spectral High Temperature Infrared Scene Projection (IRSP) Display, Transparent Display, and Mirrored TV/Monitor. The MPSP generates both static and video images (up to 200 Hz) with 512x512 spatial resolution with active spatial, spectral, and polarization modulation on pixel level with user selectable wavelength (850-1650 nm) and bandwidth (12-100 nm) in the short wave infrared (SWIR) regime. The IRSP, generating high frame rate (up to 200 Hz) images with 512x512 pixels in both Midwave IR (MWIR) and Long Wave IR (LWIR), has demonstrated simulated apparent temperatures exceeding 1500 K, more than doubling the maximum temperature capability of prior-art pixilated scene projector devices. The Transparent Display is a large size flat pane enabling three utility functions, i.e., uniform transparent state for see-through purpose with 90% colorless transmittance, opaque state for privacy protection, and graphic/texture state for information display. The Mirrored TV/Monitor is an integrated flat panel display unit with our switchable mirror having ~90% colorless transmittance in the transparent state, and silver-mirror-like apperance with >90% reflectivity in the mirror state. The unit allows normal TV show without color distortion and brightness attenuation when the mirror is switched into transparent state; and is converted into a mirror when the TV is turned-off.

8279-12, Session 4

Thin film polarizer based on photo-curable chromonic liquid crystalline solutions

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Lyotropic chromonic liquid crystals (LCLCs) form a columnar discotic liquid crystalline (LC) phase in aqueous solution due to the disc-like or plank-like molecular shape of chromonic dyes and their ionic peripheries. Such columnar structures in the chromonic columnar N phase can be coated on a glass substrate, and aligned in one direction by applying external forces. The resulting thin crystalline film (TCF) can absorb a polarized light parallel to the molecular axis while transmitting a polarized light parallel to the columnar axis, which constructs an E-polarizer. Although the concept of the coatable polarizer known, it has not been commercially successful due to numerous problems mainly originated from the use of aqueous solution. It is extremely difficult to coat the aqueous solution on most of substrates, especially on plastic substrates. Large volume shrinkage occurs during the crystallization process generating unfavorable defects. Also, weak adhesion becomes an important issue when a TCF is applied to a flexible substrate.

In this presentation, we demonstrate a novel preparation method of coatable polarizer from a photo-curable organic-based LCLC solution. Lyotropic LC solutions were prepared by dissolving amino-functional chromonic dye in acrylic acid containing photoinitiator and crosslinking agents. The solution was shear-coated with subsequent UV irradiation to provide a thin film polarizer. The coating processibility of this organic-based solution was outstanding, particularly on a plastic substrate. The maximum polarization efficiency was measured to be 95.2%. The resulting thin film polarizer showed excellent film characteristics, such as good adhesion strength to various substrates, superior surface hardness, good solvent resistance and decent thermal stability.

8279-13, Session 4

Multi-twist retarders for broadband polarization transformation

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Precise broadband polarization transformation is needed in many applications, including LCDs, optical storage, optical remote sensing, and optical fiber networks. Well-known methods using individual and multiple stacks of simple waveplates are often unable to achieve the broadband polarization transformation performance desired, and/or cannot easily offer large clear apertures, small thicknesses, or acceptable cost.

We introduce a family of broadband retarders, comprised of a low number of twisted nematic liquid crystal layers, that accomplishes well-controlled polarization transformation for nearly any VIS/IR wavelength, bandwidth, or incidence angle range desired. Using liquid crystal polymers on a single substrate, we show how these multi-twist retarders are embodied as a monolithic birefringent plate with excellent performance and potentially very low cost. Using Mueller matrix calculus and Berreman 4x4 simulation, we derive the full optical behavior. We show that even though these complex retarders are in general not uniaxial or biaxial (i.e., they do not have an overall optical axis), they are nevertheless useful in many common situations to transform polarization. For example, we show that broadband (i.e., achromatic) quarterwave retardation can be achieved with only two twist layers where the performance that matches the popular three waveplate approach by Pancharatnam, and that three twist layers can be used to greatly expand the bandwidth beyond well this (i.e. super-achromatic). Finally, we demonstrate a simple patterned retarder (i.e. louvered waveplate) on a photo-alignment polymer that highlights the ease of patterning waveplates with this new technology.

8279-14, Session 5

Liquid crystallinity in organic semiconductors

J. Hanna, Tokyo Institute of Technology (Japan)

No abstract available

8279-15, Session 5

Binary systems of discotic liquid crystalline semiconductors toward solution-processing thin film devices

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We reported that a phthalocyanine (Pc) mesogen having hexyl chains at 1, 4, 8, 11, 15, 18, 22 and 25-positions of the Pc ring exhibits a fast drift mobility in both columnar and crystalline phases (10-1 ~ 1.4 cm2 V-1 s-1) with an ambipolar nature. In addition, it was found that a bulk hetero-junction solar cells with the Pc mesogen and PCBM, fabricated by a solution processing perform the high external quantum efficiency (> 70 % at 650-750 nm) and the conversion efficiency reaches over 3 %. In this communication, some binary systems containing the Pc mesogens were studied on the miscibility and semiconducting properties.

A binary system used for the solar cells was also studied in terms of phase separation between the Pc mesogen and PCBM and the results indicates that a small amount of PCBM affect the mesomorphism to be destabilized and the excess of PCBM tends to show phase separation. These mean that a Pc-PCBM system forms a crystalline state in thermodynamically stable state and the spin coating technique to fabricate the bulk heterojunction layer in the cells gives a specialized case of the binary mixture.

On the other hand, a binary mixture of the Pc mesogen and the Zn complex was studied. The complete miscibility was observed and the carrier mobility was measured to give almost no change of mobility for the Colh mesophase in the 1:1 mixture. This indicates that the mixture of mesogens could make mesogenic systems more useful for new applications.

8279-16, Session 5

Directed assembly and in situ manipulation of semiconductor quantum dots in liquid crystal matrices

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Directed self-assembly of nanostructures into specific geometries with new functionalities is an important research area. Currently, controlling the spatial distribution of nanostructures in any composite material poses challenges, primarily that of non-specific aggregation and lack of directed assembly. We present our results in the manipulation of directed assemblies of uniformly dispersed, chemically-synthesized semiconducting quantum dots (QDs) in two different liquid crystal matrices.

(a) We demonstrate the formation and spatial modulation of strongly-coupled gallium selenide QD nano-assemblies suspended in a nematic liquid crystal (NLC). Using static and dynamic optical techniques we show that the coupled QDs aggregate with a well-defined directionality commensurate with the NLC director axis. The spatial orientation of the aggregates is selectively controlled in situ by the application of in-plane electric fields. The strong inter-dot coupling also enhances the excitonic recombination and the emission decay rate is both direction and electric field dependent [1].

(b) We investigate a composite system of CdSe/ZnS QDs dispersed in a chiral nematic (cholesteric) LC where the reflection band from the cholesteric LC enhances the intensity of the QD emission and modifies their peak emission wavelength. This wavelength shift is dependent on the pitch of the cholesteric and on the extent of the overlap of the reflection band with the emission spectra of the QDs. In addition, according to our preliminary investigations, the cholesteric media imparts some interesting polarization dependence on the otherwise randomly polarized QD emission.

This work was supported by NSF.

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8279-17, Session 6

Characterization and applications of liquid crystals in the THz frequency range

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In the past decade, THz studies ranging from investigations of ultrafast dynamics in materials to medical, environmental sensing and imaging have been actively explored. For these and future applications in THz communication and surveillance, quasi-optic components such as phase shifters are indispensable. The birefringence of liquid crystal (LC) is well known and extensively utilized for the manipulation of optical radiation in the visible and near-infrared range. Recently, there have been increasing interests in the study of liquid-crystal-based devices for application in the sub-millimeter wave or THz (1 THz = 1012 Hz) frequency range. In this paper, we review recent advances in liquid crystal THz optics and photonics. Here I summarize mainly outcome of our group. Advances made by other groups will also be presented. In the past five years, the optical constants of several important liquid crystals were determined in the THz regime for the first time [Appl. Opt., 42(13): 2372, 2003 and J. Biological Phys. 29(2-3):335, 2003, J. Appl. Phys. 103: 101809, 2008, Ferroelectrics 364:72, 2008]. Unexpected large birefringence was observed for the liquid crystals 5CB and E7 in the nematic phase. These properties were utilized to demonstrate both magnetically and electrically controlled THz phase shifters [APL 83(22): 4497, 2003; IEEE MWCL 14(2):77, 2004,], culminating in the first room-temperature, 0-2π tunable THz phase shifter [Opt. Exp. 12(12): 2625, 2004, Selected by the Virtual J. Ultrafast Sci., September 2004, Taiwan Patent 200186, US patent filed]. The device operates at room temperature, as opposed to previous devices needing liquid N2 for cooling and achieving phase shift of a few degrees at best. Important applications such as THz phased arrayed radar would be possible. Recently, we also reported control of enhanced THz transmission through 2-D metallic hole arrays using magnetically controlled birefringence in a nematic liquid crystal cell. [Opt. Exp. 13(11): 3921, 2005, collected by the Nanostructured Surfaces Web]. The first ever THz Lyot filter [APL 88:101107, 2006, collected by the Virtual J. of THz Sci. and Technol., US patent 7483088 B2, 2009], electrically switchable THz quarter-wave plate [OL 31(8):1112, 2006, collected by the Virtual J. of THz Science and Technology, OSA Virtual J. Biomed. Opt.] and electrically tunable room-temperature 2π Liquid Crystal Terahertz Phase Shifter [IEEE PTL 18(14): 1488, July 15, 2006, collected by Virtual J. of THz Sci. and Technol., July 2006] were demonstrated recently. Our work on THz photonic elements with liquid-crystal-enabled functionalities was highlighted by SPIE Newsroom (http://spie.org/x14608.xml) in 2007. Other novel devices such as polarizers, phase gratings, Solc birefringent filters have also been demonstrated [Opt. Lett. 33:174, 2008, Opt. Exp. 16(5):2995, 2008; Opt. Lett., 33:1401, 2008].

8279-18, Session 6

Magnetically tunable metallic photonic crystals infiltrated with liquid crystal in terahertz range

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We investigated the phenomena of a metal photonic crystal (MPC) infiltrated with liquid crystal. According to our design, the photonic crystal has specific photonic band gap (PBG) and can be utilized as a filter. The device is filled with nematic liquid crystal (NLC), MDA-00-3461. The refractive indices of NLC are magnetically switchable by reorient the NLC molecules. Additionally, the corresponding PBG and the filtering performance of the device are tunable. According to our experimental results, the low frequency boundary of PBG at 0.121 THz can be shifted to the blue by 6.17 GHz, and the high frequency boundary of PBG at 0.175 THz can be shifted to the blue by 11.04 GHz. As a tunable THz filter, the peak transmittance at 0.187 THz can be shifted to the blue by 3.66 GHz, and the insertion loss is 0.85 dB to 7.2 dB.

8279-19, Session 6

Thermally responsive polymer/liquid crystal gels exhibiting large scale color changing in cholesterics

L. E. Natarjan, M. E. McConney, M. Dunning, V. P. Tondiglia, T. J. White, T. J. Bunning, Air Force Research Lab. (United States)

Systematic investigations of a swelling/de-swelling/re-swelling transition involving helically ordered gels and liquids crystal solvents are presented. Functional LC monomers are templated and subsequently polymerized in an ordered LC fluid. The cell architecture is designed in such a way as to spatially control the placement of gel across the thickness of the cell which enables spatial anisotropic phase transitions to occur. This anisotropy in macromolecular architecture enables large scale changes in the optical properties (due to the chiral nature of the template fluid) of the as-formed gel due to localized responses of the gel near the phase transition temperature. Films which exhibit reflection across the visible and NIR spectral regions can be formed with a variety of reflection notch contrasts and bandwidths. We discuss the incorporation of helicoidal liquid crystalline polymer gels formed by anisotropically polymerizing a template LC monomer (LC mono and di-acrylates) in a cholesteric fluid. With proper design of the cell thickness, concentration of the material components, and molecular architecture of the polymer component, films which exhibit large scale tuning of the notch over 100's of nanometer's can be formed. Both light and heat have been utilized to dynamically tune the color of these naturally reflective films.

8279-20, Session 6

Observation of PDLCs by SHG laser scanning microscopy using a liquid crystal vector beam generator

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We have been focusing on liquid crystal optics for wave-front modulations over 20 years and have developed and delivered liquid crystal compensators for BD or DVD pickups and liquid crystal beam deflectors for laser printers in mass market. In this presentation, we will show our new study that applying liquid crystal optics to laser cofocal microscopes for generating z-polarized (which means polarized along with an optical axis) super-resolution beams. The liquid crystal cell is multi-aligned radially with 12 divided areas and when a linear polarized beam passes through the cell, a 12 directional divided radially polarized beam (vector beam) will be generate. By focusing the beam using high NA(>0.95) objective lenses, a z-polarized spot which is narrower than a diffraction limit spot of conventional x or y polarization appears in focusing area. Further more, a depth of focus of the beam is longer than that of x or y polarized beam. This means that we can use the z-polarized beam as z-probe of electrical fields. We have succeeded in observing a structure and molecular orientations of polymer-dispersed liquid crystal cells by SHG laser scanning microscopy that combined with liquid crystal vector beam generators. A SHG phenomenon should be occurred in surface boundary between LC molecules and polymer structure because inversion symmetric properties of LC molecules are collapsed in the surface boundaries. This method has an advantage of non-destructive measurement compared to SEM micrographs. Our next project is to apply a Laguerre-Gauss beam for resolution up.

8279-21, Session 7

A continous flow synthesis of micrometer sized actuators from liquid crystalline elastomers

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Liquid crystalline elastomers can be used for actuator applications. To realize strong shape changes, it is necessary to orient the mesogens into a liquid crystalline monodomain. This orientation step is crucial for the preparation of LC based actuators. Until now, methods like the drawing of fibers or the stretching of pre-crosslinked films have been used, yielding macroscopically structured actuators.

Using microfluidics, we realized a continuous flow synthesis of monodisperse particles from a liquid crystalline elastomer. In this approach a mixture of a liquid crystalline monomer with crosslinker and UV-initiator is molten and injected through a thin needle into a co-flowing stream of silicon oil. The resulting droplets are exposed to UV light while still flowing. This initiates polymerization as well as crosslinking, producing oriented elastomer particles. The size of the particles can, thereby, be controlled by several parameters. Thus we obtained particles with a diameter between 200 and 500 µm with a size variation coefficient as low as 1%.

Upon heating into the isotropic phase the particles change their shape from a spherical to a rod like conformation. Thereby length changes of more then 70% can be observed. The actuation is completely reversible and very fast. At present we focus on the tuning of the device parameters (flow rate, velicity gradients) to vary size, shape und type of orientation of these particles, which -in turn- determine the direction and the magnitude of the shape variation.

8279-22, Session 7

Switchable and responsive liquid crystal-functionalized microfibers produced via coaxial electrospinning

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Electrospinning is a technique for producing very thin polymer fibers and non-woven textiles by electrostatic means [1], rapidly gaining in interest during the last few years. This is largely due to the ease in producing micron and sub-micron diameter fibers, uniform or with core-sheath geometries where the core can also be made out of traditionally non-spinnable materials. We use coaxial electrospinning (one fluid spun inside another) to produce composite fibers with a core of liquid crystal inside a polymer sheath. The resulting fibers constitute an entirely new configuration for applying liquid crystals, giving the fibers functionality and responsiveness [2-4]. For instance, with a cholesteric core we can produce non-woven mats with iridescent color (see figure) that can be tuned (or removed) e.g. by heating or cooling [4].

I will describe our method of producing these novel functionalized fibers and their characterization by complementary methods, and I will discuss the directions for future research and application possibilities. Our main current aim is to develop the technology towards applications in dynamic fiber optics or in wearable electronics or other smart textiles, e.g. in clothing-integrated sensors.

References

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8279-23, Session 7

Thermal conductivity of native and oxidized lyotropic-like low-density lipoprotein solutions studied by using the Z-scan technique

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Low-density lipoprotein (LDL) is a particle composed by a phospholipid outer shell and triglycerides and cholesterol esters core. LDL plays a key role in cholesterol human metabolism. In vivo oxidative modifications in LDL promotes pro-inflammatory reactions, stimulating the production of atherogenic plaques. It is possible to distinguish native from in vitro oxidized LDL (oxLDL) samples using Z-scan (ZS) technique in ms time scale [1]. Part of the beam is absorbed and converted into heat, generating a refractive index gradient. The normalized transmittance, measured as a function of the sample position around the beam focus, furnishes a typical peak-to-valley curve characterized by the nonlinear parameter θ. It is proportional to the density, thermo-optical coefficient, specific heat, absorbance (α) and thermal conductivity (κ) of the sample. In this communication we report measurements of all these parameters of native and in vitro oxLDL with different oxidation times. Some of them were independently measured. We observed that α decreases with oxidation time. Native LDL presented $\alpha \sim 0.42$ cm-1 and oxLDL (70 minutes oxidation), $\alpha \sim 0.25$ cm-1. The decrease on θ as a function of LDL oxidation, observed in ZS experiments, could not be explained only by α decreasing. Using the thermal-lens model we determined the κ behavior of LDL upon oxidation. Our results show that native LDL solution has $\kappa \sim 0.05$ W/cmK and a 70 minutes oxLDL solution, $\kappa \sim$

0.40 W/cmK. Moreover, we observed that κ of oxLDL solution increases monotonically with oxidation time.

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8279-24, Session 7

Photo-responsive surface topology in chiral nematic media

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We report on the design and fabrication of thin coatings that exhibit dynamic changes in their surface topology in response to exposure to light. The principle is based on photo-induced reduction of the molecular order in chiral-nematic networks which causes a macroscopic expansion along the helix axis. Three types of chiral-nematic configurations were studied. A uniaxial strain along the surface of 20%, resulting in a periodic surface relief of about 1 um, was obtained in films that contain planar chiral-nematic areas next to homeotropic areas. The surfaces deform from flat to one with a surface relief under exposure with 365 nm light and reversibly deform to the initial flat state either by thermal processes or by exposure with white light.

8279-25, Session 7

The activated morphology of grain boundaries in nematic solid sheets

C. Modes, Univ. of Cambridge (United Kingdom)

We review the current understanding of stress-free, defect-driven deformations in thin sheets of nematic solids, from simple, isolated cone-forming +1 disclination defects to more complicated textures constructed from simple building-block domains. Further, by building from these textures we may investigate the effect that grain boundaries of various types have on the material deformation, leading to faceted tubes in some cases and lines of Gaussian curvature, instead of points, in others.

8279-26, Session 8

All-optical nonlinear photonic liquid crystal devices

A. E. Miroshnichenko, The Australian National Univ. (Australia); E. Brasselet, Univ. Bordeaux 1 (France); Y. Kivshar, The Australian National Univ. (Australia)

Rapidly growing field of photonics demonstrates the possibility of versatile control of light propagation in artificial media. Periodic structures provide an efficient way to spatially route light. Usually, photonic structures are designed and fabricated in view of specific properties that cannot be changed afterwards. An active control of light propagation in these structures is therefore highly desirable. It can be achieved by using the sensitivity of liquid crystals to external fields. One of the key issues towards smart integrated photonic circuits is to achieve all-optical switching where the propagation properties of the light will be controlled by light itself. Nematic liquid crystals are particularly interesting materials due to their infiltration capabilities and huge optical nonlinearities associated with molecular ordering. The most important phenomenon of light interaction with nematic liquid crystals is the light-induced Fréedericksz transition. It turns out, that the well-known properties pure nematic cell can be altered in the presence of periodic structures. In particular, the strong enhancement of the light excitation at defect modes leads to the spectral modulation of the optical Fréedericksz transition threshold within the photonic bandgap region with drastic threshold reduction at the defect mode wavelengths. Under a linearly polarized light field, the very nature of the optical Fréedericksz transition can be changed from the second to the first-order and multistability can be achieved. In this review we will cover various aspects of light interaction with nematics in periodic structures, such as a “defect mode boost mechanism” that corresponds to a transient optical field enhancement inside the liquid crystal defect during the reorientation process.

8279-27, Session 8

Laser beam steering (and beyond) with polarization gratings: review and prospects

M. N. Miskiewicz, J. Kim, M. J. Escuti, North Carolina State Univ. (United States)

Polarization Gratings (PGs) formed using nematic liquid crystals are highly efficient diffraction gratings, and act as thin-film polarizing beam-splitters. These PGs implement a truly linear phase (without 2pi resets) via the geometric phase, and offer many unique properties: 100% diffraction into a single order, polarization-selective first-orders, wide grating-period range, and broad spectral/angular response.

In recent years, we have intensely developed PGs for non-mechanical and mechanical laser beam steering, among other VIS/NIR/MIR/LIR devices, where high efficiency, novel polarization sensitivity, image preservation, and thin-film profile lead to significant advantages. In this work, we will review non-mechanical beam steering with polymer and switchable PGs, with a particular focus the experimental impact of liquid crystal anchoring on efficiency and uniformity. We will also explore the system impact of non-ideal diffraction efficiency, grating period, absorption, and non-ideal leakages via ray-tracing simulation, and directly relate them to the degradation in PG-based beam steering and other devices. We will mention mechanical beam steering results and novel applications in remote optical sensing systems. We will also discuss the prospects for PGs to offer significant performance advantages in defense and consumer applications, including primary challenges and opportunities.

While we (et al) have experimentally achieved ~100% efficiency (polymer and switchable), this has most often been at relatively small diffraction angles (ie, <= 10deg). Furthermore, the beam steering and display applications where PGs offer breakthrough advantages require larger diffraction angles (ie, up to 45deg). Here, we review how PGs behave at larger diffraction angles and with oblique incidence.

8279-28, Session 8

Electrical tuning of index-guiding photonic liquid crystal fibers

S. Ertman, T. R. Wolinski, Warsaw Univ. of Technology (Poland)

Photonic liquid crystal fibers (PLCFs) merges unique properties of the microstructured optical fibers with tunabilty of liquid crystal materials. In great majority of the previous works devoted to PLCFs a photonic band-gap propagation was investigated, since silica glass fibers' refractive index is lower than refractive indices of the most of liquid crystals. In this work we focus on the electrical tuning of the index-guiding photonic liquid crystal fibers. The most important advantage of the index-guiding propagation in the case of the PLCF is that the light scattering is significantly reduced since mode field is well localized in the fiber's core, and thus broadband and low-loss propagation is possible. To allow index-guiding our host fibers was specially tailored from various multi-component glasses, which refractive index was enhanced to values as high as 1.95.

In our work we discuss effect of the molecular alignment and orientation on the guiding properties of such fibers - from both theoretical and experimental point of view. Impact of the electric field on the light propagation in index-guiding PLCFs has been carefully studied and effective tuning of the phase birefringence, attenuation and polarization dependent losses has been observed experimentally. We will also present electrical tuning of the guiding mechanism, where application of the electric field to the index-guiding PLCFs changes its properties, that hybrid propagation is possible - depending on the polarization light is guided either by the index-guiding or photonic band-gap phenomena. We will also discuss other practical issues concerning index-guiding PLCFs in the context of potential practical applications.

8279-46, Session 8

Green digital signage using nanoparticle embedded narrow-gap field sequential TN-LCDs

S. Kobayashi, Tokyo Univ. of Science (Japan)

We fabricated field sequential LCDs using narrow-gap TN(NTN) embedded with nanoparticles that exhibit a wide color gamut of 110% of NTSC, 1000 nit at 220W/mxm. This figure may provide a good reference for Energy Star Program.

8279-30, Session 9

Simulation of a cholesteric blue phase in a thin cell: exotic defect structures and their response to an electric field

J. Fukuda, National Institute of Advanced Industrial Science and Technology (Japan); S. Zumer, Univ. of Ljubljana (Slovenia)

We investigate the structures of a highly chiral liquid crystal confined in a thin cell. We are interested in a liquid crystal that exhibits a cholesteric blue phase in the bulk. Our calculations are based on a Landau-de Gennes continuum theory describing the orientational order using a second-rank tensor. When the cell thickness is small enough, of the order of or smaller than the cholesteric pitch, and the surface anchoring is strong enough, the bulk blue phase structure is no longer stable. The stable structures of a liquid crystal in a thin cell found in our numerical calculations are quite different from those in the bulk blue phases. They include a parallel array of disclination lines of a double-helix form, and a hexagonal array of Skyrmions. Skyrmions are particle-like excitations in a continuous vector field and have been found to play an important role in various condensed matter systems such as a two-dimensional electron gas, and chiral ferromagnets. The stability of these structures sensitively depends on temperature, cell thickness, and the anchoring conditions at the cell surfaces. We also study the dynamics of such structures of a chiral liquid crystal in a thin cell when they are subject to an applied electric field. When a strong field is applied, the disclination lines are highly distorted by the field and rearrange themselves in a non-trivial manner. These studies would facilitate the understanding of the optical properties of cholesteric blue phases confined in a thin cell towards their possible photonic applications.

8279-31, Session 9

Novel materials for polymer-stabilized blue phase

M. Wittek, Merck KGaA (Germany)

Liquid Crystal Displays (LCDs) Displays based on polymer stabilized Blue Phase (PS-BP) liquid crystals are one candidate for the next generation display technology because of the advantages like ultrafast response in sub millisecond regime, alignment layer free process, optically isotropic dark state and cell gap independency. The pure blue phase (BP I) has a rather narrow temperature range of only a few Kelvin. To be used in a display application the system has to be polymer stabilized to yield a stable temperature range of 50 degrees or more.The underlying material technology is based on specifically developed LC mixtures in combination with so-called reactive mesogens.

The latest material developments regarding reactive mesogens and polar host systems are presented. The most important parameters for PS-BP materials are an optimised host system with a good polymer stabilisation. The optimum polymer stabilisation is realised when full stabilisation of the blue phase together with a low operating voltage is achieved. To realise that, a very good compatibility of the host with the RM system used - typically consisting of one mono-reactive and one di-reactive RM -has to be ensured.

To achieve a low operating voltage of the PS-BP display device, the material properties of the host - namely the product of the optical birefringence dn and the dielectrical anisotropy de - has to be optimised. New host developments yielding a largely increased dn * de > 40 at room temperature are presented.

8279-32, Session 9

Electro-optic and photonic properties of aerosils-dispersed blue phase liquid crystals

J. Hwang, L. Chien, Kent State Univ. (United States)

Aplicaitons for photonic crystals and metamaterials require advanced optical materials with tunability in visible spectrsum and high Q factors. Blue phase are mesophases that appear exclusively in chiral liquid crystals. The assembly of blue phase forming 3D periodic structures provide a 3D dielectric template of trapping sites for colloidal particles, typically in the body-centered (BPI)and simple-cubic (BPII). The aim of this work is to explore the nano-scaled colloidal particles of fused silica that can self-assemble into stable, 3D colloidal crystals in blue phase LCs. In this presentation, we will discuss the effect of functionality of the fused silica on the optical and electro-optical properties of the dispersed liquid crystal blue phases.

8279-33, Session 10

Anomalous deformation of smectic bubbles under DC electric field

Y. Tabe, Waseda Univ. (Japan)

Thin films composed of softly condensed matter such as biomembranes, soap bubbles and polymer films have been studied for long years from the points of view of both basic science and application. A common feature of these films is the coexistence of robustness and flexibility, which plays an essential role in their mechanical properties and functions. If an appropriate field is applied to the film, it will deform in response to the field, resulting from the balance between the restoring force and the induced force, from which we can derive the physical property of the sample coupled to the applied field. In order to observe the deformation of thin films, it is convenient to use bubbles rather than flat films because the deformation should be much larger.

Based on this idea, we studied the smectic bubbles deformation under DC electric field, and found two typical deformations depending on the magnitude of the applied voltage. Under lower DC field than a threshold, the bubbles exhibited a static deformation, which let us determine the surface tension, electric conductivity and capacitance of the sample. When the field exceeds a threshold, the bubbles start a periodic oscillation driven by the ionic motion in the bubble films. Since the oscillation is sometimes accompanied by a micro-sized bubble-jet, it may be used for such applications as microfluidics and drug delivery. The easily controllable deformation of the smectic bubbles directly shows us the physical properties of the smectic LCs and also offers the potential application of flexible LC devices.

8279-34, Session 10

Shape-controlled self-assembly of plasmonic colloidal nanoparticles and microparticles in liquid crystals

J. S. Evans, B. Senyuk, I. Smalyukh, Univ. of Colorado at Boulder (United States)

We study elasticity-mediated alignment and self-assembly of anisotropic gold colloids in liquid crystals. Colloidal gold particles of controlled shapes (spheres, rods, and polygonal platelets) and sizes are prepared using well-established biosynthesis techniques with varying solvent conditions. When introduced into liquid crystalline structured solvents, these gold particles impose tangential or vertical surface boundary conditions for the liquid crystal molecules or building blocks such as chromonic molecular aggregates. This allows for multiple types of their controlled alignment and self-assembly in both lyotropic and thermotropic liquid crystals and is of interest for self-assembly-based fabrication of tunable nanostructured composite materials such as optical metamaterials.

8279-35, Session 10

Defect-driven structures for self-assembly

M. J. Bowick, Syracuse Univ. (United States)

The study of the spontaneous organization of microscopic objects into mesoscale units (superatoms) is an active research area that offers challenges on many fronts. One goal is the design of superatoms from first principles, leading directly to the creation of a rich warehouse of raw materials from which to engineer supermolecules or bulk materials with potentially novel chemical, elastic, optical or electronic behavior. I will describe two fertile sources of superatoms: the self-assembly of micron scale colloidal particles on surfaces and the coating of metallic nanoparticles by organic ligands. In both cases the nature of the ordering unit (colloid or ligand) and the nature of the substrate are crucial. The substrate is almost always a curved surface with associated geometry and topology. The interplay between the spatial curvature of the substrate and the condensed matter order of the self-assembling units frequently leads to novel structures not found in planar monolayer ordering. Most striking of all is the appearance in the ordered state of defects for either topological or energetic reasons. Topological or energetic stability then prevents the defects from being annealed away. The distinctive mathematical, physical and chemical character of the environment surrounding defects makes them natural sites for chemical functionalization by linkers. In this way superatoms can link to form supermolecules and other complex structures at scales considerably larger than the typical angstrom scales governing quantum-mechanical bonding of atoms in standard molecules. The liberation from the restricted number of elementary atoms available for conventional chemistry opens up the brave new world of supramolecular chemistry and materials science. The number of defective regions available for functionalization determines the ``valence” of the superatom and the relative geometrical distribution of the distinct defective regions determines the directional bonding occurring in supermolecules and more complex bulk materials.

8279-36, Session 11

Photoalignment and photopatterning in liquid crystal photonics

V. G. Chigrinov, Hong Kong Univ. of Science and Technology (Hong Kong, China)

Almost all the criteria of perfect LC alignment are met in case of photoalignment materials developed by us. We have already used photoalignment materials to align LC in superthin photonic holes, curved and 3D surfaces and as cladding layers in microring silicon based resonators. We will discuss optical switches, beam steering devices, optically rewritable E-paper, LC lenses and sensors, and other photonics liquid crystal elements based on LC photoalignment.

A tunable-focus liquid crystal (LC) lens was proposed using variable pretilt angle in LC layer obtained by exposing the photoalignment layer by UV light. The focal length of the LC lens can be worked out according to the retardation profile and it is electrically tunable. LC lens is compact, lightweight, low-cost, and highly efficient. The applications in adaptive optics, optoelectronics, machine vision, 2D/3D switchable LCD, and eyeglasses are envisaged.

A fibre optic high voltage sensor for high power distribution systems based on monitoring the variation of reflectivity at a boundary between a cleaved fibre end and a LC has been developed and optimized. A thin high spatial resolution, photo-patterned micropolarizer array for complementary metal-oxide-semiconductor (CMOS) image sensors was implemented for the complete optical visualization of “invisible” objects, which are transparent and colorless.

The possible but not limiting applications of the new optically rewritable (ORW) liquid crystal devices (E-paper) based on photoaligning developed by us are light printable rewritable paper, labels and plastic card displays, as well as rewritable 3D paper for security applications.

8279-37, Session 11

Controlling the alignment of liquid crystals by nanoparticle-doped and UV-treated polyimide alignment films

S. Jeng, National Chiao Tung Univ. (Taiwan); S. Hwang, National United Univ. (Taiwan); T. Chen, H. Liu, National Chiao Tung Univ. (Taiwan)

We have developed two approaches to control the pretilt angles of liquid crystal molecules by using conventional polyimide (PI) alignment material either doped with different concentrations of Polyhedral Oligomeric Silsequioxanes (POSS) nanoparticles or treated with ultraviolet light irradiation. These techniques are very simple and are compatible with current methods familiar in the LCD industry. In this talk, we will present the characteristics of modified PI alignment films and their applications for photonic devices.

8279-38, Session 11

New developments in nanoparticle-liquid crystal composites: from magic-sized semiconductor nanoclusters to alignment pattern formation by nanoparticle stencilling

J. Mirzaei, R. Sawatzky, Univ. of Manitoba (Canada); M. Urbanski, Univ. Paderborn (Germany); A. Sharma, Univ. of Manitoba (Canada); K. Yu, National Research Council Canada (Canada); H. S. Kitzerow, Univ. Paderborn (Germany); T. Hegmann, Univ. of Manitoba (Canada)

We here report on the optical, alignment and electro-optic properties of a nematic liquid crystal affected by the presence of semiconductor magic-sized nanocrystals (MSNCs). Single-sized CdSe samples were tested, exhibiting bright bandgap photoluminescence (PL) with λmax = 463 nm. The quantum dot (QD) samples were passivated with a monolayer of myristic acid. Two of them (QD1 and QD2) only vary in the amount of defects indicated by different bandgap and deep trap PL. The third MSNC sample (QD3) is compositionally different, i.e. doped with Zn. These MSNCs with almost identical sizes were doped at different concentrations (1-5 wt%) into the nematic phase of 5-n-heptyl-2-(4-n-octyloxyphenyl)-pyrimidine (LC1). Only QD3 showed the formation of birefringent stripes surrounded by areas of homeotropic alignment between plain glass slides at all concentrations as observed for many other nanoparticle-doped nematic liquid crystals reported earlier by our group. In polyimide-coated glass slides favouring planar orientation of the nematic director, planar alignment was observed. Surprisingly, only the Zn-doped magic-sized QD3 quantum dots significantly lower the dielectric anisotropy as well as the splay elastic constant of the nematic host, despite identical size and surface functionality, which highlights not only the tremendous effect of the nanocrystal core composition on the electro-optic properties of the nematic host, but also that the segregation of nanoparticles (inducing homeotropic alignment) leads to more pronounced electro-optic effects. To investigate this further we also investigated the patterning of metal NP motifs by a process called stencilling that allowed us to generate patterns of homeotropic LC alignment in a continuum of planar alignment using a nematic liquid crystal. The electro-optical response of these patterned cells will be presented and discussed.

8279-39, Poster Session

Tunable multi-spatial frequency optical profilometry using single liquid crystal cell with micro-pinhold array

H. Kim, K. Joo, C. Park, K. Park, M. Park, H. Y. Noh, S. Kang, Kyungpook National Univ. (Korea, Republic of)

We demonstrate a tunable optical profilometry by using a single liquid crystal (LC) cell, where a micro-pinhole array is formed to generate multi-spatial frequency interference. Holographic profilometries reconstruct 3-dimensional surface profile of an object by measuring distorted fringe patterns projected onto a surface. However, in case of conventional optical surface profilometries utilizing fringe patterns with a single spatial frequency, the generated fringe patterns can be overlapped depending on the shape and the height variation of an object so that the ambiguity of the depth information can take place during extracting the depth information from the projected fringe patterns. On the other hand, conventional tunable multi-spatial frequency profilometries require bulky and high-cost spatial light modulators such as liquid crystal on silicone or digital micro-mirror devices. In this paper, to realize the multi-frequency and four-step phase shifting of the fringe patterns with a single LC cell, we formed the micro-pinhole array on the LC cell, where the phase retardation on each pin-hole is independently controlled by using patterned ITO structures. With the proposed structure utilizing multi-spatial frequency fringe pattern as well as four steps of phase shifting, the ambiguity of depth extraction can be eliminated and the accuracy of the depth extraction can be improved with a simple structure.

8279-40, Poster Session

Synthesis and mesomorphism of new 2-methoxy-3-cyanopyridine mesogens

A. V. Adhikari, National Institute of Technology, Karnataka (India)

ABSTRACT

In the recent years a large number of substances made of banana shaped molecules and revealing liquid crystalline properties have been synthesized and studied. They form a new class of thermotropic mesogens that exhibit mesophases. Most of the reported mesogens are resorcinols, biphenyls, terphenyls, naphthalenes and other symmetric and non-symmetric V-shaped structures have also been presented. Such molecules have usually contained two or three phenyl rings joined directly or connected through ester or imino or vinylic group. The incorporation of heterocyclic moiety into these molecules influences their liquid crystal properties.

Amongst various heterocycles, pyridines, pyrimidines, pyrazines, pyradazines, etc. have been used most commonly. Against this background, six bent-shaped compounds with the 2-methoxy-3-cyanopyridine as central core possessing an outer phenylene unit at the lengthening arm with different alkoxy chain lengths (C-10 and C-12) were synthesized and characterized by IR, NMR and elemental analyses. Mesomorphic behaviour of the new compounds was studied using optical polarizing microscopy, DSC and electrooptic techniques. Further, the structures of mesophases were identified by X-ray diffraction studies. Also, the effect of structural variables on mesogenic properties was investigated. Interestingly, all the six 2-methoxy-3- cyanopyridine derivatives showed good liquid crystalline properties and exhibit smectic phase. In these new heterocycles, mesomorphic properties were mainly due to the presence of cyano group on the central pyridine core and the properties could retain even after replacement of hydrogen atom of phenylene ring by methoxy or ethoxy group at one of the arms. Further investigations of their dielectric and nonlinear optical properties are in progress.

8279-41, Poster Session

Analysis of nanoparticles in controlling the vertical alignment of nematic liquid crystals

A. Choudhary, G. Li, Univ. of Missouri-St. Louis (United States)

Recently several new techniques have been developed to control the vertical alignment of nematic liquid crystals (NLCs) in the cell geometry such as multi-domain vertical alignment, dye doped photo-induced alignment, etc. But these techniques require complicated fabrication process or have limitations in some applications such as flexible display where alignment control becomes difficult. Nanoparticles (NPs) induced vertical alignment becomes prominent and is an active research topic due to the independence of alignment from the control of substrate surface. The mechanism has not been investigated. Here, we present a complete analysis of the dynamics of the NP-induced vertical alignment in the NLC material and its applications.

We have observed that the strong vertical anchoring of the LC molecules on the surface of NPs has large contribution in the orientation of the bulk NLC director up to long range. It has been observed in this analysis that the vertical anchoring of NLC molecules over the NP surface induces the anisotropic topological defect and the elastic constants have been found as a function of position vector and the angle between bulk and local NLC molecular director accordingly. This behavior of the elastic constants is sources of the enhancement in the elastic free energy which is helpful in making the coupling between two NPs (pair) mediated by the NLC materials. It has been shown that the orientation of this pair tends to orient the NLC director in between them and in beside scenario up to long range due to elastic properties of NLC.

8279-42, Poster Session

Characterization of a PDLC mixed with crystal violet dye

J. F. Villa-Manríquez, M. Ortiz-Gutiérrez, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); M. Pérez-Cortés, Univ. Autónoma de Yucatán (Mexico); J. C. Ibarra-Torres, Univ. de Guadalajara (Mexico); A. Olivares-Pérez, M. J. Ordoñez-Padilla, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

In this work we show the optical characterization of a Polymer Dispersed Liquid Crystal which was made mixing Norland Optical Adhesive No. 65, nematic liquid crystal and crystal violet dye, deposited between two glass substrates with indium tin oxide (ITO) as electrodes. In this device, we recorded low frequency (104 lines/mm) holographic gratings made with the interference of two beams from an Ar laser at 515 nm in emission line. We measured the diffraction efficiency of the gratings obtaining 6% when the grating was read with a beam from a He-Ne laser at 612 nm. We show some experimental results.

8279-43, Poster Session

Tunable optical filter based on nanocomposite (liquid crystal)/(porous silicon)

G. V. Tkachenko, Kharkov National Univ. of Radio Electronics (Ukraine); I. A. Sukhoivanov, Univ. de Guanajuato (Mexico); O. V. Shulika, Kharkov National Univ. of Radio Electronics (Ukraine); V. Tkachenko, Univ. degli Studi di Napoli Federico II (Italy)

Spectral characteristics of the interference optical filter based on a free-standing mesoporous silicon film containing nematic liquid crystal E7 are studied experimentally. The porous structure represents two distributed Bragg reflectors divided by a quarter-wave microcavity having resonance near 1600 nm. Transmission spectra of the filter are measured in the temperature range from 27°C to 80°C. For the temperatures less than 62°C (clearing point of the liquid crystal), we have observed continuous red shift of the microcavity resonant wavelength in the range of 11 nm. Measured thermal dependence of the shift has sharply increasing slope near the clearing point. For temperatures exceeding 62oC the microcavity resonant wavelength exhibits slow linear decrease. We have also investigated spectra of the filter using local heating of the sample with laser. Our studies have shown, that laser beam with power of 100 mW provides total tuning of the microcavity.

8279-44, Poster Session

Pretile angle control of liquid crystal from homogeneous to homeotropic alignment using photocurable pre-polymer

D. Kang, J. Lee, Soongsil Univ. (Korea, Republic of)

We study pretilt angle control of liquid crystal from homogeneous to homeotropic using phase separation technique of photocurable prepolymer by UV irradiation. Pretilt angle was controlled by change the weight ratio of LC/prepolymer in homogeneous PI coated LC cell. Homogeneous alignment was observed in a mixture of weight ratio of 99.9:0.1 after UV irradiation for 20 minutes. Tilted alignment was observed in weight ratio of 99.8:0.2. Finally homeotropic alignment was observed in weight ratio of over 99.7:0.3.

8279-45, Poster Session

Innovated shear stress sensing technique using liquid crystal

A. S. Abu-Abed, E. C. Lemley, A. Spivey, M. Jordan, S. Sah, S. Munoz, Univ. of Central Oklahoma (United States); S. A. Alboon, Yarmouk Univ. (Jordan)

For decades, the measurement of the dynamic shear stress has been a topic of great interest for many of fluid dynamics monitoring and diagnostics applications. In particular, shear stress monitoring is of crucial importance in biomedical, aircrafts, gas turbine, turbulent flow, and aerodynamics. The measurement of shear stress is critical in all these applications as it helps in delivering robust system design.

This paper presents a capacitive liquid crystal-based technique to measure wall shear stress. In this work, the authors have developed an alternative method which utilizes LC film embedded in an interdigital capacitive microstructure. This innovation will transduce the shear force, which deforms the LC profile, into a measurable capacitive quantity via tracking the LC deformation. This promising sensor has strong potential applications in bioengineering systems where monitoring the blood shear stress is critical such as carotid artery experiments. Some of the issues addressed in this work are the impact of the shear stress on the liquid crystal molecular ordering (order parameter) and the influence of electrode geometries and material properties on the measured capacitances.

The proposed mechanism replaces the present optical transduction techniques in LC-based shear stress sensors, and offers remarkable advantages over the conventional visual inspection optical methods. For example, it provides greater insight into the fundamental distortion occurring in the LC film due to the shear stress force, and offers the ability to identify and track the average deformation. In addition, a simpler system with autonomous operation and reduced possible false alarms is achievable.

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8280-01, Session 1

Recycling of light in LEDs with brightness increase and etendue reduction

K. K. Li, Wavien, Inc. (United States)

No abstract available

8280-02, Session 1

Arc lamps for high power digital projection

K. K. Li, G. X. Ouyang, Wavien, Inc. (United States)

No abstract available

8280-03, Session 1

MgO:PPLN based green lasers for portable laser projectors

Y. Lu, Q. Xu, C2C Link Corp. (Canada); Y. Gan, C. Xu, McMaster Univ. (Canada)

In portable laser projectors, high efficient, compact green lasers with an output power of more than 500 mW are needed. Intra-cavity frequency doubling of diode-pumped solid-state laser is an attractive method to obtain green light efficiently. MgO doped periodically poled lithium niobate (MgO:PPLN) is the most promising nonlinear crystal due to its large nonlinear coefficient, high optical damage threshold, and low cost. We have successfully developed intra-cavity frequency doubled green lasers based on MgO:PPLN. The laser is packaged in a simple packaging scheme, which is only composed of a 808-nm pump LD, a Nd:YVO4 crystal, and a MgO:PPLN. A plano-parallel cavity is utilized to reduce the total cavity length. It is shown that this simple structure can generate more than 500 mW green light with high wall-plug efficiency (nearly 20%) and small volume (3c.c.). The pump laser was a 3-W c-mount 808-nm LD. A 2-mm long 1 at.% Nd-doped YVO4 was employed as a laser medium. A 0.5-mm thick MgO:PPLN (made by CQ Laser Technologies Co., Ltd.) with a length of 1 mm was used as a frequency doubling crystal. The temperature tolerance of the 1-mm long MgO:PPLN is about 30 ºC. It is considered that the developed green lasers are suitable for portable laser projection application due to their excellent properties including high wall-plug efficiency, small size, low cost, and easy mass production.

8280-04, Session 1

MgO:PPLN frequency doubling optical chips for green light generation: from lab research to mass production

C. Xu, Y. Gan, J. Sun, McMaster Univ. (Canada)

Laser based displays have recently attracted much attention due to their potential applications in pico-projectors, portable projectors, and large screen display. In laser display, red, green and blue (RGB) lasers with low-cost, high wall-plug efficiency, and small size are required. Although red and blue lasers emitting from semiconductor chips are readily available commodities, but to date, semiconductor chips emitting green light with sufficient power and efficiency are not available on the market. Green light power of about 100 mW, 500 mW and several watts are required for pico-projector, portable projector and large screen application, respectively. It is considered that a practical solution to the "green" problem is to employ the diode pumped solid state laser (DPSSL) technology, in which a low-cost 808 nm semiconductor laser diode is used to pump a laser crystal to generate 1064 nm light, and the generated 1064 nm light is then converted to 532 nm light by a frequency doubling crystal. Despite the fact that the DPSSL is a mature technology with wide applications such as laser pointers, the conventional frequency doubling crystals (i.e. KTP: Potassium Titanium Oxide Phosphate and LBO: Lithium Triborate) cannot meet the strict cost/performance requirements for the laser display applications mentioned above. Therefore, developing frequency doubling crystals with low-cost, high conversion efficiency, and easy mass production is a key to the wide spread applications of the laser displays. In this paper, recently progress of MgO doped periodically poled lithium niobate (MgO:PPLN) frequency doubling optical chips will be presented. History of MgO:PPLN will be briefly reviewed. It will be shown that after two decades of significant R&D efforts around the world, MgO:PPLN is the one which satisfies all of the requirements for laser display and is ready for mass production.

8280-05, Session 2

Fast switching liquid crystal display modes

L. Komitov, Göteborg Univ. (Sweden); G. Hegde, Univ. Malaysia Pahang (Malaysia)

Important characteristics of the electro-optic response of the conventional nematic liquid crystal devices and displays are the switching rise and fall time, which usually are in the range of a couple of milliseconds. In many device applications of the liquid crystals, such as 3D LCD TV for instance, fast switching of the liquid crystal with both rise and fall time, being preferably in the microsecond region, is required for reduction of the motion blurs and color break up when color sequential illumination is used. We present several LCDs' switching modes enabling short response times, rise and fall time, being in the microsecond range in most of the modes. Extended surface/liquid crystal interface area, in the form of polymeric network, created in the liquid crystal bulk as well as the presence of flexoelectric polarization are among those employed for achieving of fast switching modes in LCDs. Proper assembling and electronic driving of two parallel nematic liquid crystal cells, arranged in a double cell and inserted between crossed polarizers, is another approach by means of which a fast switching mode between bright and dark state of the device is realized. We discuss these modes in terms of device performance and their suitability for application in LCDs.

8280-06, Session 2

Unusually large surface electroclinic effects in liquid crystals and the implications for ferroelectric liquid crystal displays

K. Saunders, California Polytechnic State Univ., San Luis Obispo (United States)

The surface electroclinic effect (SECE) is phenomenon in the chiral Sm-A* phase whereby a coupling between molecular dipoles and a surface induces local tilt of the smectic layer normal away from the surface rubbing direction. In chiral smectic devices, like ferroelectric liquid crystal (FLC) displays, the smectic layers should ideally be homogeneously aligned perpendicular to the cell substrates. The SECE makes such alignment challenging, and often necessitates carefully matched cross-rubbing of surfaces to compensate for the SECE.

Many FLCs show great technological promise given their unusually strong electro-optical response close to the Sm-A* -- Sm-C* phase transition. Among these FLCs, de Vries smectics are especially appealing due to the absence of layer shrinkage at the Sm-A* -- Sm-C* transition, which avoids chevrons and the related zig-zag defects. However, we show that the underlying physics responsible for the unusually strong electro-optical response will also lead to an unusually strong SECE. Such is the strength of the SECE, that if the enantiomeric excess (EE) of the FLC is gradually increased, there will be a jump in the induced tilt of the layer normal. We present a state map in EE - temperature space exhibiting a line of such discontinuities, terminating at a critical point. We discuss the implications of the unusually strong SECE and how it might be mitigated by careful tuning of the material and cell parameters. We also discuss how the SECE can be controlled through the application of an electric field as the system is cooled into the Sm-A* phase.

8280-07, Session 2

Dual mode operation of fast switching liquid crystal devices

D. H. Song, J. Kim, M. Jo, K. Kim, J. Lee, T. Yoon, Pusan National Univ. (Korea, Republic of)

We studied two types of bistable liquid crystal devices that can be operated in the memory mode as well as in the dynamic mode. One of them is a pixel-isolated twist-splay nematic LC cell that has two stable states of π-twist and splay. Polymer walls are formed at pixel boundaries by anisotropic phase separation between nematic liquid crystals and reactive mesogens. Operation in the memory mode can be achieved through bistable switching between the splay and π-twisted states. The other one is a bistable twisted-nematic mode that has two stable states of $-\pi/2$ and $+\pi/2$ twist. Three-terminal electrodes are used to apply both vertical and in-plane electric field to both devices. The proposed bistable modes has an infinite memory time and the fast transition time compared to other bistable liquid crystal modes.

8280-08, Session 3

A fast-switching contrast-enhanced liquid crystal polarization modulator for high-end single-lens stereoscopic 3D projector applications

J. Osterman, LC-Tec Displays AB (Sweden); C. Ward, Lightspeed Design, Inc. (United States); T. Scheffer, Motif, Inc. (United States)

A fast-switching, contrast-enhanced liquid crystal polarization modulator suitable for time-multiplexed stereoscopic 3D applications is presented. By using a double-cell structure together with a dedicated driving scheme and an external quarter-wave retarder, fast powered switching between two polarization output states with completely symmetric operation between left and right eye images, including high extinction at all wavelengths for the dark states, can be achieved. The modulator is especially attractive for the use together with high-end DLP-based single-lens stereoscopic 3D projectors and enables high-brightness, low-ghost viewing using lightweight and comfortable circular passive 3D eyewear. A theoretical benchmarking with other modulator configurations is conducted.

The main principle of the proposed modulator is to use two LC cells that are arranged in optical series in such way that the second cell compensates the first one to exhibit a combined property of not changing the state of polarization of normally incident light passing through them. This not only holds for the field-off state of both cells, but is also valid if the same voltage is applied to both cells as well as if the applied voltage is changed from one voltage level to another and the liquid crystal material in the cells relaxes to the new voltage level in tandem. The specific optical configuration uses a combination of two ECB (Electrically Controlled Birefringence) LC cells operating at the half-wave plate condition together with an external passive quarter-wave retarder.

8280-09, Session 3

Optical characterization of different types of 3D displays

P. M. Boher, T. Leroux, T. Bignon, ELDIM (France)

All 3D displays have the same intrinsic method to provide depth perception, provide different images in the left and right eye of the observer to obtain the stereoscopic effect. The three most common solutions already available on the market are active glass, passive glass and auto-stereoscopic 3D displays. The three types of displays are based on different physical principle (polarization, time selection or spatial emission) and consequently require different measurement instruments and techniques. In the proposed paper, we present some of these solutions and the technical characteristics that can be obtained to compare the displays.

8280-10, Session 3

Effect of Petzval curvature in integral imaging display

G. Baasantseren, L. Choimoo, National Univ. of Mongolia (Mongolia); J. Park, Chungbuk National Univ. (Korea, Republic of)

Integral imaging (InIm) is interesting research area in the three-dimensional (3-D) display technology because it is simple in structure and it can show full color, and full parallax. However, the InIm display has drawbacks such as shallow depth, narrow viewing angle, and resolution. InIm display uses simplest lens array, so displayed 3-D image has distortions because of lens array. A dominating distortion is a Petzval curvature. In the first, we analyzed an effect of the Petzval curvature in InIm display. Main effect of Petzval curvature is that depth plane of InIm display becomes the curved plane array because each lens creates one curved plane. From the results of simulation and experiment, the effect of Petzval curvature reduces a depth range, changes a viewing direction, reduces a viewing angel, and increases a black stripe. Therefore, InIm display using conventional lens array does not display the correct 3D image. The full explanation and the experimental verification of the proposed method will be provided at the presentation.

8280-11, Session 3

Three-dimensional floating display by a concave cylindrical mirror and rotational wedge prisms

G. Park, J. Kim, K. Hong, B. Lee, Seoul National Univ. (Korea, Republic of)

We design a 3D floating display system using the DMD, a concave cylindrical mirror (CCM), wedge prisms, and a lenticular sheet. DMD can be used to project a large number of directional images to many directions in real-time. And the CCM can float images from the DMD at the position by the lens formula in the polar axis of the CCM. A directional image from the DMD should show an image which should be seen in a specific direction. To project directional images to the respective directions, wedge prisms and motor driving are used. A wedge prism can deviate a beam to a different angle in the longitudinal plane from the incident angle. We drive an electric motor to rotate wedge prisms. The rotation of the wedge prisms makes the deviation angle of the incident images to the wedge prisms change. Deviated images are reflected and distorted by the CCM. The image distortion is similar to that in anamorphosis. To correct the distortion caused by the CCM, inversely distorted images are generated by ray tracing method and those images are projected to the CCM. The exit aperture size and diverging angle of the DMD are not big enough to cover the vertical positions of viewers. In other words, a viewer can see only some lines from the DMD. To solve this problem, a lenticular sheet is attached to the CCM, and used to diffuse images in only vertical direction. Specific information and further explanations of each component will be provided and experimental results will be presented for verification.

8280-12, Session 4

Performance of correlated speckle patterns for speckle reduction in laser projectors

S. V. Egge, U. L. Österberg, A. Aksnes, Norwegian Univ. of Science and Technology (Norway)

If the arc lamp in standard display projectors is replaced by lasers, the projector can gain several advantages like small etendue, miniaturization potential, multiplexing possibilities, improved color gamut, higher contrast, deeper focus, and higher brightness. Coherent by nature, the laser also adds one significant disadvantage to the projector: the presence of speckle, which manifests itself as noise-like intensity fluctuations over the image. To obtain a good viewing experience, these fluctuations should be reduced below a certain threshold.

The speckle contrast is a measure of the presence of speckle. To reduce this presence, the coherence should be decreased either temporally or spatially. In this paper, we look into reduction of spatial coherence by rotating a diffraction pattern on a diffuser. Discrete variation is first considered, and then the theory is further developed to continuous rotation. The theory is applied to a specific example which involves a sinusoidal grating. The advantage of such a grating is that the zeroth order can be extinguished without loss of power. Hence, no part of the diffraction pattern remains stationary when rotated.

In this paper we present an overview of formulas for speckle contrast which are functions of the correlations between individual speckle patterns. A more general formula for arbitrary diffraction patterns is also shown. Furthermore, the influence of the diffraction pattern's complex amplitude distribution on the speckle contrast is investigated. The results show that it is possible to obtain a good reduction of speckle contrast even with a significant overlap of positions on the diffuser.

8280-13, Session 4

High luminance tapered diode lasers for flying-spot display applications

G. Blume, D. Feise, Ferdinand-Braun-Institut (Germany); C. Kaspari, LayTec AG (Germany); A. Sahm, K. Paschke, Ferdinand-Braun-Institut (Germany)

Flying-spot display applications require high luminance (> 100 TCd/m²) red-emitting lasers. High luminance is defined as a high optical output power and a nearly diffraction limited beam quality at a wavelength with a good visibility of the human eye. Diode lasers, with all their beneficial properties such as direct modulation capability, small size and good electro-optical efficiency, are so far unable to achieve such high luminance, due to catastrophic optical mirror damage (COMD) caused by high facet loads.

We will present tapered diode lasers emitting near 635 nm with a larger vertical waveguide to lower the facet load and to alleviate the COMD risk. The lateral structure consists of an index-guided ridge waveguide section for lateral mode filtering, and a gain-guided tapered section for the amplification of radiation and a further reduction of the facet load. The tapered lasers are mounted p-side down on diamond heat spreaders and on copper heat sinks.

We achieved an optical output power of 1.1 W at 635 nm at a laser temperature of 5°C. The emitted beam is nearly diffraction limited (M^2(1/e^2) 85%). At 635 nm the eye sensitivity is 148 lm/W according to the CIE 1931 photopic eye response curve. Hence, we achieved a luminous flux of 168 lm and a luminosity of 108 TCd/m^2. At the conference, we will present design strategies and latest results of our research on visible, high-luminance diode lasers.

8280-14, Session 4

Collimation of asymmetric laser diode at 405 nm using multimode fiber for speckle reduction through diffractive diffusers

W. Thomas, C. Middlebrook, Michigan Technological Univ. (United States)

Advancements in laser diode technology have lead to their utilization in pico-projector systems. These newly developed devices will need to take full advantage of the source coherence - infinite focus, more distinct color - while lessening the negative effects that can occur. Previous work has been completed analyzing 532 nm green diodes in conjunction with hadamard-matrix diffusers in reducing the disruptive speckle noise caused by coherent sources. In addition to the speckle, many small form factor laser diodes have aspheric or non-symmetric beam shapes upon excitation. Collimation and beam symmetry is critical to keep power in the lower order diffractive modes that are formed through beam shaping optics such as diffusers and micro-lens arrays. However, non-circular beam shapes are difficult to collimate accurately. Due to unique diode structure, generic spherical lenses alone will not suffice, leading to new techniques for laser diode beam collimation. This paper looks at creating the proper beam shape through the use of multimode fibers. The output beam from the fiber is then passed through a lens for collimation prior to incidence on the diffuser surface. Speckle contrast measurements will be measured and analyzed for both rotating and stationary instances of the diffuser. These results will be compared with previous speckle contrast values obtained from other laser diode types. A rigorous investigation into the effects of collimation techniques on final speckle contrast will be conducted. In addition, other techniques for creating more functional beam shapes will be evaluated in comparison with the mutimode fiber setup.

8280-15, Session 5

Vertical-field-driven polymer-stabilized blue-phase liquid crystal display mode by using two prism sheets for lower operating voltage, higher brightness, and hysteresis-free switching

H. Kim, Y. Kim, Kyungpook National Univ. (Korea, Republic of); S. Hur, Kyung Hee Univ. (Korea, Republic of); J. Park, D. H. Park, Kyungpook National Univ. (Korea, Republic of); S. Choi, Kyung Hee Univ. (Korea, Republic of)

A novel polymer-stabilized blue-phase liquid crystal device (PS-BPLC) driven by a vertical electric field is demonstrated in this paper. By attaching two prism sheets on the top and the bottom substrates, the normal incident beams can be transformed into oblique ones, which make it possible to obtain grayscale property also in using a uniform vertical field for field-induced retardation. Generally, conventional BPLC devices employ in-plane switching (IPS) method since the amount of retardation increases along an electric field direction by Kerr effect, which means that the incident polarization cannot be changed regardless of the applied field amount when the vertical-field scheme is used in conventional cell structure. The conventional IPS PS-BPLC mode has several problems: low optical efficiency, high operation voltage, and high hysteresis property, which are due to limited aperture ratio by the IPS electrodes, low electric field amount near the top substrate, and non-uniform electric field distribution. In this paper, we demonstrate the vertical-field-driven PS-BPLC mode, of which operation voltage can be lowered by about 20 V, brightness can be enhanced to become twice, and hysteresis problem can be completely eliminated. These properties can be obtained by utilizing uniform vertical electric fields and eliminating patterned electrode structure required in IPS schemes. Our simple structure and switching scheme for PS-BPLC mode can be applied to display applications requiring fast response time, such as 3D display panels, shutter glasses for 3D TV, and color sequential driving displays, etc.

8280-16, Session 5

Temperature independent low voltage polymer stabilized blue phase liquid crystalline

E. Kemiklioglu, Kent State Univ. (United States)

Blue phases are types of liquid crystal phase which can appear in a temperature range between a chiral nematic phase and isotropic liquid phase. In this study, we showed the stabilization of blue phases over a temperature range of 30.4 0C including room temperature. We observed the temperature independent of Bragg wavelength. Furthermore, the polymer effect on the electo-optic properties of a self assembled nano-structured blue phase liquid crystal composites have been investigated. As well as the ratio between two monomers, the overall monomers concentration is controlled. We demonstrated low switching voltage polymer stabilized blue phase (PSBP) liquid crystal device.

8280-17, Session 5

Pixel structure for higher optical efficiency in the patterned vertical alignment LC mode

B. W. Park, E. Jeon, K. Kim, J. Kim, D. H. Song, J. Lee, T. Yoon, Pusan National Univ. (Korea, Republic of); G. S. Lee, K. Shin, H. S. Kim, SAMSUNG Electronics Co., Ltd. (Korea, Republic of)

Several liquid crystal (LC) modes, such as twisted nematic, vertical alignment (VA), and in-plane switching, are in competition with each other in the LC display market. Among them, the VA mode has been widely used because of the high contrast ratio. However, disclination lines at the boundaries between domains lower the transmittance in the VA mode. Although micro-slit patterned electrodes have been employed to enhance the transmittance of the patterned VA mode, crossed disclination lines at domain boundaries still reduce the light throughput. In addition, the brightness is decreased at the edges of the pixel because the angle between LCs and the transmission axes of polarizers is less than 45°.

In this paper, we propose a new pixel structure for high transmittance in the patterned VA mode. We form the protrusion structure on the top substrate to reduce the width of disclination lines at the domain boundaries. In addition, we design the electrode structure on the bottom substrate to improve the transmittance at the edges of each pixel.

8280-28, Poster Session

Flexible signboards based on optical waveguides

S. Park, M. Kim, S. K. Park, K. Kyung, Electronics and Telecommunications Research Institute (Korea, Republic of)

We propose and realize a flexible signboard to display numbers, letters, and simple patterns. The signboard consists of light sources, optical waveguides, and scatters. The waveguides and scatters are formed in a thin polymer film which has a good flexibility and a thickness of less than 100 μm.

The principle of the flexible signboard follows as; the light signals generated from the light sources are coupled to the optical waveguides, transfer to the scatters, and emit to air. If the thin film including the waveguides and scatters is an elastic polymer, the signboard could have a good flexibility.

We designed the flexible signboard to display numbers(1,2,3), letters(ㄱ,L,C), and patterns(*,+,#). The sizes of the letter and the signboard are 0.3cm x 0.3cm and 3cm x 3cm, respectively.

We fabricated the flexible signboard by use of the elastic polymers. Firstly, the under cladding and core polymer are spin-coated on a Si wafer and cured by UV, respectively. Secondly, optical waveguides and scatters are formed by the photolithography and reactive ion etching process. Thirdly, the cladding polymer is spin-coated on the optical waveguides and cured. Finally, the polymer film is detached from the Si wafer.

In order to display the patterns, we use the red light with a 632nm-wavelength. The fabricated signboard displays the designed pattern images with a good flexibility.

8280-29, Poster Session

Volume diffraction of nanostructured optical media

S. Han, W. J. Maeng, C. Shin, H. Lee, S. Lee, Samsung Advanced Institute of Technology (Korea, Republic of)

Recent advances in optical nanostructures provide a wide variety of new materials having unique dispersion characteristics in frequency and spatial domains. Photonic crystals have various band structures and dispersion phenomena. Surface plasmons and metamaterials allow very broad, subdiffraction-limited equifrequency dispersion spaces and their active modulation; the rich properties of refraction and diffraction in such media enable negative refraction, subwavelength imaging like hyperlens, and many special devices using transformation optics. Here, we exploit those unusual optical properties for enhancing volume diffraction responses throughout the nanostructured optical media. By carefully designing phase matching conditions over the dispersion equifrequency surfaces, high resolution and active diffractive elements for future display application become possible.

8280-30, Poster Session

Extremely simple holographic projection of color images

M. Makowski, I. Ducin, K. Kakarenko, A. Kolodziejczyk, M. Sypek, Warsaw Univ. of Technology (Poland)

A very simple scheme of holographic projection is presented with some experimental results showing good quality image projection without any imaging lens. This technique can be regarded as an alternative to classic projection methods. It is based on the reconstruction real images from three phase iterated Fourier holograms. The illumination is performed with three laser beams of primary colors. A divergent wavefront geometry is used to achieve an increased throw angle of the projection, compared to plane wave illumination. Light fibers are used as light guidance in order to keep the setup as simple as possible and to provide point-like sources of high quality divergent wave-fronts at optimized position against the light modulator. Absorbing spectral filters are implemented to multiplex three holograms on a single phase-only spatial light modulator. Hence color mixing occurs without any time-division methods, which cause rainbow effects and color flicker. The zero diffractive order with divergent illumination is practically invisible and speckle field is effectively suppressed with phase optimization and time averaging techniques. The main advantages of the proposed concept are: a very simple and highly miniaturizable configuration; lack of lens; a single LCoS (Liquid Crystal on Silicon) modulator; a strong resistance to imperfections and obstructions of the spatial light modulator like dead pixels, dust, mud, fingerprints etc.; simple calculations based on Fast Fourier Transform (FFT) easily processed in real time mode with GPU (Graphic Programming).

8280-31, Poster Session

Polymer waveguide technology for flexible display applications

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We consider applications of wave-guiding technologies for flexible displays. First, a flexible backlight can be constructed by guiding laser light through an optical fiber arranged in a spiral manner. The light leaks out via the grooves fabricated on the optical fiber. For uniform illumination, the probability of light extraction at each groove and the pitch of the grooves are adjusted. Second, a polymer waveguide with successive branches distributes the optical power from a laser to two-dimensional emission points on a plane. The division ratio at each branch is an important design parameter for uniform light output. At each branch and emission point, a mirror is placed for 90-degree optical path redirection. This constitutes a flexible backlight. Third, in a more technically demanding design, a mirror based on the micro-electro-mechanical systems technology scans a laser beam on the entrance surface of the waveguide and each emission point is addressed sequentially. An image can be displayed by intensity modulation of the laser light synchronized to this scanning action. The precision of the waveguide fabrication and the beam scanning accuracy would determine the display resolution. Finally, such a waveguide may be applied for concentrated photovoltaic applications. An array of lenses is stacked on the waveguide so that the optical power is focused on each mirror. The direction of the light propagation is reversed. Now the exit surface of the waveguide is coupled to solar cells. In all these cases, the polymer waveguide technology offers a cost advantage due to its feasibility for the roll-to-roll process.

8280-18, Session 6

Strategy for developing high efficiency backlight module for LCD

C. Chen, P. Yao, National Tsing Hua Univ. (Taiwan)

Liquid crystal display(LCD) currently shares the majority of consumer market among different display technologies. Nevertheless, there remains a lot room for improvement on the relevant technologies, especially the efficiency issue. The major loss of efficiency results from the absorption in polarizer and color filter, and both can be resolved with decent backlight design which takes light polarization and spectrum separation into consideration. There exists commercial technology dealing with polarization recycling and some others underdeveloped, whereas systems capable of color separation, either temporally or spatially, are mostly research prototypes. Anyhow, these two tracks of technology are being developed in parallel but are rarely put together as a total solution for efficiency improvement. The combination of these two technologies is not trivial because the modulation and control of light behavior must be compatible. This paper will present our past and current research work on polarizing and color-filterless backlight module, as well as the effort on merging these two technologies together. The concept of light modulation and design process of both technologies will be introduced firstly with the demonstration of corresponding prototype performance, followed by the schematics of an all-in-one backlight module capable of both polarization recycling and spatial color separation. Our strategy for developing high efficiency backlight module for LCD will be elucidated with this technical description on the historical development path.

8280-19, Session 6

Modernizing the technology for controlling light, both laser and broadband, with diffractive waveplates

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The ability to print high quality, large area diffractive waveplates (DWs), with optical axis patterning at high spatial frequencies, has allowed us to demonstrate electro- and all optically controlled systems. These systems overcome the main drawbacks of typical liquid crystal devices, such as absorption and high driving voltages. We show that the capability of DWs to modulate broadband unpolarized light, combined with other functional optical films such as photonic bandgaps, allows their use not only for switching laser beams, but for display applications as well, including reflective displays. We have developed materials with fast and reversible photoalignment properties that enhance both the fabrication technology and the functionality of DW-based optical systems.

8280-20, Session 6

Integrated optical means based on waveguide for hologram recording

K. P. Pyun, Samsung Advanced Institute of Technology (Korea, Republic of); A. A. Putilin, P.N. Lebedev Physical Institute (Russian Federation); A. Morozov, Samsung Electronics Co., Ltd. (Russian Federation); G. Sung, S. Lee, Samsung Advanced Institute of Technology (Korea, Republic of)

The proposed paper relates to holographic optical elements that are used for recording micro holograms with usage of laser source of coherent radiation. Such devices for micro holograms recording are used for recording of information presented in digital view into light sensitive materials for future storage and reconstruction of recorded information.

Important characteristic of recording devices is overall active volume of device optical part. The challenging task is to provide considerably less volume of recording device optical part at the cost of using integrated optical elements. Almost all existing solutions have a big quantity of different optical elements divided by air spacers, the relative positions of all these elements affects on working efficiency of whole device. We propose a scheme providing fundamental improvements of the basic scheme in parts of overall device sizes, quantity of elements and combined functionality of each element. The main advantages of proposed solution are as follows: First, this solution utilizes various integral optical elements, where each element is a united not adjustable optical element, replacing separate and adjustable optical elements with various forms and configurations. Second, geometrical form of integral elements provides small sizes of whole device. Third, geometrical form of integral elements allows creating flat device. And finally, absence of adjustable elements provides rigidity of the whole devices. The usage of integrated optical means based on waveguide holographic elements allows creating a new type of compact and high functional display devices for consumer usage.

8280-21, Session 7

Design and implementation of wearable head-up display for mobile phone applications

Y. Takashima, T. Tran, L. Hesselink, Stanford Univ. (United States)

Recently, mobile phones take an indispensable role for communication. Users communicate via multiple combinations of information, such as voice, text, images, videos combined with auxiliary information, for example meta-data embedded in pictures and GPS data. Providing that, we expect that a sophisticated way to present rich information in mobile environment would be crucial as the amount and complexity of information further increase.

Large potion of information handled by mobile phones is related to information of user's point of interests (POI). In mobile environment, displaying POI related information by augmenting visual imagery and information on a see-through image is an attractive way to handle the data. Thus, Head-up Displays (HuD) is especially an interesting solution in a mobile environment. However, HuDs are in general bulky and expensive, which prevents them from being adopted as display devices for mobile phones

In this work, we propose, design, and implement a light-weight and low cost HuD for mobile phone applications. A virtual image of flat display device is formed by a curved surface of eye-glasses having no optical power for the see-through image. On the see-through image, the virtual image is superimposed. We constructed a ray trace model consisting of display, eye protection goggles followed by experimental evaluations of image quality as a function of image distance. Full field of view of 40 degrees, image distance of 300 mm is feasible by employing spherical surface with radius of about 50 mm. Effects of aspherization and pre-distortion technique on image quality will be also addressed.

8280-22, Session 7

Transfer-printing of colloidal quantum dots for full-color light-emitting display

B. L. Choi, T. Kim, K. Cho, E. K. Lee, J. W. Kim, S. Y. Lee, J. M. Kim, Samsung Advanced Institute of Technology (Korea, Republic of)

Light-emitting displays with colloidal quantum-dot (QD) have recently received considerable attention due to advantages of QD property such as high quantum yields, extremely narrow emission, spectral tunability, and a higher stability than other existing luminophores. However, the difficulty of patterning red, green, and blue (RGB) pixels of three individual QDs with controlled interfaces has prevented from developing a full-color QD display with acceptable quantum efficiency.

In this talk, the issues of QD EL and successful embodiment of full-color QD display by the solvent-free transfer printing of QD pattern will be presented. Modulated QD assemblies exhibit the excellent morphology, well-ordered QD structure, and clearly defined interfaces, which result in significant enhancements in the charge transport/balance in the QD layer. A large-area full-color QD displays on a glass substrate, and even on a flexible substrate can be realized in this manner with the control of nano-interfaces and carrier behaviors.

8280-23, Session 7

Designing low permeability optical grade silicone systems

M. Velderrain, NuSil Technology LLC (United States)

Unprotected electronic components exposed to moisture from high humidity may fail due to corrosion of metal leads or other unfavorable reactions on chemically sensitive components. This is of high interest for silicones that encapsulate LED dies. For these applications moisture and oxygen may react with materials such as phosphor used to make white LEDs for back lighting applications and decrease or change the light output and color over time. Of the polymeric adhesives and sealants commercially available, silicones are used for their thermal stability, clarity and that they have a comparably low modulus that provides stress relief during thermal cycling. However they are also known to be very permeable to low molecular weight gasses such as water vapor and oxygen. Recently silicones several types of silicones were tested for the oxygen and water vapor transmission rates and it was found that they can have drastically different results. Silicone properties strongly affecting permeability are the polymer backbone chemistry, crosslink density, and fillers. Phenyl (C6H5) and trifluoropropyl (CF3CH2) groups are used to optimize the refractive index of optically clear silicones. The relationship between chemical composition on the Water Vapor Transfer Rate at 400 C and 90% Relative Humidity as well as oxygen was investigated on several silicones with various refractive indices and compared to polydimethylsiloxane (PDMS) with similar hardness's. It was found that the polymer backbone chemistry had a significant influence on the permeation rates and will assist in material selection when designing for low permeable barriers to improve package reliability.

8280-24, Session 7

Versatile electrowetting display arrays: from small to large pixels on fixed and flexible substrates

H. You, A. J. Steckl, Univ. of Cincinnati (United States)

Electrowetting (EW) is the modification of surface wetting properties (which is typically hydrophobic) with an applied electric field, resulting in rapid manipulation of liquid on a micrometer scale. EW applications have recently been developed, such as optical filters, adaptive lens systems, lab-on-chip, and reflective displays. EW reflective displays have many advantages: very thin, switching speeds suitable for video, wide viewing angle, low power levels. Furthermore, EW displays have been demonstrated on flexible substrates1.

EW display prototypes were constructed with pixel sizes ranging from 50 µm × 150 µm to 2 mm × 2 mm. Colored oil dosing of the arrays was achieved by dip coating the substrate through an oil film suspended on water. The operation of EW displays on different materials used for either fixed or flexible substrate will be described, including glass, metal sheet, paper and plastic. The operation of devices driven by either DC and AC voltage will be reported. The transmission of EW display prototypes can be modulated from ~5% (zero bias) to >70% (~16 V AC), while the reflection can be modulated from ~10% to >70% with the same voltage change. The switching speed depends on the oil properties and cell size, typically ~ 10 ms for 300 µm × 900 µm pixel cells.

These characteristics indicate the promise of EW approach as the technology basis for versatile portable displays.

1 A. J. Steckl, D. Y. Kim, and H. You, SPIE Newsroom, (DOI:10.1117/2.1201012.00343), Dec. 2011.

8280-25, Session 7

Electrically-tunable optical zoom system using liquid crystal lenses

Y. Lin, M. Chen, H. Lin, National Chiao Tung Univ. (Taiwan)

An electrically tunable-focusing optical zoom system using composite liquid crystal (LC) lenses is demonstrated. The optical zoom system by adopting two composite LC lenses consisting of a sub-LC lens and a planar polymeric lens shows large zoom ratio, and the object can be zoomed in or zoomed out continuously at the objective distance of infinity to 10 cm. The optical principle is investigated. The applications of the optical zoom system are not only on an imaging system but also on projection system. The electrically tunable zooming pico-projector is also demonstrated in this paper.

8280-26, Session 7

A thin porous substrate using bonded particles for reverse-emulsion electrophoretic displays

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A thin porous layer of bonded ceramic microparticles has been developed to provide structural integrity and a stationary matrix for use in reflective-mode reverse-emulsion electrophoretic displays (REED), based on self-assembled nanodroplets dispersed in a non-polar liquid. REED ink uses low-cost materials and manufacturing processes, yet is capable of video speed and low voltage operation below 10 V. Porous layers of titanium dioxide (TiO_2) are prepared as thin as 10 microns by fluidizing the particles in a water-based slurry with polymeric adhesive. The slurry is distributed between glass shear plates, one of which serves as the substrate for the working device. Particle morphology is examined using scanning electron microscopy and layer uniformity is characterized by opacity measurements using a throughbeam fiber optic sensor. Performance of the bonded matrix with REED ink is compared to baseline performance of a paste mixture, comprised of the same ink and unbonded TiO_2 particles. Results show that at 25% volume fraction, the bonded substrate improves image bistability and is better able to maintain both light and dark intensity after extensive switching. The same bonded substrate also improves image bistability when power is disconnected, even compared to a paste with 40% volume fraction of TiO_2.

8280-27, Session 7

High performance natural semiconductors for green organic electronics development

M. Irimia-Vladu, E. D. Glowacki, G. Voss, L. Leonat, G. Schwabegger, M. Bodea, H. Sitter, S. G. Bauer, N. S. Sariciftci, Johannes Kepler Univ. Linz (Austria)

Organic electronics has a tremendous potential for the development of electronic products that are non-toxic and environmentally friendly biodegradable. An ideal solution is the production of such devices either from naturally occurring or from nature-inspired materials that have been proved to be biodegradable and/or biocompatible. Such semiconductor materials have been recently implemented in organic photovoltaics and field effect transistors, and afforded performances on par with state-of-the-art synthetic organic materials. Among the materials we have exploited are naturally-occurring Indigo and Tyrian Purple as well as synthetically produced indigoids, anthraquinone derivatives, acridones, to name a few. We have demonstrated fully-biodegradable devices and circuits featuring natural substrates, dielectric and semiconducting layers operating at state of the art performance.

Conference 8281: Practical Holography XXVI: Materials and Applications

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8281-01, Session 1

PVA glue as a recording holographic medium

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PVA (Polyvinyl acetate) glue is one of the most common forms of adhesive on the market, which is popular because it has an ability to adhere to many different surface, but besides in this research we shown that can be employed as polymeric matrix and is employed for holographic recording when this is doped with ammonium dichromate.

An thin uniform coating of photopolymer is generated by gravity settling method. The drying time for the photosensitive layers is approximately 24 h. Therefore, we present the experimental results obtained through diffraction gratings that were recorded using a laser of He-Cd (442 nm). Furthermore the average results of the diffraction efficiency parameter which is quantified by their first orders of diffraction.

The PVA with glue with ammonium dichromate can be considered as versatile holographic recording media due to their good sensitivity, low cost and itself developing process.

8281-02, Session 1

Photosensitive holographic material with a medium of fluorescent ink

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Recent researches have been reported that is possible increase the diffraction efficiency parameter from holographic gratings when photosensitive material (PVA with ammonium dichromate) it is painted after register the hologram with commercial fluorescent ink.

In this research we shown that PVA as a binder, with the fluorescent ink and ammonium dichromate, this mixed can be used as recording medium. We characterize this material by implementing holographic films in which holographic gratings are recorded with a He-Cd laser at 442nm, and measuring holographic parameters such as diffraction efficiency. We get increased the diffraction efficiency and also the lifetime of the film.

8281-03, Session 1

Photochromic materials for holography: issues and constraints

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Photochromic Materials change reversibly their color, when exposed to light of specific wavelength (usually in the UV-vis). Since irradiation drives a molecular rearrangement, it follows that many other physical-chemical properties other than color change (refractive index, redox potential, IR absorption,...). The variation of refractive index which takes place in the NIR region, can be exploited to write phase holographic elements, whereas the strong change in transparency that occurs in the visible can be exploited to make amplitude holograms. The holograms based on these materials are rewritable and self-developing. A strong modulation of these properties is obtained optimizing the chemical structure of the photochromic material and increasing as much as possible the content of the photochromic units in the material. An interesting approach aimed at achieving a large property modulation, while preserving the optical properties, is the development of photochromic polymers, where the switching units belong to the main polymer chains. The writing of these photochromic substrates to be used in holography evidences that the thickness that can be fully converted in the uncolored/colored form is limited due to the strong absorption of the materials. It turns out that the writing step is strongly nonlinear and the intensity light pattern is not reproduced, but a completely different conversion pattern results through the volume of materials. Results on holographic optical elements based on photochromic diarylethenes will be reported showing the efficiency and the open issues.

8281-04, Session 1

Performances of new green sensitive liquid photopolymers for volume phase holographic gratings

A. Zanutta, A. Bianco, G. Pariani, INAF - Osservatorio Astronomico di Brera (Italy)

Liquid photopolymers are interesting materials for holography; Polygrama-Lynx produces such materials sensitive in the blue - red range. We focus the attention to green sensitive photopolymers, in particular SM532TR and SM532TRF. In order to test material performances, volume phase holographic gratings (VPHGs) have been realized. The substrates were prepared by placing a thin liquid film between two glass slides and using microspheres to control the thickness. The gratings were written using a Lloyd's mirror holographic set-up with a 532 DPSS laser. During the writing step, the grating zero order efficiency has been monitored by means of a red laser. Different samples have been realized, varying the line density (600 - 2000 l/mm), the laser power density, pre- and post- exposure treatments, maintaining in all cases the overall optical quality of the substrates. The grating performances were measured mainly in terms of efficiency at different wavelengths (in both s and p polarizations) and at different angles. Film thickness and refractive index modulation have been determined applying to the experimental efficiency curves the Kogelnik model and/or the RCWA approach. The main results showed refractive index modulation up to 0.008 and 0.03 for SM532TR and SM532TRF photopolymers, respectively. It is therefore possible to obtain, with the latter photopolymer, wide efficiencies curves with peaks larger than 90% useful for spectroscopic instrumentation.

8281-05, Session 1

Holograms with nitrocellulose and FeCl3

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Hologram of transmission with nitrocellulose is used as matrix and ferric chloride as photosensitizer. To record holograms, we use the line 442 nm of laser He-Cd. We describe the behavior of the diffraction efficiency of holographic gratings based on the parameters of energy, concentration ratio, and thickness. This material shows the behavior of phase modulation and amplitude modulation at the same time.

8281-06, Session 2

Wide viewing-zone-angle hologram generation using phase-shift hologram capturing method for holographic media communications

R. Oi, Y. Ichihashi, K. Yamamoto, T. Senoh, T. Kurita, National Institute of Information and Communications Technology (Japan)

Recently, auto-stereoscopic displays are intensively investigated. Holography is one of the most promising methods to satisfy the whole clues of human's 3D vision.

In our group, we are researching a high-resolution phase-shift hologram capturing method for a holographic image/video communication. Once the hologram is captured by a CCD, the data are processed in the computer for eliminating conjugate images and for converting pixel pitches between input and output holograms. Finally, the generated hologram is reconstructed by an optical holographic display which uses high-resolution LCD (Liquid Crystal Displays) in order to reproduce a 3D image volume in the space.

During a phase-shift hologram capturing, if we use multiple reference beams those incident angles are slightly different to each other, the viewing-zone-angle of the phase-shift hologram can be expanded by few times compared to the original.

In the experiment, a phase-shift hologram was captured using the 3 reference beams by 5.6 degree spacing with 8000 × 4000 resolution CCD image sensor. Reconstruction optics also uses three incident angles of illumination beams in order to enlarge horizontal viewing zone angle of that hologram. The SLM is 4.8micron pixel pitch, 7680 × 4320 resolution LCD. We observed a 20mm height of holographic reconstructed object image with 16 degree of viewing-zone-angle in horizontal direction. The viewing-zone angle was magnified by three times and the conjugate image was properly eliminated by the processing in this experiment.

8281-07, Session 2

Measurements of accommodation responses to horizontally scanning holographic display

M. Yokouchi, Y. Takaki, Tokyo Univ. of Agriculture and Technology (Japan)

Because holography can reconstruct the wavefront of the light emitted from an object, eyes can focus on holographically generated three-dimensional (3D) images; thus, eye accommodation is considered to function properly for holographic 3D images. However, the measurement of the accommodation responses to 3D images generated by electronic holographic displays have not been reported, because their viewing zone angle and screen size are limited, thus rendering it difficult to observe the reconstructed 3D images with both eyes.

We have developed a horizontally scanning holographic display that enables the increase of both horizontal viewing zone angle and screen size. In this technique, a series of elementary holograms, which are generated by a high-speed spatial light modulator (SLM) and projected by an anamorphic imaging system to reduce the horizontal pixel pitch and increase the vertical image height, are scanned horizontally by a galvano mirror on the display screen to increase the image width. The use of a digital micromirror device as the high-speed SLM operating at the frame rate of 13.333 kHz enabled the demonstration of the horizontal viewing zone angle at 14.6° and the screen size at 4.3 inches. The reconstructed images can be observed with both eyes.

In this study, we measured the accommodation responses to the 3D images generated by a horizontally scanning holographic display. We found that the accommodation responses to the 3D images displayed within 400-450 mm from the display screen were similar to the responses to real objects.

8281-08, Session 2

Depth perception and user interface in digital holographic television

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A holographic television system, featuring realtime incoherent 3-D capture and live holographic display, is used for experiments in depth perception. Holographic television has the potential to provide more complete visual representations, including smooth motion parallax and more natural affordances for accommodation. Although this technology has potential to improve realism in many display applications, we investigate benefits in uses where direct vision of a workspace is not possible. Applications of this nature include work with hazardous materials, teleoperation over distance, and laparoscopic surgery. In this study, subjects perform manual 3-D object manipulation tasks where they can see the workspace only through holographic closed-circuit television. Performance at manual tasks using holographic television is compared to performance with displays that provide 2-D images, and stereoscopic television with two and multiple views.

8281-09, Session 2

Transmission of hologram data and 3D image reconstruction using white LED light

K. Sato, M. Tozuka, Shonan Institute of Technology (Japan); K. Takano, Tokyo Metropolitan College of Industrial Technology (Japan); M. Ohki, Shonan Institute of Technology (Japan)

Transmission of hologram is very important to realizing the holographic 3D TV.

Transmission of Computer Generated Hologram(CGH) data using SSTV wire-less method is tried before and one frame with 76.8k bit data is transmitted by 2kbps is reported.

We thought that white color LED wireless light optical transmission and illumination system is useful for hologram 3D TV. We considered about high speed transmission and high resolution hologram data transmission using white color LED light. We could get good contrast reconstructed image.

This time we consider about using same white color LED to illuminate CGH and reconstruct image.

8281-10, Session 2

Across light and through colour

M. I. Azevedo, M. J. Richardson, De Montfort Univ. (United Kingdom); L. M. Bernardo, Univ. do Porto (Portugal)

The speed at which our world is changing is reflected in the shifting way artistic images are created and produced. I use the medium of holography to express my perception of space with light and colour, to make the material / immaterial with experiments utilizing digital holography.

This paper is my personal reflection on the final product of that process surrounding a debate of ideas for new experimental methodologies applied to holographic images. Holography is a time-based medium and the irretrievable linear flow of time is responsible for a drama unique to traditional cinematography. If the viewer moves to left or right, they see glimpses of the next scene, or see again the one perceived a second ago. This interaction of synthetic space makes us ask questions such as ‘Can we see in “reality” two shapes in the same space? To this end I have developed a series of work titled “Across Light & Through Colours” embryonic to a series of digital art holograms and lenticulars. The technique employed to create these works required some technical research and comparison between effects from different camera types.

Keywords: Digital Holography, time-based medium, camera types.

8281-11, Session 3

Instantaneous shape measurement of moving surface with high accuracy by one-shot digital holography

K. Sato, Y. Iwayama, Univ. of Hyogo (Japan)

Instantaneous measurement of shape of various kinds of moving objects is strongly required in industry. Present methods such as optical stylus, confocal microscopy, and grating projection have limitations as, for example, complexity in optical systems, not enough robustness, and measurement time. In digital holography, both amplitude and phase of light reflected from objects can be recorded by simple setups without imaging lens, and their 3-D distributions with no-distortion can be reconstructed numerically. The digital holographic interferometry has been studied for the shape measurement of rough surface until now. It, however, is not possible to measure the shape of moving objects in the principle because two holograms are required for the interferometry.

We develop a new method for non-contacting and instantaneous measurement of 3-D shape of moving rough surface by using one-shot digital holography that improves capability of phase-shifting digital holography. The present method consists of projection of interference fringes with a constant period on rough surfaces, one-shot recording of the complex-amplitude in-line hologram, reduction of speckle from reconstructed images, and calculation of depth from focus. It is possible to measure the complicated shape of moving objects with a large depth at once by the present method. We calculate 3-D position of each measured point on the surface by the method of depth from focus. Measurement with high accuracy is achieved by reducing speckles into a low level. Optical experiments of depth measurement are carried out to demonstrate measurement with a small error ratio.

8281-12, Session 3

Real-time recording and reconstruction of moving 3D images using electronic holography

K. Furuichi, K. Sato, Univ. of Hyogo (Japan)

A technology of one-shot digital holography has recently developed for instantaneous extraction of the complex-amplitude hologram from one off-axis hologram applying simple data processing. This one-shot holography is applicable to recording of 3-D images of moving objects or of changeable phenomena for the holographic television in future, because it enables us to capture the complex-amplitude holograms in real time when pulsed lasers are adopted as reference light sources.

Purposes of the present paper are to record images of a moving object by adopting a pulse laser, and to demonstrate the recording and the reconstruction of moving 3-D images in real-time by the electro-holography. A holographic recording system with a high-power pulse laser is developed for recording time-sequential 3-D images of moving objects by applying the one-shot digital holography. Off-axis holograms are recorded sequentially by adopting CCD camera, and hologram data recorded are transmitted to a computer where the 0-th order and the conjugate beams are eliminated by the fast and simple data processing. The digital output signals from the computer are transmitted to the holographic LCD display system to reconstruct the moving 3-D images. Optical experiments are carried out to demonstrate the recording and the reconstruction of 3-D images in real time: the complex-amplitude holograms are recorded under the room lighting, and moving 3-D images are reconstructed from the holographic LCD display system.

8281-13, Session 3

Full parallax computer generated hologram using GPU-accelerated ray tracing method

T. Ichikawa, Y. Sakamoto, Hokkaido Univ. (Japan)

Computer Generated Hologram (CGH) is made by simulating the light wave from the virtual object in the computer. In CGH, hidden surface removal is needed for displaying multiple 3D objects. Some methods have been proposed as hidden surface removal such as the wave optics way using a silhouette mask, the geometric optics way that applying Z buffer of the CG (Computer Graphics) technique to CGH, and so on. However, these methods are unsuitable to make realistic images that have complicated the reflection, refraction and shadowing.

Therefore we propose a calculation method using the ray tracing method. The reflection and refraction can be faithfully reproduced by the ray tracing method though the algorithm is very simple. The ray tracing method is avoided ever in CGH having a very high resolution because of enormous calculation cost. However, the calculation within realistic time became possible by improving a recent computer performance. So we introduce the technique to apply the ray tracing method to CGH. In this study, hologram plane is divided into elementary holograms, and the center of each elementary hologram is made the starting point of the ray. Then, the light wave of elementary hologram is obtained by making sets of point light at each elementary hologram using the ray tracing method. Besides, we report an acceleration method using GPU because our algorithm is suitable for the parallel computation. By optical reconstructions, it was confirmed that hidden surface removal was done when plural objects were in one scene.

8281-14, Session 3

Multi-color full field imaging in low coherence digital holographic microscopy

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In off-axis digital holographic microscopy, the short coherence length of the light source reduces unwanted parasitic interference and provides optical sectioning of a microscopic object. However, this is obtained at the expense of a reduced field of view, because interference between the off-axis reference and on-axis object beams occurs only over a fraction of the detector area. We propose and experimentally demonstrate an inline diffractive optical element (DOE) that provides full field of view at multiple wavelengths. The DOE is based on a combination of high efficiency transmission volume phase gratings holographically recorded into a thin photopolymer. The multiplexing capability of the DOE allows to manipulate the coherence plane tilt of the reference beam at a plurality of wavelengths simultaneously. By providing a coherence plane tilt of the reference beam equal to the crossing angle between the object and reference beams, interference occurs over the full detector area. We experimentally demonstrate full field of view imaging by inserting the DOE device in the reference arm of an off-axis low coherence digital holographic microscope (DHM). An axial resolution of 9 nanometers and unambiguous depth recovery up to 2.5 micrometers over the full field of view is achieved with a two color DHM at 685 nanometers and 795 nanometers.

8281-15, Session 3

Ray-casting CRT algorithm for holographic 3D display with full parallax occlusion effect

X. Liang, Y. Pan, X. Xu, A*STAR - Data Storage Institute (Singapore)

Holographic 3D display is believed to be the only technology capable of providing all depth cues, which human vision system (HVS) can sense. Several holographic 3D display systems have been demonstrated successfully. Currently, most of the systems are based on computer generated hologram (CGH), as it can be calculated directly from virtual 3D object. However, if the relative positions of the primitives are not taken into consideration during computation, the occlusion effect will disappear. In this paper, a full parallax occlusion algorithm for holographic 3D display is developed. The motion parallax and occlusion effect of the reconstructed 3D object are successfully demonstrated. In this new algorithm, the ray-casting, directional clustering and vertical angle marking technologies are integrated with coherent ray tracing (CRT) algorithm for hologram computation. By applying the vertical angle marking technology, only a single pass of the entire horizontal viewing angle is needed to compute full parallax occlusion. The algorithm complexity is reduced by about a half as compared to standard occlusion algorithm. The standard occlusion algorithm considers the entire range of both horizontal and vertical viewing angles. Compared to conventional CRT computation which does not consider occlusion effect, our new algorithm also increases the computation speed to about 350%.
The algorithm is able to work with any forms of 3D data. The optimal horizontal angular resolution has been identified as 0.007 degree for our system. Various 3D objects with full parallax occlusion effect are reconstructed optically.

8281-16, Session 3

Shading of holographic reconstructed image by two-dimensional amplitude modulation of zone plates

T. Kurihara, Y. Takaki, Tokyo Univ. of Agriculture and Technology (Japan)

We propose a technique to shade reconstructed images of electronic holography. Our technique modifies the zone plate technique, which represents a three-dimensional object as an aggregate of object points, and zone plates, which generate spherical waves conversing to object points, are summed to calculate a hologram.

Our technique is based on the Phong reflection model developed for computer graphics, which assumes that light reflected from an object consists of three components: diffuse reflection, specular reflection, and ambient light. The intensity of the diffuse component of light is determined by the angle between a light vector and a normal vector of an object surface, that of the specular component is determined by the angle between a view vector and a reflection vector, while that of the ambient component is constant.

A holographic reconstructed image changes depending on the viewing direction. Therefore, among the three reflection light components, the specular component changes for different viewing directions. Because light modulated by a zone plate converges to an object point, we assumed that light is redirected differently at each point on the zone plate. Therefore, two-dimensional amplitude modulation of the zone plate would generate an object point that emits light with different intensities in different directions. Then, specular reflection would change for different viewing directions.

The proposed two-dimensional amplitude modulation comprises variable and constant modulation: the former controls the specular light component and the latter controls the diffuse and ambient ones. We experimentally verified the proposed technique.

8281-17, Session 3

A hard-threshold based sparse inverse imaging algorithm for optical scanning holography reconstruction

F. Zhao, X. Qu, Xidian Univ. (China); X. Zhang, Institute of Automation (China); T. Poon, Virginia Polytechnic Institute and State Univ. (United States); J. Liang, Xidian Univ. (China)

The development of specific fluorescent probes has promoted the renaissance of optical microscopy in tissue and cell biology, while the complicated three-dimensional structure of tissue or cell requires a high axial and lateral resolution in three-dimensional optical microscopy. Both confocal microscopy and optical coherence tomography can deliver two-dimensional optical images with superior axial resolutions, but the axial and lateral scanning is a time-consuming process. Optical scanning holography (OSH) is a technique which integrates three-dimensional object into a two-dimensional hologram through a two-dimensional optical scanning raster. The advantage of high axial resolution and fast image acquisition offer it a great potential application in three-dimensional optical microscopy, but the prerequisite is the accurate and practical reconstruction algorithm. Conventional marching filter, Wiener filter and Wigner filter methods were adopted to reconstruct sectional images, and obtained fine results, but their drawbacks restricted their practicality. An optimization method based on L2 norm obtained more accurate results than that of the conventional methods, but the utilization of the smooth operator blurs the reconstruction result, and memory-cost of matrices multiplication is also a serious problem. In this paper, a hard-threshold based sparse inverse imaging algorithm is proposed to improve

the sectional image reconstruction. The proposed method, which is characterized by adaptive hard-threshold iterating with exponential function, only involves lightweight vector operations and matrix-vector multiplication. The performance of the method has been validated by real experiment, which demonstrated great improvement on reconstruction accuracy at appropriate computational cost.

8281-18, Session 3

Phase retrieval of THz radiation using set of 2D spatial intensity measurements with different wavelengths

N. V. Petrov, V. G. Bespalov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Using infrared matrix of photodetectors (Ophir Pyrocam) and THz band pass filters (Tydex) allow to record the 2D intensity distribution of THz radiation with a high degree of monochromatization. This allows use a different approaches to solve the phase problem, developed for the visible frequencies. In this contribution we present the results of the numerical simulation of the wavefront reconstruction using THz radiation at several wavelengths and recording at various distances.

8281-19, Session 4

Applying field mapping refractive beam shapers to improve holographic techniques

A. V. Laskin, V. Laskin, AdlOptica Optical Systems GmbH (Germany)

Performance of various holographic techniques can be essentially improved by homogenizing the intensity profile of the laser beam with using beam shaping optics, for example, the achromatic field mapping refractive beam shapers like piShaper. The operational principle of these devices presumes transformation of laser beam intensity from Gaussian to flattop one with high flatness of output wavefront, saving of beam consistency, providing collimated output beam of low divergence, high transmittance, extended depth of field, negligible residual wave aberration, and achromatic design provides capability to work with several laser sources with different wavelengths simultaneously. Applying of these beam shapers brings serious benefits to the Spatial Light Modulator based techniques like Computer Generated Holography or Dot-Matrix mastering of security holograms since uniform illumination of an SLM allows simplifying mathematical calculations and increasing predictability and reliability of the imaging results. Another example is multi-colour Denisyuk holography when the achromatic piShaper provides uniform illumination of a field at various wavelengths simultaneously.

This paper will describe some design basics of refractive beam shapers of the field mapping type and optical layouts of their applying in holographic systems. Examples of real implementations and experimental results will be presented as well.

8281-20, Session 4

In-line hologram reconstruction with Hartley transform and iteration

M. Ozcan, Sabanci Univ. (Turkey)

In in-line recorded holograms where the object wave and the reference wave is parallel it is not trivial to separate the object image from others. Since the highest resolution is provided by the in-line recording it is important to find an effective way to isolate the object image. For this purpose there has been several methods developed over the years such as the phase shifting, digital filtering and iteration methods.

All of these methods have limitations while the phase shifting method would be the most general one which requires at least three hologram recordings with a different reference wave phase in each hologram.

Here we propose a new method to isolate object wave in in-line holography using just two consecutively recorded holograms.

The method involves the use of Hartley transform on the difference of the recorded holograms and combination of a phase retrieval type of an algorithm. Two cases will be presented, case 1: there will be a quadrature phase shift in the reference beams' phase between the recordings, and case2: there will be a 180 degree phase shift in the reference beams' phase in between the recordings.

A suggested experimental setup and simulation results are presented.

8281-21, Session 4

Novel modulation techniques for coaxial holographic data encoding

P. S. Chung, City Univ. of Hong Kong (Hong Kong, China); W. Jia, Shanghai Institute of Optics and Fine Mechanics (China); Z. Chen, T. Chung, F. Wen, Y. T. Chow, City Univ. of Hong Kong (Hong Kong, China)

We describe two novel modulation techniques for coaxial holographic data encoding, employing a spatial light modulator (SLM) based on twisted nematic LCD. In the Fourier transform holographic storage system, the reference beam in the coaxial outside part and the object beam in the inside part are simultaneously modulated by one single SLM, with different modulation techniques. One of the modulation methods is to phase modulate the reference beam and amplitude modulate the object beam. The reference beam is first modulated with a circular blazed grating pattern, then diffracted into the central part to interfere with the object beam. Multiple holograms can be recorded on the same location with reference beams of different grating period. Another modulation method is to modulate both the reference beam and the object beam with pure phase modulation by the SLM. The binary ones, representing the object and the reference beams, are encoded with random phase shift from 0 to 2π, while the binary zeroes, representing the background, are encoded with a constant phase of 0. On the Fourier transform plane, the binary zeroes will generate a high intensity dc component. As long as the dc component of the spatial frequency is blocked, a homogeneous hologram will be obtained, and the amplitude object will be reconstructed directly. In this paper, both of the two modulation methods are performed theoretically and experimentally. These techniques are demonstrated to be attractive for applications in data storage and encryption systems.

8281-22, Session 4

The volume hologram printer to record the wavefront of a 3D object

O. Miyamoto, T. Yamaguchi, H. Yoshikawa, Nihon Univ. (Japan)

We have studied the fringe printer as the output device of a computer-generated hologram (CGH), and have realized the high resolution CGH. However, since the fringe printer can only output a transmission hologram, the large-scale reconstruction system is necessary to realize the full parallax and full color CGH. As a method of the simple reconstruction, it is only necessary to use a volume hologram which has wavelength selectivity. However, the making of a volume hologram needs to transfer a CGH by use of an optical system. On the other hand, the holographic stereogram printers are known as the output device of a volume hologram, and have realized the full parallax and full color hologram. However, the reconstructed image gets blurred when the recorded object depth is large. This is attributed to the sampling rays of the 3D object. Therefore, in this study, we propose the volume hologram printer to record the wavefront of a 3D object. Thereby, the reconstructed image is observed more naturally. In addition, to transfer the CGH which is displayed on the LCoS, the proposed printer can output a volume hologram which has full parallax. The printed volume hologram has been able to reconstruct a monochrome 3D object by white light. In addition, we showed that the large volume hologram is able to be printed by transferring plural CGH which recorded dividing 3D object in turn.

8281-23, Session 5

Adaptation of holoprinter technology to fabricate a holoscreen for a fixed-frame animated 3D holographic display

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A holographic display containing a fixed number of frames is presented. The display system comprises a holographic screen, a controller and an illumination subsystem. The holographic screen contains a fixed number of pre-configured interference patterns that are spatially multiplexed and interleaved across its surface. Any of the stored holograms can be reconstructed simply by shining a pattern of light on to the holographic screen, and changing the pattern changes the reconstructed image. This can be done in any sequence or combination to make simple 3D animations.

A holographic display based on transmission holograms fabricated using classical analogue holography has already been reported. Whereas this approach had good results, it is not easy to make, being a manual process, and relies on the use of physical objects. This work looks at making a second-generation holographic screen using digital holoprinter technology which has a number of inherent advantages including reflection mode holograms, synthetic models and automated manufacture. A holoprinter is a holographic printing machine that produces digital reflection holograms, or stereograms, as a matrix of small pixels, or holopixels. A scheme to reconfigure the digital holoprinter to produce a set of independent interleaved holograms is proposed, implemented and the resulting holographic screen is measured.

The first generation display used a laser projector to both illuminate and form patterns on on the transmission mode holographic screen. The current display system uses classical illumination combined with an optical shuttering sub-system to do the hologram selection. The optical shuttering is provided by an LCD screen.

8281-24, Session 5

Holographic fabrication of graded index materials for transformation optics applications

K. Ohlinger, Univ. of North Texas (United States); Z. Poole, Univ. of Pittsburgh (United States); Y. Lin, H. Zhang, Univ. of North Texas (United States); K. Chen, Univ. of Pittsburgh (United States)

Transformation optics approaches to optical material design have tremendous potential for use in arbitrary design in a wide range of applications, including cloaking, and other tailored light interactions. One oft implemented transformation parameter is that of the index of refraction. In practice this can be a difficult parameter to control in three dimensions. One approach is sub-wavelength patterning of binary materials systems by direct laser writing. The local density of the material is controlled by the scan routine to achieve an effective index of refraction within the bounds of the two component materials. The direct writing approach has its limitations when attempting large scale monolithic structures and scaled efficiency as a consequence of its serial processing. One answer to this shortcoming is that of holographic fabrication, which offers the potential for rapid, parallel processing. This communication presents on local density control of holographically formed interference structures by coupling a single optical optical element top-cut prism with a spatial light modulator (SLM) to individually address voxels. The phase control afforded by SLM is used to directly influence the interference structures filling fraction. The available design landscape, fabrication tolerance, and a proof of concept demonstration are presented.

8281-25, Session 5

A compact holographic recording setup for tuning pitch using polarizing prisms

J. Kim, R. K. Komanduri, M. J. Escuti, North Carolina State Univ. (United States)

We introduce and demonstrate a new polarization holography technique for tuning pitch of the polarization hologram utilizing multiple polarizing prisms. Conventionally, polarization holograms/ gratings have been fabricated by an interference of two orthogonally polarized beams. This method requires large room and several elements such as polarizing optics; moreover the relative distance between these optics increase as larger active area is needed, that limits the range of grating period achievable, and is not commercially viable. To overcome the above limitations, we propose new approaches that are scalable, and can reduce the exposure distance significantly by using multiple polarizing prisms. The technique does not need a bulky holographic setup so it while maintaining a compact working space. The method can be used for recording two dimensional space-variant polarization holograms as well since a stack of the multiple prisms can make locally various hologram patterns. We demonstrate the polarization holography technique and compare our approach with conventional methods.

8281-42, Session 5

IHMA widens its remit: why this matters to you

I. M. Lancaster, Reconnaissance International Ltd. (United Kingdom)

The formal objective of the International Hologram Manufacturers' Association is "to represent and promote the interests of hologram manufacturers and the hologram industry worldwide." The IHMA has grown its membership 300 since its founding in 1993 and now has 95 members worldwide. Reflecting the commercial focus and growth of the holography industry with embossed holography for security, packaging and related applications, most of these members are surface-relief hologram producers. This membership growth (members represent around 80% of significant hologram producers) demonstrates the value that these producers place on their membership of the Association.

The IHMA recognises that holography is changing, and while surface-relief holograms still predominate this is not the only type of hologram being produced commercially, and nor are security and packaging the only commercially viable applications for holography. Accordingly, the IHMA has adopted a new mission statement to reflect this changing holographic world.

The Mission of the IHMA is to support, set standards for and advance holography through promoting and encouraging the understanding, use and development of holograms and holographic technology for:

the authentication of products and documents

decoration and illustration

displays and display systems

data storage and processing

energy systems

environmental improvements

healthcare

and other fields that emerge as potential applications of holography

for the protection and benefit of individuals and society at large.

This paper will show why the Association has adopted this broader Mission Statement, then move to examine the role of a wider-reaching industry association and the benefits that this can bring to hologram producers and practitioners in all these fields of holography.

8281-26, Poster Session

Hologram pattern of the electromagnetic wave diffraction from a pyramidal horn antenna

M. Ohki, Shonan Institute of Technology (Japan); K. Takano, Tokyo Metropolitan College of Industrial Technology (Japan); M. Tozuka, K. Sato, Shonan Institute of Technology (Japan); S. Kozaki, Gunma Univ. (Japan)

In the microwave band, the radiated wave from the pyramidal horn antenna is calculated in the diffracted field by the Fresnel approximation. In addition, the Fresnel approximation has been

introduced into the diffracted field with half infinite diffraction plane. This phenomenon is examined compared with the experiment value based on a hologram interpretation.In this report, the electromagnetic diffracted field with the pyramid horn antenna is calculated as the first stage under the Fresnel approximation. As a result, the hologram was made by interfering with the reference wave whose obtained diffracted field and angle of incidence are 60[deg] on the computer. It can be interpreted that this is one computer generated hologram. Moreover, the image that this hologram pattern is reconstructed in optics with the He-Ne laser was obtained.

8281-27, Poster Session

Two-dimensional signal processing using morphological filter for holographic memory

Y. Kondo, Y. Shigaki, M. Yamamoto, Tokyo Univ. of Science (Japan)

The practical use of the hologram memory is expected as next generation's large capacity and high-speed memories. However, it is necessary to examine the nonlinear filter processing because nonlinear bit error factors may exist in the reconstruction signal. Up to now, the researches such as QMMSE filters and Volterra Equalizer have been studied as a nonlinear filter. The filter processing that used the morphological operation as a signal processing method is first applied to hologram memory in this paper.

The filter processing by morphology is achieved by combining basic operations of Opening and Closing that combines the Dilation processing and the Erosion processing. In the hologram memory, because the signal is recorded cutting the high frequency element by a Nyquist's space filter, the signal edge is not clear by intersymbol interference between each bit. Because the edge can be detected in the morphological operation, it is possible to bring it close to former signal by removing the interference part of the reproduction image. In this paper, the experiments on a multiple hologram recording was carried out using photopolymer material. As a result, it is confirmed that the signal quality is greatly improved by applying morphology filter to the hologram memory.

8281-28, Poster Session

Acceleration of calculation method for CGH with spherical basic object light by using graphic processing units

K. Hosoyachi, Y. Sakamoto, Hokkaido Univ. (Japan)

A computer generated hologram(CGH) is hologram made by computer simulation. However, an enormous amount of computational time is required for calculating CGHs. To solve this problem, basic object light method has been proposed as fast calculation method for CGHs. In this method, basic object light is precalculated object light of a basic object. And lightwaves of arbitrary object shapes are calculated by transforming basic object light. However, this method has the problem that data size of basic object light is enormous. As solution for this problem, calculation method with spherical basic object light has been proposed to reduce data size. Spherical basic object light is lightwave distribution on spherical surface which has center on basic object. We proposed transformations which are slide, rotation, distance, tilt, scaling and skew with spherical basic object light. In transforming calculation, calculation results for each pixel on holograms have parallelism for each others. The parallelism is useful for acceleration of CGH using multi-core systems. Calculation for each pixel on hologram is appropriated for each processor. However, data size of basic object light is larger than video memory. Thus We divide data of basic object light and improve the algorithm to enable GPU to calculate at high speed. In the processing speed measurement, processing speed on GPU with basic object light is about 700 times faster than CPU.

8281-29, Poster Session

Read/write characteristics of reflection type hologram memory using spherical reference beam

A. Nakajima, S. Ozawa, K. Yamada, M. Yamamoto, H. Akamatsu, K. Okubo, Tokyo Univ. of Science (Japan)

We studied the reflection type hologram memory using spherical reference beam. This memory system is able to record multiple holograms by simply shifting the medium. The reflection type hologram memory irradiates the signal beam and the reference beam from the opposite side of the medium and the reference beam propagates as a spherical wave in the medium. The feature of this method is that it is possible to make a large capacity of single hologram and the optical system becomes simple compared with a generally studied transmission type recording system. But, in the practical use of this method, it becomes a problem that the influence of the medium shrinkage causes the signal degradation greatly. From this point of view, we studied the influence of medium shrinkage on the reconstruction signal of this recording method.

In our experimental system, photopolymer of several hundred micrometer film is used as a recording medium. The wavelength of the laser beam is 532 nm. The shift selectivity of the multiple recording hologram was evaluated. By our experiment, the shift of the signal peak from the original position is caused by the medium shrinkage after recording. The beam irradiation angle is also changed by a medium shrinkage. But after the shift of the peak position had been corrected, the tolerance of the beam irradiation angle was improved. By our experiment, the possibility of multiple recording by medium shift is confirmed and by using a thick medium (about 1 mm), the large capacity memory system over than 1 Tb/in2 can be obtained.

8281-30, Poster Session

Calculation method for reconstruction at arbitrary depth in CGH with Fourier transform optical system

Y. Sato, Y. Sakamoto, Hokkaido Univ. (Japan)

A computer-generated hologram (CGH) is a hologram generated by simulating light waves propagation from virtual objects, and we are able to observe natural 3D images without feeling tired by CGH. However, resolution of current output devices like a LCD is not high enough to display CGH data, so size of reconstructed images are restricted. Therefore, In order to enlarge image size, a method by using the Fourier transform optical system has been proposed. The Fourier transform optical system converges reconstruction lights between a observer and a hologram by arranging a lens, and it reconstructs floating images near the observer. In the Fourier transform optical system, a reconstruction position is confined around a focal point of the lens because CGH calculation method has not been established so far. To solve this problem, this paper describes a CGH calculation method using a unified formula to reconstruct images at arbitrary depth. This formula is derived by considering image formation of lens and hologram. Moreover, unnecessary lights elimination processing is describes in this paper.

By changing the elimination processing according to reconstruction position, images are reconstructed without overlapping unnecessary lights at arbitrary depth. To confirm effectiveness of the proposed method, we conducted optical reconstruction experiments.

The result show that correct size images are reconstructed at correct depth, and unnecessary lights are eliminated. It is possible to observe large and free-depth 3D images by the proposed method.

8281-31, Poster Session

Enlargement of visual field considering depth of object for eyepiece-type electro holography

C. Yang, Y. Sakamoto, Hokkaido Univ. (Japan); F. Okuyama, Suzuka Univ. of Medical Science (Japan)

Electro Holography is one of 3-D display technologies displaying 3-D images reconstructed from hologram using electronic output device. It needs high resolution and low dot pitch of device to display reconstructed images, but current output devices don’t have enough resolution and dot pitch. Because of this limit of output devices, there are some problems such as limited visual field and viewing zone, conjugate images, ghost images, and 0th-order light. In this paper, we propose a method to enlargement visual field for displaying the 3-D image of bigger object in wide angle, and we also derive maximum border of visual field theoretically. Because of its very narrow viewing zone, we call our method eyepiece type electro holography.

In our method, we use a convex lens to enlarge visual field. A 3-D image of object is expressed as a virtual image behind lens by putting real image within the inside focal point of the lens, so finally we can see the virtual image, and the shape of visual field is a truncated cone. This truncated cone starts on the lens as upper base and continues infinitly on the z-axis. The border of truncated cone is maximum border of visual field. To calculate the border, we use those factors of size of human eye, distance between two eyes, exit pupil by lens and hologram factors like wavelength and dot pitch.

8281-32, Poster Session

Computer-generated holograms at arbitrary positions using multi-view images

Y. Ohsawa, Y. Sakamoto, Hokkaido Univ. (Japan)

Computer-Generated Hologram (CGH) is a technique that simulates a process of recording of hologram in a computer, and is noted as an ideal 3D display technology. CGH required model data of objects, and it is difficult to create precise 3D model data of actual objects manually. To solve this problem, many researches generating CGH using multi-view images (MVIs) have been proposed. They made it possible to generate CGH from actual objects under natural light. Although the method using common digital cameras enabled to get high resolution reconstructed images without special device, it is necessary to capture a huge number of images or to use a huge number of cameras to obtain sufficient continous motion parallax. It is not realistic way to construct 3D display application by these method.

Then, there are researches to generate 3D models from a small number of images automatically, and obtain a sufficient number of MVIs from acquired models. In this paper, we describe the method to generate voxel models from captured images, and generate CGH using MVIs obtained by the voxe models. Voxel models are generated with Shape-From Silhouette, colored with captured images, and rendered into MVIs. Using the method, it is possible to arrange holograms at arbitrary positions in the range where voxel models are generated correctly. Furthermore, we obtain sufficient continuous motion parallax by generating MVIs rendered from voxel models in spite of capturing only a small number of images. We conrm effectiveness of proposed method by optical experiments.

8281-33, Poster Session

Image-type high-definition CGHs encoded by optimized error diffusion

H. Yamashita, K. Matsushima, S. Nakahara, Kansai Univ. (Japan)

Recently, we presented polygon-based high-definition CGHs (PBHD-CGH) that reconstruct brilliant 3D images of occluded virtual 3D scenes. These PBHD-CGHs are fabricated by using a laser lithography system available on the market. All PBHD-CGHs created so far were Fresnel-type holograms, i.e. all objects comprising the 3D scene were set in the position of several centimeters behind the hologram. If we would place the objects too close or so as to slice the hologram, the shade and texture of the objects could be lost in the optical reconstruction. This is generally caused by image-type binary holograms that are produced by the laser lithography system. Binary amplitude fringe patterns are commonly unable to reconstruct object shading and texture-mapping, because amplitude information of the object field is removed by binarization if the object is too close to the hologram.

In this paper, optimized error diffusion is applied to encoding binary-amplitude image-type CGHs in order to improve the object shading and texture-mapping. In this technique, a set of coefficients for the error diffusion are iteratively optimized so that brightness of a test pattern is correctly reproduced in simulated reconstruction. It is verified that error diffusion using the optimized coefficients are effective for improving reconstruction of binary-amplitude image-type CGHs. In addition, image-type PBHD-CGHs created by the technique can be reconstructed by white light source. We will demonstrate some actual CGHs created by the proposed technique.

8281-34, Poster Session

Advanced rendering techniques for producing specular smooth surfaces in polygon-based high-definition computer holography

H. Nishi, K. Matsushima, S. Nakahara, Kansai Univ. (Japan)

In the past three years, we presented some brilliant computer holograms. These synthetic holograms are composed of more than billion pixels and reconstruct fine spatial 3D images comparable with those in classical holography. The object fields of the holograms are numerically synthesized by a polygon-based method that imitates the object surfaces by polygon-mesh. However, the early CGHs created by this method reconstructed only diffuse surfaces.

An issue of the polygon-based method as well as other point-based methods could not create specular surfaces. To resolve the problem, in the last meeting, we proposed a technique for creating flat specular surfaces by controlling the spectrum of the surface function. Here, the surface function is a complex function used for defining the polygonal surfaces and its property. Specular smooth surfaces, however, cannot be reconstructed by the proposed method, because the polygonal surfaces reflect the illumination light in the same direction. To create curved specular surfaces by the method, a polygon must be subdivided into smaller sub-polygons, i.e. tessellation is required. However, this is most likely too time-consuming to create high-definition computer holograms.

In this paper, we proposed a novel method for creating specular smooth surfaces without tessellation. In this new method, instead of dividing a polygon, the surface function is divided into many smaller segments and the reflection direction is controlled for each segment. In addition, this new method increases freedom for lighting the object. Some actual holograms will be demonstrated for verifying the proposed method.

8281-35, Poster Session

Study of holograms made with saccharides and iron ions

M. J. Ordóñez-Padilla, A. Olivares-Pérez, I. Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); M. Ortiz-Gutiérrez, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); V. Dorantes-García, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Characterization of photosensitive film performance for holographic recording of the following substances: pectin, fructose, glucose and sugar (Glass ®), with certain physicochemical conditions. The photo-oxidation was carried out by changing the concentrations of iron ions, Fe+3. Analysis was performed by holographic diffraction gratings with the parameters of the diffraction efficiencies of each of the saccharides.

8281-36, Poster Session

Analysis of albumin hologram

M. J. Ordóñez-Padilla, A. Olivares-Pérez, L. R. Berriel-Valdos, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); M. Ortiz-Gutiérrez, J. F. Villa-Manríquez, Univ. Michoacana de San Nicolás de Hidalgo (Mexico)

We show a characterization of photosensitive films based on albumin gallus gallus and callipepla cali for holographic recording. The albumins were combined with propylene glycol to build stable colloidal systems, with adding the ammonium dichromate solution at certain concentrations. Thus took place the process of photo-oxidation, with laser λ = 442 nm. and obtaining holographic diffraction gratings of high quality that allowed the analysis of the diffraction efficiency parameter.

8281-37, Poster Session

Interferometric measurement of refraction index of dye-doped photopolymer

G. Mellado-Villaseñor, M. Ortiz-Gutiérrez, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); M. Pérez-Cortés, Univ. Autónoma de Yucatán (Mexico); J. C. Ibarra-Torres, Univ. de Guadalajara (Mexico); A. Olivares-Pérez, S. Toxqui-López, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Holographic interferometer is used with a dye-doped photopolymer on one of its arms, the sample is radiated simultaneously with two wavelengths, and measuring the pattern fringe displacement we can calculate the refraction index changes. The photopolymer we use is a mix of Norland Optical Adhesive No. 65 and Crystal Violet dye deposited between two glass plates making a cell of 330 microns thickness. The sample is radiated with a beam from an Ar-ion laser at 515 nm; in the interferometer we employed a He-Ne laser at 633 nm in emission line. We show some experimental results.

8281-38, Poster Session

The efficiency of holograms with registration nitrocellulose and FeCl3

R. Vallejo-Mendoza, A. Olivares-Perez, N. A. Korneev, V. Dorantes-Garcia, M. J. Ordóñez-Padilla, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

We study experimentally the efficiency of transmission holograms record with phase and amplitude modulation with nitrocellulose. This is used as the matrix and ferric chloride as a photosensitizer. They use different sources of radiation to which type of light is more effective for recording holograms.

8281-39, Poster Session

The behavior of the diffraction efficiency of a function of thickness using holographic gratings as material registration with gum Arabic ammonium dichromate

B. Pinto-Iguanero, Benemérita Univ. Autónoma de Puebla (Mexico); A. Olivares-Pérez, S. Toxqui-López, I. Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

A study was made with gum arabic and ammonium dichromate with holographic recording material, varying the thickness of the material. This material shows excellent properties for this purpose, also exhibits low moisture absorption in environmental conditions, has a behavior that is hydro-phobic and produces a thin homogeneous film with a smooth texture, also has adhesive properties.

We present experimental results obtained from diffraction gratings holographically constructed, the material was deposited by the technique of gravity on a glass substrate.

8281-40, Poster Session

Fabrication of the multi-level phase type hologram for display using the Laser Direct Write Lithography System

N. Seiji, S. Nakahara, S. Singubara, Kansai Univ. (Japan)

To make the person who is situated on the long distance recognize image data using the hologram, the hologram must have bright image reconstruction ability and a high SN ratio.

Because it supposed that the size of the object was big, it adopted a computer-generated hologram (CGH). Also, it used laser direct write lithography system for the making of a hologram.

The fidelity of the reproduction image is the most important to the hologram for transmitting information. It is necessary to increase the brightness of the reconstruction images and the SN ratio by the speckle noise in order to improve the visibility of images.

Therefore, we made the multi-level phase type hologram for the former and adopted a method to modulate a reproduction illumination source of light for the latter.

For an evaluation method of the diffraction efficiency, we used 2-, 4-, and 8-level phase type Fresnel Zone Plate (FZP) and the Fresnel hologram with an image of a small disk as diffusing objects.

As a result of experiment, the efficiency of 67.3% was provided in 8-level phase type FZP, and became higher than 2- , 4-level FZP. Furthermore, fabricating 2-, 4-, and 8-level phase type hologram of the diffusing object, and after comparing the brightness of the reconstruction image, succeeded in improvement of the brightness.

8281-41, Poster Session

Multiplex and multilevel optical recording for optical mass storage by retardagraphy

H. Sekiguchi, D. Barada, T. Ochiai, Utsunomiya Univ. (Japan); T. Fukuda, National Institute of Advanced Industrial Science and Technology (Japan); S. Kawata, T. Yatagai, Utsunomiya Univ. (Japan)

Recently, retardagraphy, which is a new optical recording technique utilizing polarization. In retardagraphy, optical information consisted of the phase retardation between two orthogonal polarization components on a polarization-sensitive medium using a single beam. The advantages of this technique are robustness for vibration and simplicity for optical system. Additionally, this technique can be regarded as a kind of in-line polarization holography, thus it's possible to the holographic multiplex recording cause of Bragg selectivity in the case using a thick recording medium. Then, the optical information is recorded as a three-dimensional birefringence pattern on the polarization-sensitive medium. In our previous work, the improving method of recording density was investigated only the multiplex recording using binary pattern, but now we propose a method that uses the multiplex recording using multilevel pattern to further improve recording density.

In experiment, a diode laser (405 nm) was used recording and reconstruction. The phase of two orthogonal polarization components included in a recording beam was independently modulated by a parallel aligned liquid crystal spatial light modulator (SLM). The recording pattern was recorded on the polarization-sensitive medium by focusing the recording beam, and three patterns were multiply recorded by shifting the focal point. The shift distance was 100 μm and focal point size was 170 μm. The recorded images can be independently recorded and reconstructed. The combined multiplex recording technique with the multilevel recording can effectively improve the recording capacity.

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8282-02, Session 1

Optical signal processing for wireless transmission

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Recently, huge capacity optical transmission over 10Tb/s was demonstrated by using advanced optical modulation schemes. However, data rates of conventional commercial wireless links would not achieve to more than 10 Gb/s. The capacity mismatches between optical wired and radio wireless link technologies could cause the bottleneck in future wired and wireless seamless networks. Millimeter-wave bands are attracting attention because of the availability of wideband for high-speed transmission. However, due to the limitation of the performance of electric signal processing, it is rather difficult to modulate and demodulate millimeter-wave signals with high-speed baseband modulation. In this presentation, we discuss optical signal processing for high-speed modulation of millimeter-wave, based on high-speed and precise lightwave control. In optical fiber communication systems, various types of modulation formats, such as quadrature-amplitude-modulation, are reported to achieve high-speed transmission. Optical two-tone signals can be converted into millimeter-wave signals by using high-speed photodetectors. This technique can be used for distribution of stable reference signals in large-scale antenna arrays for radio astronomy. By using the millimeter-wave signal generation technique and the optical advanced modulation formats, we can achieve high-speed modulation of millimeter-waves, where the carrier frequency and bit rate can be over 90GHz and 30Gb/s, respectively.

8284-03, Session 1

Multi-input injection locking in single mode Fabry-Pérot laser diode and its application in optical signal processing

B. Nakarmi, M. Rakib-Uddin, Y. H. Won, KAIST (Korea, Republic of)

In recent years, all-optical signal processing has been receiving more attention due to their numerous capabilities such as less electromagnetic interference, and data transparency in high speed optical computing and networking. One of the various technologies that have been used for the optical signal processing is FP-LDs which are based on the injection locking principle. Till now all the signal processing based on FP-LDs works on the single input injection locking which had made the constraint on its application on various signal processing scheme.

In this paper, we proposed a new idea of multi-input injection locking (MIL) and combinational multi-input injection locking (CMIL) in SMFP-LDs. The basic idea behind MIL and CMIL is the proper power management of the input injected beams. We propose injection locking of multiple inputs and the suppression of the dominant mode will occur only when certain conditions are fulfilled else the dominant mode will not be suppressed even there are inputs which are injection locked to some of the side modes of FP-LD. With these principles the multi-input logic gates using SMFP-LDs can be realized. The dependence of the suppression of dominant mode of SMFP-LD with numbers of input (2, 3 and 4 input) with input wavelength detuning, modes of input injected, and the combined input power are analyzed. We will show how the proposed injection locking can be used for realizing different optical subsystems such as logic gates for signal processing with 10 Gbps input data signals. with this principle the multi-logic functions can be implemented using SMFP-LDs.

8282-03, Session 1

Adjustable transfer function optical filter for microwave applications

N. Madamopoulos, J. Kuang, The City College of New York (United States); A. J. Prescod, Corning Incorporated (United States)

All-optical techniques for microwave and radio frequency (RF) signal processing has attracted considerable attention in recent years. An important optical component in these all-optical signal processing techniques is the optical filter. Tunable optical filters with a variety of transfer functions have been proposed. However, adjustability of the optical filter transfer function is required to provide an extra degree of control. This adjustability of the shape of the transfer function has not been addressed adequately in the literature. In this paper, we report on the theoretical basis for an all-fiber based adjustable transfer function optical filter. In particular, we model the optical filter using FO-circuit transfer matrices and Jones matrices to fully describe the state of polarization changes of the optical signals through the optical filter. The filter is based on an all fiber Michelson Gires-Turnois interferometer (MGTI). The Gires-Turnois resonators (GTRs) required for the formation of the MGTI are realized by pairs of fiber-loop mirrors in the two arms of the Michelson interferometer. The optical reflectivity of the GTRs is control via adjustment of the polarization in the fiber loop mirrors. We show that arbitrary transfer functions can be realized by adjusting the reflectivities of the FLMs as well as the length of the GTRs. Arbitrary filter transfer functions are accomplished by proper control of the reflectance of fiber loop mirrors and the cavity length of the GTRs.

8284-04, Session 1

Super receiver design for superchannel coherent optical systems

C. Liu, J. Pan, T. F. Detwiler, A. J. Stark, Y. Hsueh, G. Chang, S. E. Ralph, Georgia Institute of Technology (United States)

To meet the bandwidth requirement of future optical networks, 1Tb/s and beyond transmission systems based on "super-channel" architectures have recently been considered as alternatives to electrical OFDM. Nyquist WDM and Coherent Optical-OFDM are the two main approaches to achieve ultra high spectral efficiency in super-channel coherent systems. We investigate receiver architectures for Nyquist WDM super-channel coherent system, and propose a new "super receiver" architecture, which achieves better performance compared to conventional coherent receivers.

In Nyquist WDM coherent systems, in which the conventional WDM subcarriers are packed tightly to realize near-baud-rate or baud-rate spacing operation, inter-channel interference (ICI) occurs, which significantly degrades system performance. It is possible to eliminate ICI with baud-rate spacing in a CO-OFDM system, however this requires frequency locking and sinc-pulse shaping per transmitter via digital-to-analog converters (DACs). Otherwise, baud-rate spacing is non-orthogonal and incurs significant ICI. The traditional way to mitigate the impact of ICI is by applying aggressive optical filter to each channel before optical multiplexing, however this induces severe inter-symbol interference (ISI). Accordingly previous research focused on how to mitigate the linear ISI penalty associated with the tight filtering.

In this work, we propose a novel super-receiver scheme which jointly detects and demodulates multiple channels simultaneously. By taking advantage of information from side channels using DSP to cancel ICI, we achieve improved performance compared to conventional schemes which process the channels independently. Several joint DSP algorithms are developed and tested through simulated data. Simulation results demonstate that more than 2 dB ONSR gain is achieved at narrow channel spacing conditions.

8284-05, Session 1

Uncooled MIMO WDM system using advanced receiver signal processing techniques

S. H. Lee, R. V. Penty, I. H. White, Univ. of Cambridge (United Kingdom); D. G. Cunningham, Avago Technologies Ltd. (United Kingdom)

Current DWDM systems require components such as laser diodes and multiplexers to operate at precise wavelengths with precise temperature control. We propose a new form of narrow channel spacing WDM system which uses uncooled lasers, DE/MUXes and receivers. It removes control of laser wavelengths and thus energy consumption of their temperature control systems at the expense of a slightly more complicated receiver design. The system allows the wavelength of the lasers to drift but uses a cyclic demultiplexer at the receiver with more detectors than signal channels so that the separate WDM signals can be decoded with carefully designed signal processing algorithms. The system is designed with narrow channel separations, typically 0.65nm to 1.00nm. By tracking the individual signals, weighting all the received signals and canceling crosstalk, channel restoration and hence low error rate uncooled WDM transmission is achieved. In extreme cases, if too many signal channels fall within a single receiver channel and hence too much crosstalk limits the electronic signal decoding performance, modest D.C. current tuning of the laser wavelength can be used to ensure the required separation. The weights used in crosstalk cancellation unit are calculated by minimize-mean-square-error algorithm, being similar to that used in 10GbE currently. Simulation and experimental results with offline signal processing for a 4-wavelength 10Gb/s WDM system over 25km SMF prove the feasibility of this approach with a maximum of 5dBe penalty in the worst-case states. Further work on extending the approach to a 32-wavelength system will be presented in the conference.

8282-04, Session 2

Coherent OCDMA communication systems

X. Wang, Heriot-Watt Univ. (United Kingdom)

The recent progress of coherent OCDMA system will be reviewed in this paper.

8282-05, Session 2

VCSEL-based optical transceiver module operating at 25 Gb/s and using a single CMOS IC

G. Afriat, L. Horwitz, D. Lazar, A. Issachar, A. Pogrebinsky, A. Ran, E. Shoor, R. Bar, R. Saba, Intel Corp. (Israel)

We present here a low cost, small form factor, optical transceiver module composed of a CMOS IC, a high bandwidth 850nm emission wavelength VCSEL, and an InGaAs/InP PIN Photo Diode (PD). The CMOS IC is fabricated in standard 28nm CMOS process and integrates all the required transmitter and receiver circuits including a PLL generating the TX (Transmit) clock, a VCSEL Driver modulating the off-chip VCSEL at 25-Gb/s, a Transimpedance Amplifier (TIA), a Limiting Post Amplifier, and a Clock Data Recovery (CDR) block sampling the RX (receive) data at 25-Gb/s.

The module is designed to support 4 channels of 25-Gb/s each for a total data rate of 100-Gb/s and measures 12mm X 12mm, although at this point we have utilized only one channel out of the four. The transceiver module couples into a 62.5/125 um multi-mode TX/RX fiber pair (OM1) via a low cost plastic cover and a simple connector realizing the transmitter and receiver lens systems and bringing the module height to a mere 1.85mm.

An on-chip data generator generates PRBS data sequences in the length of 211-1. This data is transmitted and recorded on an external scope at the TX fiber output to construct the transmitter optical eye. The TX Eye shows an OMA of 1.5dBm and ER of 5.8dB, while a jitter analysis gives DJ (Deterministic Jitter) of 6.6ps and RJ (Random Jitter) of 0.9ps RMS.

The receiver sensitivity was tested by injecting an optical PRBS-11 sequence, generated by an external pattern generator, into the OM1 TX/RX fiber pair that couples into the transceiver module. An on-chip Error Checker compares the received data to a PRBS-11 sequence and reports via JTAG any error detected as well as the bit count received and checked for errors. The receiver sensitivity at BER = 10-12 was found to be -4.6 dBm OMA under stressed conditions of 1.2dB VECP (Vertical Eye Closure Penalty) and 7 ps ptp DJ due to ISI (Inter Symbol Interference).

For a full link BER test, two modules were connected at each side of a TX/RX fiber pair, transmitting PRBS-11 data sequences which are asynchronous to each other. The Error Checkers on each side were used to verify the RX data integrity and the transceiver modules demonstrated BER < 10-12 at the 25-Gb/s data rate over 3-meters of OM1 (62.5/125 um) fiber and over 30-meters of OM3 (50/125 um) fiber.

8284-08, Session 2

Optical OFDM based on the fractional Fourier transform

G. Cincotti, Univ. degli Studi di Roma Tre (Italy)

Orthogonal Frequency Division Multiplexing (OFDM) is still quite popular within the fiber-optic community, mainly because many theoretical and experimental results have demonstrated that this technique is fairly effective in mitigating chromatic dispersion, polarization mode dispersion and nonlinear effects.

Typically, the standard OFDM is based on the fast Fourier transform (FFT) algorithm, that is easy to be electronically or optically implemented, and frequency-domain decomposes the input signal into several parallel streams. The equally spaced subcarriers are orthogonal, present overlapping spectra and are free from intersymbol interference.

In this paper, we describe a novel OFDM technique based on orthogonal chirped subcarriers, that correspond to the fractional Fourier transform (FrFT). The FrFT is a generalization of the Fourier transform (FT) in the time-frequency plane: whereas the standard FT can be seen as the projection of a given signal on the frequency axis (a rotation of pi/2 with respect to the time axis), the FrFT can be interpreted as the projection of the signal on an axis that forms an angle p pi/2, with 0<p<2, i.e. a rotation in the time-frequency plane.

We show that the FrFT can be electronically implemented with a complexity equivalent to the traditional FFT; on the other hand, the planar device that implements the FrFT is similar to the arrayed waveguide grating (AWG) component that performs the FFT.

We analyze the spectral efficiency, the crosstalk, the peak-to-average power ratio (PAPR), the phase noise sensitivity of a FrFT-based optical OFDM system, and make an accurate comparison with the standard FT-based implementation.

8284-09, Session 2

Reconfigurable optical transmitters and receivers

W. Freude, R. Schmogrow, D. Hillerkuss, J. Meyer, M. Dreschmann, Karlsruher Institut für Technologie (Germany); B. Nebendahl, Agilent Technologies Deutschland GmbH (Germany); M. Huebner, J. Becker, C. Koos, J. Leuthold, Karlsruher Institut für Technologie (Germany)

Recent advances in electronic data processing allow constructing reconfigurable optical transmitters and receivers, where modulation formats and symbol rates are set by software-controlled field programmable gate arrays (FPGA). We report on such a real-time optical transmitter for 8 modulation formats, which can be swapped in 5 ns without data loss. With single-polarization 64QAM symbols generated at 28 GBd, we transmit data at 168 Gbit/s in real time. A similar arrangement defines a single-polarization orthogonal frequency division multiplexing (OFDM) transmitter for a data rate of 101.5 Gbit/s, where 58 subcarriers are encoded with 16QAM data. With a different software setup, the FPGA realizes an optical 56 Gbit/s transmitter for sinc-shaped so-called Nyquist pulses, the spectrum of which is rectangular having the minimum theoretically achievable bandwidth (suitable for Nyquist wavelength division multiplexing, N-WDM). For terabit OFDM reception, optical pre-processing is required to demultiplex high-bitrate signals down to lower-bitrate tributaries, which then can be processed electronically. We discuss a 10.8 Tbit/s (26 Tbit/s) receiver employing an all-optical fast Fourier transform to demultiplex 75 (325) optical subcarriers modulated with 16QAM-formated symbols at a rate of 18 GBd (10 GBd). Groups with any number of subcarriers can be selected with a simple hardware recon-figuration step.

8284-10, Session 2

Performance of 32-Gbaud PDM-QPSK in nonlinear transport regimes with different phase recovery methods

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We experimentally investigate the performance of WDM coherent polarization-division multplexed-return to zero-quadrature phase shift keying (PDM-RZ-QPSK) network in nonlinear transport regimes. Six, 32-Gbaud PDM-RZ-QPSK channels are employed on a 50-GHz grid and transmitted over 1600-km fiber on an all-EDFA recirculating loop without any dispersion compensation module (DCM). The transmission link is configured entirely of either standard single-mode fiber (AllWave) or nonzero dispersion fiber with large effective area (TrueWave Reach). We sweep the launch power of the center channel and side channels independently to measure the nonlinear effects of self-phase modulation (SPM), cross-phase modulation (XPM), and cross-polarization modulation (XPolM) on the center channel's BER performance. Furthermore, for all link configurations, we employ three different carrier phase recovery methods in the demodulation routine - Viterbi-Viterbi, Viterbi-Viterbi with a minimum mean-squared error (MMSE) filter, and phase-locked loop (PLL) - to ascertain their relative performance in the presence of nonlinear effects.

8284-11, Session 2

Performance of PM QPSK and PM 16-QAM coherent optical fiber communication systems

J. C. Cartledge, Queen's Univ. (Canada); J. D. Downie, J. Hurley, Corning Incorporated (United States); A. Karar, J. H. Ke, Queen's Univ. (Canada); I. Roudas, Corning Incorporated (United States); K. Roberts, Ciena Canada (Canada)

The performance of polarization multiplexed, quadrature phase shift keying (PM-QPSK) and polarization multiplexed 16-ary quadrature amplitude modulation (PM-16QAM) is considered with an emphasis on the signal processing algorithms that compensate transmission impairments and implement key receiver functions.

8283-04, Session 3

SOA-based Mamyshev-type regeneration: towards an all-optical error correction?

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Photonic balancing has been previously introduced as a novel all-optical regenerative scheme for phase-noise degraded RZ-D(Q)PSK signals. This concept is based on the counter-propagation of demodulated “ones” and “zeros” inside a semiconductor optical amplifier (SOA) working in the saturation regime. Some of the many demonstrated advantages of photonic balancing are: a dual arm output enabling the use of electrical balanced detection, the high saturation output power, as well as a 3-dB optical signal to noise ratio improvement.

In this paper, we demonstrate how photonic balancing can be further improved and extended to a new promising application aimed at removing the in-band noise. We show how the combination of a deeper saturation regime and an appropriate detuned filtering technique can yield total suppression of the demodulated nonlinear phase noise present in the zeros. Furthermore, we present a detailed filtering optimization analysis by means of numerical simulations that provide Q-factor and BER estimates based on a Chi-Squared noise statistics.

Finally, we present a discussion of the different possible interpretations at the origin of these new improvements and investigate some similarities with the existing fiber-based regeneration solutions.

8283-05, Session 3

Integrated photonic components for 100G and beyond

A. K. Srivastava, OneTerabit (United States)

No abstract available

8282-06, Session 3

Microring resonator for optical access networks

M. F. Lipson, Cornell Univ. (United States)

No abstract available

8282-07, Session 3

Power balancing effect on the performance of IMPACC modulator under critical coupling (CC), over coupling (OC), and under coupling (UC) conditions at high frequency

B. B. Dingel, Nasfine Photonics, Inc. (United States); N. Madamopoulos, The City College of New York (United States); A. Prescod, Corning Incorporated (United States); R. Madabhushi, Madabhushi Consultants, LLC (United States)

In this report, we investigate the power balancing effect of an input optical signal on the performance of a linear optical modulator called IMPACC (Interferometric Modulator with Phase-modulating and Cavity-modulating Components). One configuration of IMPACC, which we discuss here, consists of a phase modulator and a ring resonator on different arms of a Mach Zehnder interferometer (MZI). External control of the power split ratio from an input radio frequency (RF) signal into the two separate arms of the interferometer has been shown to add design flexibility and the ability to achieve high spurious free dynamic range (SFDR) of more than 130 dB, when compared to the single-ring RAMZI (Resonator-assisted MZI). Our previous reports have assumed that the power split ratio of the input optical signal into the MZI is 50:50. Here, we include additional power balancing of the input optical signal into the two arms of IMPACC. The resultant effect is reported on for three different conditions; namely, critical coupling (CC), over coupling (OC), and under coupling (UC) conditions at high frequency. We report on this power balancing effect at two separate conditions of high frequency (~23GHz and 70GHz) for a traveling wave electrode design. Lastly, we compare the performance of IMPACC to the single-ring RAMZI with traveling-wave electrode design, both under sub-octave operations.

8284-12, Session 3

InP-based Mach Zehnder modulators for next generation systems

E. Yamada, Y. Shibata, H. Ishii, NTT Photonics Labs. (Japan)

We realized high-speed and low driving voltage InP-based Mach Zehnder modulators with traveling-wave electrodes and an npin high-mesa waveguide structure. Since n-type InP cladding layers are employed on both the signal and ground electrode sides, and there are no thick p-cladding layers, the electrical and optical losses are reduced.

Full C-band 40-Gbit/s DPSK signal was successfully generated using a compact tunable wavelength transmitter module, which incorporated a tunable DFB laser array as a wavelength tunable laser and an InP MZM in one package, with a low driving voltage of 3 Vpp in a push-pull driving configuration.

We have demonstrated 112 Gbit/s RZ-DP-QPSK modulation using two InP MZM modules. One modulator was used as a pulse carver in a push-pull configuration, and the other was used as an IQ modulator in a dual-drive configuration. Since we used an RZ pulse carver to remove the transient region, we obtained clear eye openings without any amplitude ripple.

We also demonstrated a 50 Gbit/s (12.5 Gsymbol/s x 4) 16QAM signal generation employing the novel dual-drive modulation method of a single MZM. We utilized the electro-absorption characteristics of an InP semiconductor to adjust the QPSK amplitude.

We confirmed a single MZM operated as a DPSK, a QPSK, and a 16QAM modulator with the same device. We believe these modulators to be suitable for next generation optical transmission systems.

8282-08, Session 4

LTE enhanced packet core: overview and recent enhancements

S. Varma, Tellabs, Inc. (United States)

The LTE Enhanced Packet Core or EPC, provides a number of important services to the LTE network, such as

user authentication and security, mobility, end to end QoS support, billing etc. The EPC was designed with the objective of supporting an all IP based network, and in contrast to previous generations of Network Core design, there is no dependence on circuit switched elements in the core network. The EPC also significantly reduced the complexity and number of nodes needed in the core network, thus enabling higher performance and functionality.

The objective of this presentation is to give an overview of the EPC, pointing out the differences compared to previous generations of packet core. We will also talk about some of the more recent enhancements that have ben added to the EPC architecture by the 3GPP Standards Group, to support functions such as Machine to Machine Communications.

8282-09, Session 4

Optical transport technologies in mobile broadband radio systems

Y. Horiuchi, KDDI R&D Labs., Inc. (Japan)

Broadband mobile access systems are essential for today's advanced information and communication society. The deployments of 3G mobile phone systems (CDMA2000 and UMTS) and broadband wireless access systems (WiMAX) are accelerated due to the explosion of high-speed mobile multimedia communications and Internet services. Long Term Evolution (LTE) as the leading choice for next-generation mobile access networks worldwide was also started operation. The architectures of their radio systems have drastically changed thanks to the evolution of opto-electronics and communication technologies. The optical fiber communication technologies play a major role in the development of the radio systems. The importance of its technologies in radio systems are composed mainly of an accurate RF waveform transport and an end-to-end synchronization capability.

This paper describes some of the optical transport techniques that contribute to the efficient construction and deployment of radio systems mainly including mobile communication applications. This covers following topics: in-building radio coverage systems, distributed base station architectures, UTC-traceable time distribution over optical access network and overview of future optical transport in radio systems. This paper also introduces development activities of optical transport technologies for radio systems.

8282-10, Session 4

Transportation of a microwave environment over networks and the applications

Y. Shoji, National Institute of Information and Communications Technology (Japan)

A concept to transport a microwave environment over networks using a digitized Radio-over-Fibre technique, which could construct virtual wireless access systems on a virtual network, is discussed. 10-Gbps Ethernet based microwave-to-IP packets conversion network interface (MINI), which can directly digitize received microwaves and convert them into IP packets, is developed. As an example demonstration, an IP network transportation of received multiple digital TV broadcasting signals (ISDB-T signals) is demonstrated, which reveals that the input microwave power and the quantization bit rate for digitization process should be adaptively controlled according to the number of channels and the required quality of transported microwaves.

The concept to analyze and monitor remote microwave conditions based on the transportation of microwave environments is also discussed and demonstrated. In the demonstration, WLAN signals or ISDB-T signals, which are intentionally generated, are captured by an MINI along with the signals from GPS (Global Positioning System) satellites and converted into IP/Ethernet packets. The packetized microwaves are transported to a microwave analyzing station (MAS) which analyses the packetized microwaves and reveal the RSSI (received signal strength indication), the frequency channel, and the type of the microwave along with the time and the position at which the microwaves are captured.

Distributed antenna systems (DAS) based on the concept of transportation of microwave environments, which could be effective to flexibly and virtually isolate wireless accesses and to improve wireless capacity in emergency, are additionally proposed and discussed.

8282-11, Session 4

Virtualized packet optical integrated transport network

M. Tatipamula, Ericsson, Inc. (United States)

No abstract available

8282-12, Session 5

Pricing by timing: innovating broadband data plans

S. Ha, C. Joe-Wong, S. Sen, M. Chiang, Princeton Univ. (United States)

Wireless Internet data usage is doubling every year. Users are consuming more of high-bandwidth data applications, with usage concentrated on several peak hours in a day. We review many of the pricing schemes in practice today and analyze why they do not solve this problem of growing data traffic. We propose a time-dependent pricing scheme as a viable solution, charging different prices for Internet access at different times. This pricing induces users to spread out their bandwidth consumption across different times of the day, with a large potential impact on ISP (Internet service provider) revenue, congestion management, and consumer behavior. We develop an efficient way to compute the cost-minimizing time-dependent prices for an ISP. Our representation of the optimization problem yields a formulation that remains computationally tractable for large-scale problems. We next show survey results demonstrating that users are willing to defer data usage in exchange for a lower monthly bill, as well as numerical simulations illustrating the use and limitation of time-dependent pricing. Finally, we present our system integration and implementation, called TUBE (Time-dependent Usage-based Broadband price Engineering), and proof-of-concept experimentation.

8282-13, Session 5

Multi-gigabit millimeterwave radio-over-fiber communication systems and networks

A. Stöhr, Univ. Duisburg-Essen (Germany)

The success of the Internet and the emergence of new IP-based multimedia services resulted in a widely use of optical access networks. For further deployments, it is necessary to extend the reach of the existing optical fiber infrastructure to those customers that cannot be connected directly to the fiber for economic, environmental or other reasons. Multi-gigabit capacity wireless systems are seen as a fast deployable and cost-effective solution for providing seamless integrated wired/wireless access. In addition to optical access, multi-gigabit capacity wireless systems are also of gret importance for mobile backhauling in future wireless networks. Today, more than 50% of the worldwide base stations are interconnected by microwave point-to-point wireless links that have a limited maximum channel bandwidth of up to 50/56 MHz due to worldwide regulations. Even when using high spectral efficient modulation formats and polarization multiplex, the maximum channel bandwidths only allows for total capacities of a few hundred Mbit/s, not enough for handling the backhaul traffic, e.g. in future LTE networks. Millimeter-wave wireless systems with aggregated channel bandwidths up to 10 GHz could potentially provide multi-gigabit capacities even when using rather simple modulation formats such as ASK or QPSK. This talk will discuss the potential and challenges when using photonic systems for high-capacity (>10 Gbps) wireless transmission at millimeter-wave carrier frequencies. Experimentally, wireless transmission up to 27 Gbps and photonic based solutions for millimeter-wave wireless transmission at 60 GHz, 70/80 GHz as well as in the 75-110 GHz region will be reported.

8282-14, Session 5

Analog photonic link by using DFB lasers operated in the low laser threshold current region and external modulation

A. García Juárez, Univ. de Sonora (Mexico); I. E. Zaldivar Huerta, Instituto Nacional de Astrofísica Óptica y Electrónica (Mexico); J. Rodríguez Asomoza, Univ. de las Américas Puebla (Mexico); M. d. R. Gómez Colín, A. G. Rojas Hernández, D. Berman Mendoza, R. Gómez Fuentes, A. Vera Marquina, Univ. de Sonora (Mexico)

Microwave transmission by using optical fiber is being used for high-capacity communications systems, thanks to advantages such as increased bandwidth; immunity to electromagnetic interference; reduction of size, weight, power consumption; and low loss over long distances. From these advantages, different photonic implementations of microwave systems have been proposed. On the other hand analog photonic links with ultra-high linearity, sensitivity and dynamic range over large bandwidths are required in radio-over-fiber, antenna remoting, signal processing. Besides in the CATV systems and satellite communications industries, analog photonic links are widely used as well as in military airborne, shipboard platforms, spacecrafts, radars and so on. In this paper we present a microwave photonic link architecture to transmit simultaneously two TV signals in a subcarrier multiplexed transmission system (SCM). The experimental setup used in this work is configured with two distributed feedback (DFB) laser diodes emitting at 1.5 µm. These devices are operated in the low laser threshold current region and the emissions generated in each laser are detected by two fast photodetectors. As result of this photo-detection, relaxation oscillation frequencies are obtained. These frequencies fall in microwave range and are located on C band. The microwave signals are modulated with analog TV signals and they are sent over 30 km of standard optical fiber by using a Mach-Zehnder modulator (MZM) and an erbium-doped fiber amplifier. In order to recover efficiently the sent information it is necessary that at the receiver output the modulated light is photo-detected and the recovered microwaves are amplified and filtered.

8282-15, Session 5

Evaluation on a costless 60-GHz OFDM-based indoor wireless over multimode fiber green system employing a photonic integrated smart antenna

S. S. Mikroulis, P. Sotiropoulos, E. Pikasis, Technological Educational Institute of Athens (Greece); G. Agapiou, Hellenic Telecommunications Organization SA (Greece)

Wireless communication technology has been tremendously developed since last years, powered by the simultaneous advance of high bit-rate demanding services. In such a manner, 60 GHz band offers an available bandwidth of several GHz, but on the other hand, it imposes several challenges due to the increased path loss and high density of needed radio access points. In this case, Wireless over Fiber (WoF) technology combines simple development and high capacity, through a green radio approach, due to the reduction of the emitted and consumed radio power.

In this work a microwave/optical/wireless converged design platform is presented, in order to study a low-cost 60GHz wireless over fiber indoor system, employing a photonic mm-wave microstrip patch antenna as a Remote Antenna Unit (RAU), integrated with a high-speed waveguide photodetector, and a null-point biased Mach-Zehnder $LiNbO_3$ modulator in the central base station (CBS) for all-optical frequency up-conversion. Moreover, a typical OM-4 graded index multimode fiber (GI-MMF) is selected for the optical medium as a low cost, flexible solution. Additionally, a 3Gb/s Orthogonal Frequency Division Multiplexing (OFDM) based IEEE 802.15.3c prestandard has been chosen, due to its immunity to the nonlinear optical/ wireless channels, and the system is evaluated in order to achieve the typical requirements of < 23% Error Vector Magnitude (EVM) for a coverage up to 10m. Moreover, a converged wired-wireless architecture is proposed, utilizing a FTTB single mode fiber (SMF) feeding through a backhaul optical network spare wavelength, and a MMF deployment indoors, employing a wavelength re-use in the RAUs.

8282-20, Session 5

Temperature impairment characterization in Radio-over-Multimode Fiber systems

C. Vázquez, D. S. Montero, Univ. Carlos III de Madrid (Spain)

An emerging theme in next-generation access research includes seamless wireline-wireless convergence addressed by Radio-over-Fibre (RoF) technologies. Optical cabling solutions offer the possibility for semi-transparent transport through the access network microwave to mm-wave radio carriers commonly employed for creating high-capacity picocell wireless networks, attending present demands from the wireless technologies, with portable/mobile devices converging with photonics. Advanced RoF techniques can efficiently generate and transport such carriers, and deliver them to simplified antenna stations or radio access points (RAPs). Thus, they can convey high data rates in comprehensive modulation formats on multiple-GHz carriers in MMF networks.

Selective mode-launching schemes combined with the use of narrow linewidth optical sources are experimentally demonstrated to enable broadband RF, microwave and mm-wave transmission in short- and middle-reach distances over silica-based multimode optical fibers (MMFs); and are reviewed in this paper. However, arbitrary operating conditions, such as the temperature dependence in the fiber link, impose a great challenge for the extension of this RoMMF technology. Temperature impairment characterization is analyzed over the broadband transmission bands that are present, under certain operating link conditions, in the frequency response performance of multimode optical fibers to support multiple-GHz carriers delivering schemes, thus contributing to fault link prevention.

8283-06, Session 6

An efficient solution for building high-bandwidth active metro and access networks

P. Hostalka, Huawei Technologies Co., Ltd. (Germany); L. Pang, A. Shen, Huawei Technologies Co., Ltd. (China)

No abstract available

8283-07, Session 6

Service driven packet-optical convergence for data-center campus applications and metro applications

H. Schmidtke, Juniper Networks, Inc. (United States)

No abstract available

8282-16, Session 6

Visible light communication in dynamic environment using image/high-speed communication hybrid sensor

K. Maeno, M. Panahpour Tehrani, T. Fujii, H. Okada, M. Tanimoto, T. Yamazato, Nagoya Univ. (Japan); T. Yendo, Nagaoka Univ. of Technology (Japan)

Visible Light Communication (VLC) is a wireless communication method using LEDs. LEDs can respond in high-speed and VLC uses this characteristics. In VLC researches, there are two types of receivers mainly, one is photodiode receiver and the other is high-speed camera. A photodiode receiver can communicate in high-speed and has high transmission rate because of its high-speed response. However in dynamic environment, the receiver requires a camera to detect and track the transmitter. Therefore, it is difficult to detect and track the transmitter accurately since the position of the camera is different from that of the photodiode. In addition, tracking speed is slow due to the low frame rate of the camera. In contrast, a high-speed camera can detect and track the transmitter easily because it is not necessary to move the camera. But the transmission rate is low because it depends on the frame rate of high-speed camera. In this paper, we use a hybrid sensor designed for VLC which has advantages of both photodiode and high-speed camera, that is, high transmission rate and easy detecting of the transmitter. The light receiving section of the hybrid sensor consists of communication pixels and video pixels, which realizes the advantages. This hybrid sensor can communicate in static environment in previous research. However in dynamic environment, high-speed tracking of the transmitter is essential for communication. So, we realize the high-speed tracking of the transmitter by using the information of the communication pixels. Experimental results show the possibility of communication in dynamic environment.

8282-17, Session 6

Energy efficient lighting and communications

Z. Zhou, M. Kavehrad, The Pennsylvania State Univ. (United States); P. Deng, Wuhan National Lab. for Optoelectronics (China)

As LED's increasingly displace incandescent lighting over the next few years, general applications of visible light communication (VLC) technology are expected to include wireless internet access, vehicle-to-vehicle communications, broadcast from LED signage, and machine-to-machine communications.

Power consumption is a very important consideration in home LED illumination infrastructures. We are seeking methods to reduce power consumed by illumination which will bring both economic and environmental benefits. Actually, a scientific management of lights potentially can achieve the power savings goal, as well. Motion triggered illumination is a good approach; however, it provides only two status for each bulb. We are looking for an adaptive, continuous power control scheme.

Our main objective in this paper is to adaptively change working status of each LED respectively according to users' locations. Multiple LEDs on the ceiling builds up an illumination grid where each LED is independently controlled. According to the users locations, grid controller designs an illumination pattern and sends dimming signal to each LED. The program minimizes total power emitted while simultaneously ensuring sufficient light for each user.

The paper also compares OFDM and OOK signals performance in indoor optical wireless communications. The simulation is carried out for different locations where different multi-path spread is experienced. OFDM seems a better choice than prevalent OOK for indoor VLC due to its high resistance to multi-path and delay spread.

8282-18, Session 6

The Smart Room: a 100 Mb/s integrated optical access point transceiver for indoor visible light communication

N. B. Datiri, A. Mirvakili, C. Sthalekar, E. Fu, C. Xi, S. C. Nercessian, T. Shah, B. Noorani, V. M. J. Koomson, Tufts Univ. (United States)

Recent developments in visible light communication (VLC) technology have solidified utilizing light-emitting diodes (LEDs) for not only illumination, but also optical wireless networking. These dual features are implemented in a "smart room" network of LEDs. VLC, in comparison to radio, has provided the ability to attain extremely high data rate densities (Mb/s/m2) to meet growing data traffic demands of portable computing and multimedia wireless devices. The unique attributes of optical signals, such as immunity to electromagnetic interference and spatial confinement, provides an opportunistic medium for optical networking. Furthermore, transceiver integration using well-developed silicon processing paradigms (e.g. CMOS), which are inherently low-power, show promise in providing combined illumination/communication networks with "net-zero" energy increase using LEDs. This paper presents a novel optical access point transceiver that features an addressable transmit/receive matrix of LED and photodetectors arrays. The transmitter array enables combined illumination control and serial data communication for an array of 16 LEDs producing an aggregate data rate of 100 Mb/s using a convolution-based discrete time interleaved driver circuit architecture. A negative feedback circuit provides regulated current for the LED driver. The optical receiver consists of a 16-element array of broadband receiver channels, including a low-power transimpedance amplifier (TIA) driving a differential output limiting amplifier with DC offset cancellation. The access point transceiver is capable of processing multiple user requests by implementation of a winner-take-all control circuit topology. The transceiver was designed in a 0.5μm CMOS process to enable miniaturization and VLC system integration.

8282-19, Session 6

Hybrid positioning with lighting LEDs and Zigbee multihop wireless network

Y. U. Lee, S. Baang, J. Park, Hallym Univ. (Korea, Republic of); Z. Zhou, M. Kavehrad, The Pennsylvania State Univ. (United States)

A simple, accurate, secure, long-lasting, and portable hybrid positioning system is proposed and designed in this paper. It consists of a lighting LED that generates visible light data corresponding to position information of a target and a Zigbee wireless network communication module with low power, security, and service area expansion characteristics. Under an indoor environment where there is 23.62m distance between an observer and the target, the presented hybrid positioning system is tested and is verified with the functions of Zigbee three hop wireless networking and visible light communication (VLC) scheme. The test results are analyzed and discussed.

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8283-02, Session 1

Advanced modulation formats for high-capacity transmission system at 100 G and beyond

J. Yu, ZTEK Corp., Inc. (United States)

No abstract available

8283-03, Session 1

Energy-efficient hybrid coded modulations enabling terabit optical ethernet

I. B. Djordjevic, The Univ. of Arizona (United States)

The exponential internet traffic growth projections require considerable increase of transmission data rates at every level of the underlying information infrastructure, ranging from core to access networks. Higher volumes of traffic also increase the energy consumption of transmission and switching equipment needed to route this traffic. Recent studies indicate that the energy consumed by the Internet equipment is roughly 8% of the total energy consumed in the US with predictions that it can grow up to 50%, with current trend, by the end of this decade. Therefore, the Internet is becoming constrained not only by capacity, but also by its energy consumption.

In order to solve high-bandwidth demands and energy-efficiency problems simultaneously, in this invited paper, we describe several energy-efficient hybrid coded-modulation schemes enabling Terabit optical Ethernet: energy-efficient four-dimensional (4D) single-carrier/multicarrier coded-modulation, energy-efficient 4D-multiband-coded-OFDM, energy-efficient generalized-OFDM, and energy-efficient spatial-domain-based-coded-modulation. The common properties of these schemes are: the employment of energy-efficient coded-modulations, the employment of multiple degrees of freedom for the conveyance of the information on single-carrier optical signal and rate-adaptive coding based on quasi-cyclic LDPC codes. These energy-efficient schemes are called hybrid as they employ all available degrees of freedom for the transmission over optical fiber including amplitude, phase, polarization and orbital angular momentum (OAM). Namely, from Shannon's theory we know that the channel capacity is a linear function in number of dimensions, and by increasing the number of dimensions basis functions originating from different degrees of freedom that are mutually orthogonal in nature we can dramatically improve the overall channel capacity. On the other hand, the energy-efficiency problem can be solved by properly designing the multi-dimensional signal constellations such that the trans-information is maximized, while taking the energy constraint into account. The high potential of these schemes is demonstrated by Monte Carlo simulations. These hybrid coded-modulation schemes are very flexible, as they can be used for various applications ranging from short-haul to long-haul, and can be used in SMF, MMF and free-space optical links.

8284-06, Session 1

Efficient multiplexing and demultiplexing of orbital angular momentum beams

K. M. Birnbaum, B. I. Erkmen, Jet Propulsion Lab. (United States)

In the near-field regime, the number of modes that a free-space communication system can efficiently use is given by the product of the Fresnel numbers of the transmit and receive apertures. It can be advantageous to decompose the field into modes that have rotational symmetry or definite orbital angular momentum (OAM modes). A key challenge to using OAM modes as parallel channels in a practical communication system is multiplexing and demultiplexing the orthogonal OAM modes to an array of single-spatial-mode transmitters and receivers. We discuss various approaches that have been taken to solve this problem and assess their optical efficiency (including the limitations due to finite Fresnel numbers). We also identify a new method, using lenses and holographic phase plates, to efficiently and reversibly convert concentric Laguerre-Gauss OAM beams into an array of separated Gaussian beams.

8284-07, Session 1

Continuous phase modulation parameter optimization for DWDM systems

T. F. Detwiler, A. Blanquet, A. J. Stark, Georgia Institute of Technology (United States); B. E. Basch, Verizon Labs., Inc. (United States); S. E. Ralph, Georgia Institute of Technology (United States)

The constant envelope characteristic of CPM signal is particularly interesting for use in fiber optic links since it can be leveraged to avoid nonlinear phase modulation. Implementation complexity of CPM systems is generally higher than their QPSK counterpart, partly due to the nontrivial task of generating the signal as well as the need to observe the received signal over multiple symbol periods to make an optimal decision. Because of this complexity, the use of full-response CPM systems is favorable for complexity since optimal reception is achieved with lower order, however, partial response systems can achieve higher minimum distance. We analyze parameter selection for CPM transmission, optimizing error performance and spectral efficiency in a tightly filtered reconfigurable optical add-drop multiplexor (ROADM) application. We illustrate their impact on the normalized minimum Euclidean distance (as a proxy for error performance). The impact of parameters on spectral efficiency is implicit on the choice of ROADM filters. The results provide guidance for a suitable choice of CPM scheme for consideration in DWDM systems. Optimal parameters are given for full and partial response systems for a variety of filter scenarios.

8283-04, Session 2

SOA-based Mamyshev-type regeneration: towards an all-optical error correction?

H. Chaouch, College of Optical Sciences, The Univ. of Arizona (United States); F. Küppers, Technische Univ. Darmstadt (Germany)

Photonic balancing has been previously introduced as a novel all-optical regenerative scheme for phase-noise degraded RZ-D(Q)PSK signals. This concept is based on the counter-propagation of demodulated “ones” and “zeros” inside a semiconductor optical amplifier (SOA) working in the saturation regime. Some of the many demonstrated advantages of photonic balancing are: a dual arm output enabling the use of electrical balanced detection, the high saturation output power, as well as a 3-dB optical signal to noise ratio improvement.

In this paper, we demonstrate how photonic balancing can be further improved and extended to a new promising application aimed at removing the in-band noise. We show how the combination of a deeper saturation regime and an appropriate detuned filtering technique can yield total suppression of the demodulated nonlinear phase noise present in the zeros. Furthermore, we present a detailed filtering optimization analysis by means of numerical simulations that provide Q-factor and BER estimates based on a Chi-Squared noise statistics.

Finally, we present a discussion of the different possible interpretations at the origin of these new improvements and investigate some similarities with the existing fiber-based regeneration solutions.

8283-05, Session 2

Integrated photonic components for 100G and beyond

A. K. Srivastava, OneTerabit (United States)

No abstract available

8282-06, Session 2

Microring resonator for optical access networks

M. F. Lipson, Cornell Univ. (United States)

No abstract available

8282-07, Session 2

Power balancing effect on the performance of IMPACC modulator under critical coupling (CC), over coupling (OC), and under coupling (UC) conditions at high frequency

B. B. Dingel, Nasfine Photonics, Inc. (United States); N. Madamopoulos, The City College of New York (United States); A. Prescod, Corning Incorporated (United States); R. Madabhushi, Madabhushi Consultants, LLC (United States)

In this report, we investigate the power balancing effect of an input optical signal on the performance of a linear optical modulator called IMPACC (Interferometric Modulator with Phase-modulating and Cavity-modulating Components). One configuration of IMPACC, which we discuss here, consists of a phase modulator and a ring resonator on different arms of a Mach Zehnder interferometer (MZI). External control of the power split ratio from an input radio frequency (RF) signal into the two separate arms of the interferometer has been shown to add design flexibility and the ability to achieve high spurious free dynamic range (SFDR) of more than 130 dB, when compared to the single-ring RAMZI (Resonator-assisted MZI). Our previous reports have assumed that the power split ratio of the input optical signal into the MZI is 50:50. Here, we include additional power balancing of the input optical signal into the two arms of IMPACC. The resultant effect is reported on for three different conditions; namely, critical coupling (CC), over coupling (OC), and under coupling (UC) conditions at high frequency. We report on this power balancing effect at two separate conditions of high frequency (~23GHz and 70GHz) for a traveling wave electrode design. Lastly, we compare the performance of IMPACC to the single-ring RAMZI with traveling-wave electrode design, both under sub-octave operations.

8284-12, Session 2

InP-based Mach Zehnder modulators for next generation systems

E. Yamada, Y. Shibata, H. Ishii, NTT Photonics Labs. (Japan)

We realized high-speed and low driving voltage InP-based Mach Zehnder modulators with traveling-wave electrodes and an npin high-mesa waveguide structure. Since n-type InP cladding layers are employed on both the signal and ground electrode sides, and there are no thick p-cladding layers, the electrical and optical losses are reduced.

Full C-band 40-Gbit/s DPSK signal was successfully generated using a compact tunable wavelength transmitter module, which incorporated a tunable DFB laser array as a wavelength tunable laser and an InP MZM in one package, with a low driving voltage of 3 Vpp in a push-pull driving configuration.

We have demonstrated 112 Gbit/s RZ-DP-QPSK modulation using two InP MZM modules. One modulator was used as a pulse carver in a push-pull configuration, and the other was used as an IQ modulator in a dual-drive configuration. Since we used an RZ pulse carver to remove the transient region, we obtained clear eye openings without any amplitude ripple.

We also demonstrated a 50 Gbit/s (12.5 Gsymbol/s x 4) 16QAM signal generation employing the novel dual-drive modulation method of a single MZM. We utilized the electro-absorption characteristics of an InP semiconductor to adjust the QPSK amplitude.

We confirmed a single MZM operated as a DPSK, a QPSK, and a 16QAM modulator with the same device. We believe these modulators to be suitable for next generation optical transmission systems.

8283-17, Poster Session

Design of the optical fibers for differential mode delay compensation

V. A. Burdin, A. V. Bourdine, Povolzhskaya State Academy of Telecommunications and Informatics (Russian Federation); O. R. Delmukhametov, Ufa State Aviation Technical Univ. (Russian Federation)

We introduce a method for differential mode delay (DMD) compensation by using a special silica GeO2-doped graded-index multimode optical fiber, which provides a reverse reproducing of mode group velocity diagram of the target fiber, and algorithm for design it. Results of proposed method approbation for synthesis of DMD compensation fiber for OM2+/OM3 category target multimode fiber under both central and overfilled launch conditions are represented.

8283-18, Poster Session

Optical link upgrade by dispersion and nonlinearity management technique realized by compensating optical cable coiled around of fiber optic closure

V. A. Burdin, A. V. Bourdine, K. A. Volkov, Povolzhskaya State Academy of Telecommunications and Informatics (Russian Federation)

We represent results of numerical simulations for upgrade of optical link with SMF by using the dense dispersion management technique based on application of compensating optical cable coiled around of optical closure. It is well known, the main complication of any fiber optic link (in particular, for Metropolitan Area Networks) reconstruction is associated with allotment of land costs. We propose a technique based on compensating fiber optic cable coiled around of fiber optic closure to decrease them. Nonlinearity management for decreasing of quasi-soliton interaction is considered. Based on nonlinear Schrodinger equation the model of optical link regeneration section with dense dispersion and nonlinearity management is described. The nonlinear Schrodinger equation was solved numerically by split-step and variational methods. Estimated values for optical system performance were derived by taking into account the amplified spontaneous emission (ASE) noise, parameters of dispersion map (DM) deviations, and the interaction of solitons.

8283-06, Session 3

An efficient solution for building high-bandwidth active metro and access networks

P. Hostalka, Huawei Technologies Co., Ltd. (Germany); L. Pang, A. Shen, Huawei Technologies Co., Ltd. (China)

No abstract available

8283-07, Session 3

Service driven packet-optical convergence for data-center campus applications and metro applications

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8282-16, Session 3

Visible light communication in dynamic environment using image/high-speed communication hybrid sensor

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As LED's increasingly displace incandescent lighting over the next few years, general applications of visible light communication (VLC) technology are expected to include wireless internet access, vehicle-to-vehicle communications, broadcast from LED signage, and machine-to-machine communications.

Power consumption is a very important consideration in home LED illumination infrastructures. We are seeking methods to reduce power consumed by illumination which will bring both economic and environmental benefits. Actually, a scientific management of lights potentially can achieve the power savings goal, as well. Motion triggered illumination is a good approach; however, it provides only two status for each bulb. We are looking for an adaptive, continuous power control scheme.

Our main objective in this paper is to adaptively change working status of each LED respectively according to users' locations. Multiple LEDs on the ceiling builds up an illumination grid where each LED is independently controlled. According to the users locations, grid controller designs an illumination pattern and sends dimming signal to each LED. The program minimizes total power emitted while simultaneously ensuring sufficient light for each user.

The paper also compares OFDM and OOK signals performance in indoor optical wireless communications. The simulation is carried out for different locations where different multi-path spread is experienced. OFDM seems a better choice than prevalent OOK for indoor VLC due to its high resistance to multi-path and delay spread.

8282-18, Session 3

The Smart Room: a 100 Mb/s integrated optical access point transceiver for indoor visible light communication

N. B. Datiri, A. Mirvakili, C. Sthalekar, E. Fu, C. Xi, S. C. Nercessian, T. Shah, B. Noorani, V. M. J. Koomson, Tufts Univ. (United States)

Recent developments in visible light communication (VLC) technology have solidified utilizing light-emitting diodes (LEDs) for not only illumination, but also optical wireless networking. These dual features are implemented in a “smart room” network of LEDs. VLC, in comparison to radio, has provided the ability to attain extremely high data rate densities (Mb/s/m2) to meet growing data traffic demands of portable computing and multimedia wireless devices. The unique attributes of optical signals, such as immunity to electromagnetic interference and spatial confinement, provides an opportunistic medium for optical networking. Furthermore, transceiver integration using well-developed silicon processing paradigms (e.g. CMOS), which are inherently low-power, show promise in providing combined illumination/communication networks with “net-zero” energy increase using LEDs. This paper presents a novel optical access point transceiver that features an addressable transmit/receive matrix of LED and photodetectors arrays. The transmitter array enables combined illumination control and serial data communication for an array of 16 LEDs producing an aggregate data rate of 100 Mb/s using a convolution-based discrete time interleaved driver circuit architecture. A negative feedback circuit provides regulated current for the LED driver. The optical receiver consists of a 16-element array of broadband receiver channels, including a low-power transimpedance amplifier (TIA) driving a differential output limiting amplifier with DC offset cancellation. The access point transceiver is capable of processing multiple user requests by implementation of a winner-take-all control circuit topology. The transceiver was designed in a 0.5µm CMOS process to enable miniaturization and VLC system integration.

8282-19, Session 3

Hybrid positioning with lighting LEDs and Zigbee multihop wireless network

Y. U. Lee, S. Baang, J. Park, Hallym Univ. (Korea, Republic of); Z. Zhou, M. Kavehrad, The Pennsylvania State Univ. (United States)

A simple, accurate, secure, long-lasting, and portable hybrid positioning system is proposed and designed in this paper. It consists of a lighting LED that generates visible light data corresponding to position information of a target and a Zigbee wireless network communication module with low power, security, and service area expansion characteristics. Under an indoor environment where there is 23.62m distance between an observer and the target, the presented hybrid positioning system is tested and is verified with the functions of Zigbee three hop wireless networking and visible light communication (VLC) scheme. The test results are analyzed and discussed.

8283-08, Session 4

Next-generation ROADM technologies and architecture

M. Sharma, P. B. Hansen, B. Nayar, P. J. Wigley, Oclaro, Inc. (United States)

No abstract available

8283-09, Session 4

Polarization division multiplexed 2x10-Gbps transmissions over 10-km long holey fiber in 1.0-µm waveband photonic transport system

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Photonic transport systems in the C band (1530-1565 nm, 4.3-THz bandwidth) and L band (1565-1625 nm, 7.1-THz bandwidth) have been extensively employed in conventional networks. Continuously expanding demand for greater photonic network capacities has created a need for the use of additional wavebands to strengthen transmission capacities. We recently focus on use of a novel wavelength band such as 1.0-µm (thousand band: T band) together with the conventional C and L bands for enhancing usable optical frequency resources in future photonic networks employing wave-band division multiplexing. Furthermore, we successfully demonstrated an ultra-broadband T-band photonic transport system using a holey fiber (HF) transmission line to create a wide usable optical frequency resources over 8.4-THz (wavelength range: 1037-1068 nm). To construct the ultra-broadband photonic transport system for the T-, C-, and L-bands, the HF is considered to be a great candidate for an ultra-broadband and high-capacity data transmission line. In this study, we demonstrate a polarization division multiplexing (PDM) photonic transport system for doubling optical frequency resources in the T-band. Error-free PDM photonic transmissions in the T band with a clear eye opening at 10 Gbps were successfully achieved over a long-distance of 11.4-km HF transmission line for the first time. To upgrade the present photonic network system, we believe the technologies of the demonstrated T-band PDM together with WDM photonic transport systems using the >10-km long HF transmission line represent a pioneering breakthrough in the use of ultra-broadband optical frequency resources.

8283-10, Session 4

Optimization of broadband detector performance for optical communication: design and simulation

A. Lange, R. Olah, A. Dutta, Banpil Photonics, Inc. (United States); N. K. Dhar, Defense Advanced Research Projects Agency (United States)

High performance detectors are important components in high transmission optical communication networks. Broadband sensors with UV to Infrared detection capabilities are a promising solution as they offer simplicity at low development costs by eliminating the need for multiple detector designs. Significant improvements in the sensitivity of detectors have recently been made due to new material systems, fabrication techniques, and by utilizing novel architectures. However, the application of broadband detectors as common receivers for all optical communication bands (i.e. 650 nm, 980 nm, 1300 nm, 1550 nm) has not yet been achieved. We have developed a detector with a spectral response ranging from near UV to shortwave infrared (SWIR) for optical communication. This work studies the optimization of our detector specifically for its use as a receiver in optical networks. Detailed theoretical and experimental results will be presented during the conference.

8284-27, Session 4

Reduction of crosstalk in a colourless multicasting LCOS based wavelength selective switch by the application of wavefront encoding

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A technique of crosstalk reduction in a wavelength selective switch (WSS) based on phase-only liquid crystal on silicon spatial light modulator technology is demonstrated. These switches typically operate by spatially de-multiplexing the WDM signals, and displaying a corresponding set of blazed gratings to deflect the m = +1 signal order to the required output fibers. Wavefront encoding involves purposefully building defocus into the layout of the optical system. To ensure optimal coupling into an output fiber, focusing power must be added to the gratings. When we route to a single output port this correction is valid for only one diffraction order, with defocus increasing for the other orders. Thus crosstalk can be reduced compared to a standard symmetric Fourier transform based switch where all diffraction orders focused at the fiber plane. Tests at 674nm validate this, and show that there is no measureable reduction in diffraction efficiency, whilst the worse case crosstalk is reduced by >10dB. It is also shown that the replay field can be calculated using a fractional Fourier transform if certain optical symmetry conditions are met. This transform is well suited to hologram design as it can be expressed in terms of standard FFTs, and blends seamlessly into a Gerchberg-Saxton iterative optimization algorithm. An outline of an experiment where defocus was introduced into an optical switch and how the fractional Fourier transform can be applied to wavefront encoding are given. In addition, the suitability of this technique to a multicasting WSS will be discussed.

8284-28, Session 4

Radiation-resistant erbium-doped optical fiber for space applications

J. Thomas, M. Myara, P. Signoret, Univ. Montpellier 2 (France); A. Pastouret, E. Burov, D. E. Boivin, O. Cavani, Draka (France); M. Sotom, M. Maignan, Thales Alenia Space (France); O. Gilard, Ctr. National d'Études Spatiales (France)

In the last decade, there has been increased interest in photonic technology for new satellite applications. One critical issue is the high sensitivity to radiative environments of the Erbium Doped Fiber (EDF). It leads to a radiation-induced absorption (RIA) that is not due to erbium content but mainly to the aluminium that ensures the erbium inclusion in glass.

As the radiation induced losses grow as an exponential function of fiber length, the principal way so far to reduce EDFA degradation has consisted in increasing erbium concentration using conventional doping techniques. However, this is limited by the quenching effect, which impacts the fiber length needed to reach high gain, but also by the Aluminium-induced RIA.

It has been recently proposed an original nanoparticle (NP) doping approach, which allows codopant content decrease with reduced quenching impact, while keeping EDF amplifying performances. A radiation-resistant amplifier can thus be designed as a "quenching-free", heavily-erbium-doped amplifier with low RIA.

We demonstrate for the first time an aluminium-free EDF, exhibiting low quenching and low RIA. Despite the lack of aluminium, using silica NPs allows an erbium concentration close to the one of standard EDFs (200 ppm). This fiber is compared to a 1400 ppm Erbium-doped optical fiber with a strong aluminium concentration. Whereas the two fibers exhibit similar initial optical gain (15 dB under saturation conditions), the NP doped Al-free EDF shows only 2 dB gain reduction after a 600 Gy gamma deposit, while the Al/Er EDF incurs more than 10 dB gain degradation.

8284-29, Session 4

Advanced high-speed polarimeter for telecommunications, optical channel monitoring, and fiber sensing

V. Mikhailov, P. S. Westbrook, OFS Labs. (United States)

Optical Stokes polarimetry is useful in many fields, including telecommunications, test and measurement and sensing. A particularly attractive type of polarimeter uses fiber gratings in a length of hibi fiber. Such polarimeters can have wide optical and RF bandwidths and exhibit a form factor smaller than other polarimetric optical heads. We demonstrated that the device can be used for fast (>100 MHz) characterization of polarization rotation. We also present a generic calibration procedure allowing calibration of the polarimeter without reference polarimeter or known state-of-polarization. Our calibration procedure allows the remote calibration of the polarimeter and was demonstrated using a 30 km fiber spool affected by environmental perturbations. In addition, the device can be used as an optical header/label receiver in telecommunications systems operating with advanced modulation formats such as dual-polarization (DP) QPSK or QAM-16.

We present details of the design and calibration of our in-line fiber polarimeter. In particular, our polarimeter is formed in a single PM fiber and thus has the form of a polarization maintaining (PM) patch chord. We show that the presence of the polarimeter in the patch-chord has minimal effect on the transmitted signal, having very low polarization dependent loss and very little degradation of the PM extinction ratio. We show how the polarimeter can be used as an accurate, high speed monitor of the extinction ratio of the light in a PM patch chord. Thus our active PM patch-chord would allow for active monitoring of the state of polarization launched into any PM fiber.

8283-11, Session 5

Operation View: the key challenges for the implementation of new functionalities in a new 40G/100G (terabit) network

H. Mayer, Deutsche Telekom AG (Germany)

No abstract available

8283-12, Session 5

Modern transmission networks: high bandwidth, long ranges, and high flexibility

F. Masiak, A. Reinking, Vodafone D2 GmbH (Germany)

No abstract available

8283-13, Session 5

Network architecture in a converged optical + IP network

W. Wakim, H. Zottmann, Cisco Systems, Inc. (United States)

No abstract available

8283-14, Session 5

On-line routing, wavelength assignment, and spectrum allocation in wavelength convertible flexible optical WDM networks

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Traffic in Metropolitan Area Networks (MANs) that bridge between access and backhaul networks is highly dynamic and requires heterogeneous bandwidth granularities. Flexible optical WDM (FWDM) networks can support such emerging traffic by offering finer granularity line rates using flexible amounts of spectral resources. While establishing connections in FWDM networks, a control plane must observe spectral continuity and spectral conflict constraints in addition to the wavelength continuity constraint, and that may cause higher blocking in the network. To relax the spectral and wavelength continuity constraints along the routes, in this paper, we introduce a wavelength convertible flexible WDM network (WC-FWDM) architecture that offers wavelength conversion capability in addition to dynamic allocation of network resources, and dynamic provisioning of connections. A key issue in WC-FWDM networks is for a given network, and arrival/departure distributions of traffic demands with heterogeneous line rates, how to establish lightpaths, assign wavelengths, and allocate spectrum on-line, such that the connection blocking probability is minimized. We refer to this problem as on-line Routing, Wavelength assignment, and Spectrum Allocation problem in WC-FWDM networks. We propose an auxiliary-graph based polynomial-time heuristic-algorithm for the first time. Numerical results demonstrate that WC-FWDM networks with full, limited, and sparse conversion capability can reduce the blocking of connections, and improve network throughput over FWDM and fixed grid networks. Furthermore, sharing of wavelength converters over time and space in limited and sparse wavelength conversion can achieve the same benefits as in the full wavelength conversion in WC-FWDM networks.

8283-15, Session 5

Using omnipresent ethernet based packet optical transport networks

A. Gumaste, Indian Institute of Technology Bombay (India)

No abstract available

8283-16, Session 5

100G and beyond: optical transmission activities in Brazil

J. C. R. F. de Oliveira, V. B. Ribeiro, J. C. M. Diniz, R. Silva, E. P. Silva, L. H. H. Carvalho, D. M. Pataca, F. D. Simoes, Fundacao CpqD (Brazil)

No abstract available

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8282-02, Session 1

Optical signal processing for wireless transmission

T. Kawanishi, National Institute of Information and Communications Technology (Japan)

Recently, huge capacity optical transmission over 10Tb/s was demonstrated by using advanced optical modulation schemes. However, data rates of conventional commercial wireless links would not achieve to more than 10 Gb/s. The capacity mismatches between optical wired and radio wireless link technologies could cause the bottleneck in future wired and wireless seamless networks. Millimeter-wave bands are attracting attention because of the availability of wideband for high-speed transmission. However, due to the limitation of the performance of electric signal processing, it is rather difficult to modulate and demodulate millimeter-wave signals with high-speed baseband modulation. In this presentation, we discuss optical signal processing for high-speed modulation of millimeter-wave, based on high-speed and precise lightwave control. In optical fiber communication systems, various types of modulation formats, such as quadrature-amplitude-modulation, are reported to achieve high-speed transmission. Optical two-tone signals can be converted into millimeter-wave signals by using high-speed photodetectors. This technique can be used for distribution of stable reference signals in large-scale antenna arrays for radio astronomy. By using the millimeter-wave signal generation technique and the optical advanced modulation formats, we can achieve high-speed modulation of millimeter-waves, where the carrier frequency and bit rate can be over 90GHz and 30Gb/s, respectively.

8284-03, Session 1

Multi-input injection locking in single mode Fabry-Pérot laser diode and its application in optical signal processing

B. Nakarmi, M. Rakib-Uddin, Y. H. Won, KAIST (Korea, Republic of)

In recent years, all-optical signal processing has been receiving more attention due to their numerous capabilities such as less electromagnetic interference, and data transparency in high speed optical computing and networking. One of the various technologies that have been used for the optical signal processing is FP-LDs which are based on the injection locking principle. Till now all the signal processing based on FP-LDs works on the single input injection locking which had made the constraint on its application on various signal processing scheme.

In this paper, we proposed a new idea of multi-input injection locking (MIL) and combinational multi-input injection locking (CMIL) in SMFP-LDs. The basic idea behind MIL and CMIL is the proper power management of the input injected beams. We propose injection locking of multiple inputs and the suppression of the dominant mode will occur only when certain conditions are fulfilled else the dominant mode will not be suppressed even there are inputs which are injection locked to some of the side modes of FP-LD. With these principles the multi-input logic gates using SMFP-LDs can be realized. The dependence of the suppression of dominant mode of SMFP-LD with numbers of input (2, 3 and 4 input) with input wavelength detuning, modes of input injected, and the combined input power are analyzed. We will show how the proposed injection locking can be used for realizing different optical subsystems such as logic gates for signal processing with 10 Gbps input data signals. with this principle the multi-logic functions can be implemented using SMFP-LDs.

8282-03, Session 1

Adjustable transfer function optical filter for microwave applications

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All-optical techniques for microwave and radio frequency (RF) signal processing has attracted considerable attention in recent years. An important optical component in these all-optical signal processing techniques is the optical filter. Tunable optical filters with a variety of transfer functions have been proposed. However, adjustability of the optical filter transfer function is required to provide an extra degree of control. This adjustability of the shape of the transfer function has not been addressed adequately in the literature. In this paper, we report on the theoretical basis for an all-fiber based adjustable transfer function optical filter. In particular, we model the optical filter using FO-circuit transfer matrices and Jones matrices to fully describe the state of polarization changes of the optical signals through the optical filter. The filter is based on an all fiber Michelson Gires-Turnois interferometer (MGTI). The Gires-Turnois resonators (GTRs) required for the formation of the MGTI are realized by pairs of fiber-loop mirrors in the two arms of the Michelson interferometer. The optical reflectivity of the GTRs is control via adjustment of the polarization in the fiber loop mirrors. We show that arbitrary transfer functions can be realized by adjusting the reflectivities of the FLMs as well as the length of the GTRs. Arbitrary filter transfer functions are accomplished by proper control of the reflectance of fiber loop mirrors and the cavity length of the GTRs.

8284-04, Session 1

Super receiver design for superchannel coherent optical systems

C. Liu, J. Pan, T. F. Detwiler, A. J. Stark, Y. Hsueh, G. Chang, S. E. Ralph, Georgia Institute of Technology (United States)

To meet the bandwidth requirement of future optical networks, 1Tb/s and beyond transmission systems based on "super-channel" architectures have recently been considered as alternatives to electrical OFDM. Nyquist WDM and Coherent Optical-OFDM are the two main approaches to achieve ultra high spectral efficiency in super-channel coherent systems. We investigate receiver architectures for Nyquist WDM super-channel coherent system, and propose a new "super receiver" architecture, which achieves better performance compared to conventional coherent receivers.

In Nyquist WDM coherent systems, in which the conventional WDM subcarriers are packed tightly to realize near-baud-rate or baud-rate spacing operation, inter-channel interference (ICI) occurs, which significantly degrades system performance. It is possible to eliminate ICI with baud-rate spacing in a CO-OFDM system, however this requires frequency locking and sinc-pulse shaping per transmitter via digital-to-analog converters (DACs). Otherwise, baud-rate spacing is non-orthogonal and incurs significant ICI. The traditional way to mitigate the impact of ICI is by applying aggressive optical filter to each channel before optical multiplexing, however this induces severe inter-symbol interference (ISI). Accordingly previous research focused on how to mitigate the linear ISI penalty associated with the tight filtering.

In this work, we propose a novel super-receiver scheme which jointly detects and demodulates multiple channels simultaneously. By taking advantage of information from side channels using DSP to cancel ICI, we achieve improved performance compared to conventional schemes which process the channels independently. Several joint DSP algorithms are developed and tested through simulated data. Simulation results demonstate that more than 2 dB ONSR gain is achieved at narrow channel spacing conditions.

8284-05, Session 1

Uncooled MIMO WDM system using advanced receiver signal processing techniques

S. H. Lee, R. V. Penty, I. H. White, Univ. of Cambridge (United Kingdom); D. G. Cunningham, Avago Technologies Ltd. (United Kingdom)

Current DWDM systems require components such as laser diodes and multiplexers to operate at precise wavelengths with precise temperature control. We propose a new form of narrow channel spacing WDM system which uses uncooled lasers, DE/MUXes and receivers. It removes control of laser wavelengths and thus energy consumption of their temperature control systems at the expense of a slightly more complicated receiver design. The system allows the wavelength of the lasers to drift but uses a cyclic demultiplexer at the receiver with more detectors than signal channels so that the separate WDM signals can be decoded with carefully designed signal processing algorithms. The system is designed with narrow channel separations, typically 0.65nm to 1.00nm. By tracking the individual signals, weighting all the received signals and canceling crosstalk, channel restoration and hence low error rate uncooled WDM transmission is achieved. In extreme cases, if too many signal channels fall within a single receiver channel and hence too much crosstalk limits the electronic signal decoding performance, modest D.C. current tuning of the laser wavelength can be used to ensure the required separation. The weights used in crosstalk cancellation unit are calculated by minimize-mean-square-error algorithm, being similar to that used in 10GbE currently. Simulation and experimental results with offline signal processing for a 4-wavelength 10Gb/s WDM system over 25km SMF prove the feasibility of this approach with a maximum of 5dBe penalty in the worst-case states. Further work on extending the approach to a 32-wavelength system will be presented in the conference.

8283-02, Session 2

Advanced modulation formats for high-capacity transmission system at 100 G and beyond

J. Yu, ZTEK Corp., Inc. (United States)

No abstract available

8283-03, Session 2

Energy-efficient hybrid coded modulations enabling terabit optical ethernet

I. B. Djordjevic, The Univ. of Arizona (United States)

The exponential internet traffic growth projections require considerable increase of transmission data rates at every level of the underlying information infrastructure, ranging from core to access networks. Higher volumes of traffic also increase the energy consumption of transmission and switching equipment needed to route this traffic. Recent studies indicate that the energy consumed by the Internet equipment is roughly 8% of the total energy consumed in the US with predictions that it can grow up to 50%, with current trend, by the end of this decade. Therefore, the Internet is becoming constrained not only by capacity, but also by its energy consumption.

In order to solve high-bandwidth demands and energy-efficiency problems simultaneously, in this invited paper, we describe several energy-efficient hybrid coded-modulation schemes enabling Terabit optical Ethernet: energy-efficient four-dimensional (4D) single-carrier/multicarrier coded-modulation, energy-efficient 4D-multiband-coded-OFDM, energy-efficient generalized-OFDM, and energy-efficient spatial-domain-based-coded-modulation. The common properties of these schemes are: the employment of energy-efficient coded-modulations, the employment of multiple degrees of freedom for the conveyance of the information on single-carrier optical signal and rate-adaptive coding based on quasi-cyclic LDPC codes. These energy-efficient schemes are called hybrid as they employ all available degrees of freedom for the transmission over optical fiber including amplitude, phase, polarization and orbital angular momentum (OAM). Namely, from Shannon's theory we know that the channel capacity is a linear function in number of dimensions, and by increasing the number of dimensions basis functions originating from different degrees of freedom that are mutually orthogonal in nature we can dramatically improve the overall channel capacity. On the other hand, the energy-efficiency problem can be solved by properly designing the multi-dimensional signal constellations such that the trans-information is maximized, while taking the energy constraint into account. The high potential of these schemes is demonstrated by Monte Carlo simulations. These hybrid coded-modulation schemes are very flexible, as they can be used for various applications ranging from short-haul to long-haul, and can be used in SMF, MMF and free-space optical links.

8284-06, Session 2

Efficient multiplexing and demultiplexing of orbital angular momentum beams

K. M. Birnbaum, B. I. Erkmen, Jet Propulsion Lab. (United States)

In the near-field regime, the number of modes that a free-space communication system can efficiently use is given by the product of the Fresnel numbers of the transmit and receive apertures. It can be advantageous to decompose the field into modes that have rotational symmetry or definite orbital angular momentum (OAM modes). A key challenge to using OAM modes as parallel channels in a practical communication system is multiplexing and demultiplexing the orthogonal OAM modes to an array of single-spatial-mode transmitters and receivers. We discuss various approaches that have been taken to solve this problem and assess their optical efficiency (including the limitations due to finite Fresnel numbers). We also identify a new method, using lenses and holographic phase plates, to efficiently and reversibly convert concentric Laguerre-Gauss OAM beams into an array of separated Gaussian beams.

8284-07, Session 2

Continuous phase modulation parameter optimization for DWDM systems

T. F. Detwiler, A. Blanquet, A. J. Stark, Georgia Institute of Technology (United States); B. E. Basch, Verizon Labs., Inc. (United States); S. E. Ralph, Georgia Institute of Technology (United States)

The constant envelope characteristic of CPM signal is particularly interesting for use in fiber optic links since it can be leveraged to avoid nonlinear phase modulation. Implementation complexity of CPM systems is generally higher than their QPSK counterpart, partly due to the nontrivial task of generating the signal as well as the need to observe the received signal over multiple symbol periods to make an optimal decision. Because of this complexity, the use of full-response CPM systems is favorable for complexity since optimal reception is achieved with lower order, however, partial response systems can achieve higher minimum distance. We analyze parameter selection for CPM transmission, optimizing error performance and spectral efficiency in a tightly filtered reconfigurable optical add-drop multiplexor (ROADM) application. We illustrate their impact on the normalized minimum Euclidean distance (as a proxy for error performance). The impact of parameters on spectral efficiency is implicit on the choice of ROADM filters. The results provide guidance for a suitable choice of CPM scheme for consideration in DWDM systems. Optimal parameters are given for full and partial response systems for a variety of filter scenarios.

8282-04, Session 3

Coherent OCDMA communication systems

X. Wang, Heriot-Watt Univ. (United Kingdom)

The recent progress of coherent OCDMA system will be reviewed in this paper.

8282-05, Session 3

VCSEL-based optical transceiver module operating at 25 Gb/s and using a single CMOS IC

G. Afriat, L. Horwitz, D. Lazar, A. Issachar, A. Pogrebinsky, A. Ran, E. Shoor, R. Bar, R. Saba, Intel Corp. (Israel)

We present here a low cost, small form factor, optical transceiver module composed of a CMOS IC, a high bandwidth 850nm emission wavelength VCSEL, and an InGaAs/InP PIN Photo Diode (PD). The CMOS IC is fabricated in standard 28nm CMOS process and integrates all the required transmitter and receiver circuits including a PLL generating the TX (Transmit) clock, a VCSEL Driver modulating the off-chip VCSEL at 25-Gb/s, a Transimpedance Amplifier (TIA), a Limiting Post Amplifier, and a Clock Data Recovery (CDR) block sampling the RX (receive) data at 25-Gb/s.

The module is designed to support 4 channels of 25-Gb/s each for a total data rate of 100-Gb/s and measures 12mm X 12mm, although at this point we have utilized only one channel out of the four. The transceiver module couples into a 62.5/125 um multi-mode TX/RX fiber pair (OM1) via a low cost plastic cover and a simple connector realizing the transmitter and receiver lens systems and bringing the module height to a mere 1.85mm.

An on-chip data generator generates PRBS data sequences in the length of 211-1. This data is transmitted and recorded on an external scope at the TX fiber output to construct the transmitter optical eye. The TX Eye shows an OMA of 1.5dBm and ER of 5.8dB, while a jitter analysis gives DJ (Deterministic Jitter) of 6.6ps and RJ (Random Jitter) of 0.9ps RMS.

The receiver sensitivity was tested by injecting an optical PRBS-11 sequence, generated by an external pattern generator, into the OM1 TX/RX fiber pair that couples into the transceiver module. An on-chip Error Checker compares the received data to a PRBS-11 sequence and reports via JTAG any error detected as well as the bit count received and checked for errors. The receiver sensitivity at BER = 10-12 was found to be -4.6 dBm OMA under stressed conditions of 1.2dB VECP (Vertical Eye Closure Penalty) and 7 ps ptp DJ due to ISI (Inter Symbol Interference).

For a full link BER test, two modules were connected at each side of a TX/RX fiber pair, transmitting PRBS-11 data sequences which are asynchronous to each other. The Error Checkers on each side were used to verify the RX data integrity and the transceiver modules demonstrated BER < 10-12 at the 25-Gb/s data rate over 3-meters of OM1 (62.5/125 um) fiber and over 30-meters of OM3 (50/125 um) fiber.

8284-08, Session 3

Optical OFDM based on the fractional Fourier transform

G. Cincotti, Univ. degli Studi di Roma Tre (Italy)

Orthogonal Frequency Division Multiplexing (OFDM) is still quite popular within the fiber-optic community, mainly because many theoretical and experimental results have demonstrated that this technique is fairly effective in mitigating chromatic dispersion, polarization mode dispersion and nonlinear effects.

Typically, the standard OFDM is based on the fast Fourier transform (FFT) algorithm, that is easy to be electronically or optically implemented, and frequency-domain decomposes the input signal into several parallel streams. The equally spaced subcarriers are orthogonal, present overlapping spectra and are free from intersymbol interference.

In this paper, we describe a novel OFDM technique based on orthogonal chirped subcarriers, that correspond to the fractional Fourier transform (FrFT). The FrFT is a generalization of the Fourier transform (FT) in the time-frequency plane: whereas the standard FT can be seen as the projection of a given signal on the frequency axis (a rotation of pi/2 with respect to the time axis), the FrFT can be interpreted as the projection of the signal on an axis that forms an angle p pi/2, with 0<p<2, i.e. a rotation in the time-frequency plane.

We show that the FrFT can be electronically implemented with a complexity equivalent to the traditional FFT; on the other hand, the planar device that implements the FrFT is similar to the arrayed waveguide grating (AWG) component that performs the FFT.

We analyze the spectral efficiency, the crosstalk, the peak-to-average power ratio (PAPR), the phase noise sensitivity of a FrFT-based optical OFDM system, and make an accurate comparison with the standard FT-based implementation.

8284-09, Session 3

Reconfigurable optical transmitters and receivers

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Recent advances in electronic data processing allow constructing reconfigurable optical transmitters and receivers, where modulation formats and symbol rates are set by software-controlled field programmable gate arrays (FPGA). We report on such a real-time optical transmitter for 8 modulation formats, which can be swapped in 5 ns without data loss. With single-polarization 64QAM symbols generated at 28 GBd, we transmit data at 168 Gbit/s in real time. A similar arrangement defines a single-polarization orthogonal frequency division multiplexing (OFDM) transmitter for a data rate of 101.5 Gbit/s, where 58 subcarriers are encoded with 16QAM data. With a different software setup, the FPGA realizes an optical 56 Gbit/s transmitter for sinc-shaped so-called Nyquist pulses, the spectrum of which is rectangular having the minimum theoretically achievable bandwidth (suitable for Nyquist wavelength division multiplexing, N-WDM). For terabit OFDM reception, optical pre-processing is required to demultiplex high-bitrate signals down to lower-bitrate tributaries, which then can be processed electronically. We discuss a 10.8 Tbit/s (26 Tbit/s) receiver employing an all-optical fast Fourier transform to demultiplex 75 (325) optical subcarriers modulated with 16QAM-formated symbols at a rate of 18 GBd (10 GBd). Groups with any number of subcarriers can be selected with a simple hardware recon-figuration step.

8284-10, Session 3

Performance of 32-Gbaud PDM-QPSK in nonlinear transport regimes with different phase recovery methods

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We experimentally investigate the performance of WDM coherent polarization-division multplexed-return to zero-quadrature phase shift keying (PDM-RZ-QPSK) network in nonlinear transport regimes. Six, 32-Gbaud PDM-RZ-QPSK channels are employed on a 50-GHz grid and transmitted over 1600-km fiber on an all-EDFA recirculating loop without any dispersion compensation module (DCM). The transmission link is configured entirely of either standard single-mode fiber (AllWave) or nonzero dispersion fiber with large effective area (TrueWave Reach). We sweep the launch power of the center channel and side channels independently to measure the nonlinear effects of self-phase modulation (SPM), cross-phase modulation (XPM), and cross-polarization modulation (XPolM) on the center channel's BER performance. Furthermore, for all link configurations, we employ three different carrier phase recovery methods in the demodulation routine - Viterbi-Viterbi, Viterbi-Viterbi with a minimum mean-squared error (MMSE) filter, and phase-locked loop (PLL) - to ascertain their relative performance in the presence of nonlinear effects.

8284-11, Session 3

Performance of PM QPSK and PM 16-QAM coherent optical fiber communication systems

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The performance of polarization multiplexed, quadrature phase shift keying (PM-QPSK) and polarization multiplexed 16-ary quadrature amplitude modulation (PM-16QAM) is considered with an emphasis on the signal processing algorithms that compensate transmission impairments and implement key receiver functions.

8283-04, Session 4

SOA-based Mamyshev-type regeneration: towards an all-optical error correction?

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Photonic balancing has been previously introduced as a novel all-optical regenerative scheme for phase-noise degraded RZ-D(Q)PSK signals. This concept is based on the counter-propagation of demodulated “ones” and “zeros” inside a semiconductor optical amplifier (SOA) working in the saturation regime. Some of the many demonstrated advantages of photonic balancing are: a dual arm output enabling the use of electrical balanced detection, the high saturation output power, as well as a 3-dB optical signal to noise ratio improvement.

In this paper, we demonstrate how photonic balancing can be further improved and extended to a new promising application aimed at removing the in-band noise. We show how the combination of a deeper saturation regime and an appropriate detuned filtering technique can yield total suppression of the demodulated nonlinear phase noise present in the zeros. Furthermore, we present a detailed filtering optimization analysis by means of numerical simulations that provide Q-factor and BER estimates based on a Chi-Squared noise statistics.

Finally, we present a discussion of the different possible interpretations at the origin of these new improvements and investigate some similarities with the existing fiber-based regeneration solutions.

8283-05, Session 4

Integrated photonic components for 100G and beyond

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No abstract available

8282-06, Session 4

Microring resonator for optical access networks

M. F. Lipson, Cornell Univ. (United States)

No abstract available

8282-07, Session 4

Power balancing effect on the performance of IMPACC modulator under critical coupling (CC), over coupling (OC), and under coupling (UC) conditions at high frequency

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In this report, we investigate the power balancing effect of an input optical signal on the performance of a linear optical modulator called IMPACC (Interferometric Modulator with Phase-modulating and Cavity-modulating Components). One configuration of IMPACC, which we discuss here, consists of a phase modulator and a ring resonator on different arms of a Mach Zehnder interferometer (MZI). External control of the power split ratio from an input radio frequency (RF) signal into the two separate arms of the interferometer has been shown to add design flexibility and the ability to achieve high spurious free dynamic range (SFDR) of more than 130 dB, when compared to the single-ring RAMZI (Resonator-assisted MZI). Our previous reports have assumed that the power split ratio of the input optical signal into the MZI is 50:50. Here, we include additional power balancing of the input optical signal into the two arms of IMPACC. The resultant effect is reported on for three different conditions; namely, critical coupling (CC), over coupling (OC), and under coupling (UC) conditions at high frequency. We report on this power balancing effect at two separate conditions of high frequency (~23GHz and 70GHz) for a traveling wave electrode design. Lastly, we compare the performance of IMPACC to the single-ring RAMZI with traveling-wave electrode design, both under sub-octave operations.

8284-12, Session 4

InP-based Mach Zehnder modulators for next generation systems

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We realized high-speed and low driving voltage InP-based Mach Zehnder modulators with traveling-wave electrodes and an npin high-mesa waveguide structure. Since n-type InP cladding layers are employed on both the signal and ground electrode sides, and there are no thick p-cladding layers, the electrical and optical losses are reduced.

Full C-band 40-Gbit/s DPSK signal was successfully generated using a compact tunable wavelength transmitter module, which incorporated a tunable DFB laser array as a wavelength tunable laser and an InP MZM in one package, with a low driving voltage of 3 Vpp in a push-pull driving configuration.

We have demonstrated 112 Gbit/s RZ-DP-QPSK modulation using two InP MZM modules. One modulator was used as a pulse carver in a push-pull configuration, and the other was used as an IQ modulator in a dual-drive configuration. Since we used an RZ pulse carver to remove the transient region, we obtained clear eye openings without any amplitude ripple.

We also demonstrated a 50 Gbit/s (12.5 Gsymbol/s x 4) 16QAM signal generation employing the novel dual-drive modulation method of a single MZM. We utilized the electro-absorption characteristics of an InP semiconductor to adjust the QPSK amplitude.

We confirmed a single MZM operated as a DPSK, a QPSK, and a 16QAM modulator with the same device. We believe these modulators to be suitable for next generation optical transmission systems.

OPTO
SPIE Photonics West

8284-13, Session 5

Few mode fibers for mode division multiplexing transmission

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The state of the art transmission capacity of single-mode fiber has now exceeded 100 Tbit/s. There are two obstacles to further increae the transmission capacity. One is degradation of OSNR tolerance in transmission system, and the other is high transmitted optical power density in an optical fiber core. The mode division multiplexing is one of an emerging technology to extend transmission capacity of an optical fiber. One way to achieve 10 mode multiplexing transmission is to use first three LP modes of LP01, LP11, and LP21 modes which consists of 2, 4, and 4 modes, respectively.

The 10x10 multi-input multi-output (MIMO) processing, a straightforward technique to separate these 10 modes, requires massive computation. There may be an alternative to combine optical LP mode separation and MIMO processing. With optical mode separation, 2x2 or 4x4 MIMO separation is sufficient to separate all 2 or 4 modes within each LP mode. In this technique, mode mixing between different LP modes cause power crosstalk, that degrade transmission characteristics. Few mode fibers for this purpose should have sufficient modal index difference among different LP modes to make small mode coupling among them.

This paper focuses on required fiber properties of mode crosstalk, differential mode delay, and mode dependent loss, for mode division multiplexing transmission with optical LP mode separation.

8284-14, Session 5

Efficient optical amplification for spatial division multiplexing

P. M. Krummrich, Technische Univ. Dortmund (Germany)

Invited talk

8284-15, Session 5

Multimode fiber amplifier with tunable modal gain using a reconfigurable multimode pump

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We propose a method for controlling modal gain in a multimode Erbium-doped fiber amplifier (MM-EDFA) by tuning the mode content of a multimode pump. By adjusting the powers and orientation of input pump modes, modal dependent gain can be tuned over a large dynamic range. We investigated a EDFA which can support LP01,s and LP11,s signal modes and LP01,p, LP11,p, LP21,p and LP02,p pump modes using numerical simulation. By adjusting relative amount of LP01,p and LP21,p, the gains of the LP01,s and LP11,s signal modes can be tuned over a wide dynamic range. The relative gain between the two spatially degenerate LP11,s signal modes can also be adjusted by adding a small amount of LP11?,p which is the even LP11e,p mode rotated by angle ?. Performance impact due to excitation of unwanted pump modes at the input of the EDF, mode coupling and macro-bending loss in the fiber was also investigated. An experiment was also demonstrated for mode division multiplexing signal amplification using proposed MM-EDFA. The proposed modal gain control scheme can be generalized for an N-mode MM-EDFA by varying the powers of N well-chosen pump modes. The MM-EDFA may potentially be a key element for long haul mode-division multiplexed transmission.

8284-16, Session 5

Fabrication and characterization of ion-exchanged glass binary phase plates for mode-division multiplexing

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In response to ever growing data traffic, significant efforts are being made to increase optical network capacity. As a result, a number of technologies have been proposed and implemented to encode information in the amplitude, phase, frequency and polarization of the optical wave. The most advanced combination of such technologies has recently enabled transmission up to 100 Tb/s in a single-mode fiber (SMF). Such a striking number suggests the exploration of new strategies to further increase fiber capacity. One promising candidate is Mode-division multiplexing (MDM) in few-mode fibers (FMF), which uses space as a new information-bearing dimension.

A fundamental element for MDM is a modal transformer, which converts the fundamental mode of an SMF into the excited modes (LP11, LP21) of a FMF. Modal transformation can be implemented in a free-space basis by using multi-region phase plates. To prevent modal cross-talk at the modal MUX/DEMUX stage, high quality modal transformation is desired. In consequence, fabrication of the phase plates must provide an accurate, stable and steep phase-shift between regions. In this work we present the design, fabrication and characterization of monolithic binary phase plates by highly-uniform Ag+/Na+ ion-exchange (IE) in glass. By employing a Gaussian model for the IE process, fabrication parameters have been optimized for different operation wavelengths. The multi-region masks to get selective IE have been made by high-precision photolithography. Phase plates are characterized by interferometry together with a phase recovery algorithm. Coupling experiments onto a FMF have been conducted and high quality mode transformation has been confirmed.

8284-17, Session 6

Low-crosstalk multi-core fibers for long-haul transmission

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In current optical fiber transmission systems, transmission capacity is limited by the nonlinear effects, the fiber fuse phenomenon, and so on. In order to overcome these issues, space division multiplexing (SDM) technique based on multi-core fibers (MCFs) has been recently investigated actively. The number of cores able to be multiplexed in a fiber is determined by the core-to-core spacing with a fixed outer cladding diameter. However, the small inter-core distance results in a large crosstalk between neighboring cores. The only way to decrease the core pitch is decreasing the mode field diameter (MFD) if the cutoff wavelength is fixed, or increasing the cutoff wavelength if the MFD is fixed, in a step-index MCF (SI-MCF) with homogeneous core arrangement.

In this presentation, the limitations of crosstalk and core-to-core distance in SI-MCFs are clarified, and the low-crosstalk MCF structures, such as trench-assisted and hole-assisted MCFs, are investigated for long-haul transmission with high core density. It is shown that the crosstalk between neighboring cores can be greatly suppressed even if the MFD and the cutoff wavelength are fixed compared with SI-MCFs. Moreover, another important issue in designing MCF is a consideration of bending effect. Especially, in MCFs with homogeneous core arrangement, the inter-core-crosstalk is degraded as increasing the bending radius. On the other hand, in MCFs with heterogeneous core arrangement, the inter-core-crosstalk can be sufficiently suppressed for bending radii of larger than a specific value. The low-crosstalk heterogeneous MCFs with bending radius insensitive characteristics are also discussed.

8284-18, Session 6

Supermodes for optical transmission

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In this paper, the concept of supermode is introduced for long distance optical transmission systems. The supermodes exploit coupling between the cores of a multi-core fiber, in which the core-to-core distance is much shorter than that in conventional multi-core fiber. The number, arrangement and distance of the cores in the proposed coupled multi-core fiber (CMCF) can be manipulated to obtain better transmission performance for supermodes. Here four-core, six-core and three-core structures are selectively presented with different purposes. Due to short core-to-core distance, CMCFs achieve a higher mode density and larger mode effective area than conventional multi-core fibers, which are essential for spatial division multiplexing and nonlinearity reduction. Through simulations, we show that the proposed CMCF allows lower modal dependent loss, mode coupling and differential modal group delay than few-mode fibers, which are also crucial for spatial division multiplexing. In addition, CMCF amplifiers are expected to have higher cladding pump efficiency with a closer spacing between cores. These properties suggest that the coupled multi-core fiber could be a good candidate for both spatial division multiplexing and single-mode operation. In order to put it in practice, the supermode stability with fiber imperfections is studied analytically. Compound CMCF structures are applied to further reduce differential modal group delay and bending loss. Supermode excitation and demultiplexing methods are also demonstrated.

8284-19, Session 6

Measurement of complex mode amplitudes in multimode fiber

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In this paper a simple optical technique is described for the measurement of complex mode amplitudes in multimode fibers. This is interesting and important, because it can be used in studies of mode mixing, scattering, micro bending loss and role of many other environmental influences on the guiding of the light in the fibers. The technique described here involves the launching of laser beam into the core of the multimode fiber, which excites a mixture of normal modes. The excited mode patterns are analysised with optical components and stored in the microcomputer. The electromagnetic field in the cylindrical waveguide is represented as the supervision of Hermit polynomial modes that are linearly polarized along the direction orthogonal to the fiber axis. The field is expressed in terms of Jones vector. Using Mat lab software library of Hermit polynomial modes has been generated and complex mode amplitudes are then extracted from these recoded intensities with help of modified version of Gerchberg-Saxton algorithm.

8284-20, Session 6

Detailed modeling of integrated IQ-transmitters for 100G+ applications

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Photonic Design automation (PDA) plays a significant role when designing sophisticated photonic circuits performing very complex functions by providing a compliant, time-efficient and reliable simulation environment. One of the key technologies of modern 100G applications is the in-phase/quadrature (IQ) transmitter representing a versatile optical transmitter concept supporting various multilevel modulation formats as it allows direct electronic encoding of arbitrary points on the complex signal constellation plane. Further on, the optical transmission channel becomes transparent to the applied electrical drive signal in conjunction with coherent optical detection, allowing the application of powerful electronic signal processing techniques.

Using time-and-frequency-domain modeling (TFDM) of a Photonic Integrated Circuit (PIC), we derive detailed IQ-transmitter models based on the physics and architecture of the underlying active and passive subcomponents. This modeling approach allows linking characteristics of subcomponents (bending loss of waveguides, phase changes in multimode interference couplers, sweep-out time of electro-absorption sections) to systems-level characteristics of the integrated IQ-transmitter (extinction ratio, modulation bandwidth, chirp). On the systems design side, a behavioral transmitter model based on measured and simpler parametric characteristics is more appropriate, though. Such a model can be used for instance to derive electrical driving requirements (allowed jitter, noise, synchronization offset) and assess for various modulation formats the impact of transmitter limitations (modulation bandwidth, chirp) on system performance.

We present with this contribution different techniques for modeling the physics and systems-level characteristics of integrated IQ-transmitters for typical 100G applications and emphasize on important design aspects.

8284-21, Session 7

MLSE for linear and nonlinear ISI mitigation in optical coherent detection systems

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The applications of coherent detection and digital signal processing have enabled significant performance improvements in optical fiber transmission. The expected increase in future capacity demand could be satisfied by employing spectrally efficient modulation formats together with coherent detection and higher data rates. For long-haul transmission, however, system reach may significantly decrease when using multi-level modulation formats to improve spectral efficiency. Also, nonlinear transmission effects can be limiting factors as high bit rate and spectrally efficient systems require higher signal power to ensure adequate signal to noise ratio at the receiver. In this paper we investigate the performance of a maximum likelihood sequence estimation (MLSE) scheme in optical fiber transmission systems. We show that the MLSE scheme can effectively reduce linear and nonlinear inter-symbol interference (ISI) penalty and, thus, help to improve spectral efficiency and nonlinearity tolerance in long-haul transmissions.

8284-22, Session 7

Stimulated Raman crosstalk in WDM system employing distributed Raman amplifier for DPSK and OOK modulation format

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Stimulated Raman scattering (SRS) causes power change in ith channel of WDM system due to simultaneous power transfer from shorter wavelength channel and to longer wavelength channel. In distributed Raman amplifier (DRA) , high power pump co- and counter propagates with the WDM signals providing a continuous gain to compensate for the attenuation of signals. In this paper using statistical methods closed formed formulae has been derived to study SRS crosstalk in multi-span dispersion compensated segment of fiber links employing multi-pumped DRA for Differential-Phase- Shift- Keying (DPSK) and On-Off Keying (OOK) modulation format. Multi-pump scheme is used to achieve broad and flat gain for the signals of WDM system. Since the gain is continuously increasing along the transmission line, SRS crosstalk mean and standard deviation has been calculated for variable gain along the entire length of fiber. Using these formulae comparative study has been done between WDM systems using forward, backward and bi-directional pumped DRA.

It is found that 40 Gb/s Return-to-Zero (RZ)-DPSK signals have best crosstalk performance compared to 10 Gb/s Non-Return-to-Zero (NRZ)-DPSK, 40 Gb/s RZ-OOK and 10 Gb/s RZ-DPSK. The crosstalk performance improved for DPSK signal compared to OOK signal. The small duty cycle of the pulse also helps in reducing SRS crosstalk. Among the three pumping scheme, minimum crosstalk was observed for backward pumped DRA. Thus in final conclusion 40 Gb/s RZ-DPSK signal for WDM system using backward pumped DRA suffers from minimum SRS crosstalk.

8284-23, Session 7

Recent advances in digital backward propagation algorithm for coherent transmission systems with higher order modulation formats

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No abstract available

8284-24, Session 7

Digital nonlinear compensation techniques for high-speed DWDM transmission systems

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In order to meet the increasing traffic demand in core networks, DWDM systems are required to further enhance their spectral efficiencies in future. It can be realized by employing higher order modulation formats and/or more efficient multiplexing scheme including the concept so-called super-channel. One of the major limiting factors of transmission reach in such systems is nonlinear distortion. In this paper several approaches to address the issue of nonlinear impairments by means of digital signal processing are discussed. Firstly, implementation-efficient and novel intra-channel nonlinear compensation schemes are proposed; one is based on digital pre-distortion at the transmitter end and the other is based on digital back-propagation at the receiver end. The virtues of the two approaches and implications to various applications are discussed; the pre-distortion technique is in particular advantageous with QPSK modulation format; on the other hand, the improved version of digital back-propagation is attractive in transceivers with adaptive or variable modulation/demodulation. Second, digital signal processing algorithms to counteract inter-channel nonlinearities, namely cross-phase modulation, are discussed; nonlinear polarization crosstalk canceller (NPCC) is proposed for mitigating the impact of nonlinear-induced fast polarization crosstalk in dual-polarization systems (in the speed beyond MHz), which is too fast to be tracked by ordinary polarization demultiplexing algorithms; improvement to the carrier phase recovery circuit and its combination with NPCC are even more useful for further performance improvement. Numerical and experimental data are introduced to support the above discussions.

8284-25, Session 7

Low-complexity logarithmic step-size based filtered digital backward propagation algorithm for compensating fiber transmission impairments

M. R. Asif, C. Lin, M. F. Holtmannspoetter, B. Schmauss, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

We have investigated a new method to reduce the complexity of the digital backward propagation algorithm (DBP). A logarithmic step-size based split-step Fourier method (SSFM) is investigated in this paper to compensate fiber transmission impairments i.e. chromatic dispersion (CD) and non-linearities (NL) in dual-polarization quadrature phase shift keying (DP-QPSK) system. The algorithm is numerically investigated for coherently-detected multiple channel DP-QPSK system over 2000km (25 spans) standard single mode fiber (SMF-28) with un-compensated transmission link. The algorithm is numerically evaluated for: (a) 20 channel 56Gbit/s (14GBaud) with 25GHz channel spacing; (b) 10 channel 112Gbit/s (28GBaud) with 50GHz channel spacing and (c) 5 channel 224Gbit/s (56GBaud) with 100GHz channel spacing. Each simulation configuration has the bandwidth occupancy of 500GHz and a total transmission capacity of 1.12Tbit/s. The logarithmic DBP algorithm (L-DBP) shows efficient results as compared to the conventional DBP method based on modified SSFM (M-DBP). The results depict efficient mitigation of CD and NL, therefore improving the non-linear threshold point (NLT) upto 4dB. Furthermore by implementing a low-pass-filter (LPF) in each SSFM step, the required number of DBP stages to compensate fiber transmission impairments can be significantly reduced (multi-span DBP) by 75% as compared to L-DBP and by 50% as compared to M-DBP. The results delineate improved system performance of logarithmic step size based filtered DBP (FL-DBP) both in terms of efficiency and complexity which will be helpful in future deployment of DBP algorithm with real-time signal processing modules for non-linear compensation.

8284-26, Session 7

Non-linear tolerance of 400Gbit/s DP-RZ-QPSK transmission over 1200km SMF-28 employing digital backward propagation

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We have numerically investigated the impact of non-linear impairments on the performance of 400Gbit/s DP-RZ-QPSK transmission system over 1200km standard single mode fiber (SMF-28) having an average span loss of 16dB and with no in-line optical dispersion compensation in the transmission link. Digital backward propagation (DBP) algorithm based on split-step Fourier method (SSFM) is employed along with the coherent receiver to compensate the fiber transmission impairments i.e. chromatic dispersion (CD) and non-linear (NL) impairments. The system performance is monitored in terms of Q-value (calculated form BER) for various signal input launch powers. We further quantify the impact of inter-channel non-linear impairments such as cross-phase-modulation (XPM) and four-wave-mixing (FWM) on the performance of DBP algorithm by investigating the multiple-channel transmission, i.e. 8x400Gbit/s DP-RZ-QPSK system. Moreover, we have investigated the optical filter bandwidth (BW) requirements for multiple-channel transmission to get the maximum system efficiency. The results depict efficient performance of DBP algorithm as compared to the system where only linear dispersion compensation is implemented. This shows the promising impact of digital backward propagation algorithm on the high data-rate transmission systems such as 400Gbit/s per single channel which is expected to be a possible data rate for long-haul optical communication systems after 100Gb Ethernet in near future.

8283-08, Session 8

Next-generation ROADM technologies and architecture

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No abstract available

8283-09, Session 8

Polarization division multiplexed 2x10-Gbps transmissions over 10-km long holey fiber in 1.0-µm waveband photonic transport system

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Photonic transport systems in the C band (1530-1565 nm, 4.3-THz bandwidth) and L band (1565-1625 nm, 7.1-THz bandwidth) have been extensively employed in conventional networks. Continuously expanding demand for greater photonic network capacities has created a need for the use of additional wavebands to strengthen transmission capacities. We recently focus on use of a novel wavelength band such as 1.0-µm (thousand band: T band) together with the conventional C and L bands for enhancing usable optical frequency resources in future photonic networks employing wave-band division multiplexing. Furthermore, we successfully demonstrated an ultra-broadband T-band photonic transport system using a holey fiber (HF) transmission line to create a wide usable optical frequency resources over 8.4-THz (wavelength range: 1037-1068 nm). To construct the ultra-broadband photonic transport system for the T-, C-, and L-bands, the HF is considered to be a great candidate for an ultra-broadband and high-capacity data transmission line. In this study, we demonstrate a polarization division multiplexing (PDM) photonic transport system for doubling optical frequency resources in the T-band. Error-free PDM photonic transmissions in the T band with a clear eye opening at 10 Gbps were successfully achieved over a long-distance of 11.4-km HF transmission line for the first time. To upgrade the present photonic network system, we believe the technologies of the demonstrated T-band PDM together with WDM photonic transport systems using the >10-km long HF transmission line represent a pioneering breakthrough in the use of ultra-broadband optical frequency resources.

8283-10, Session 8

Optimization of broadband detector performance for optical communication: design and simulation

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High performance detectors are important components in high transmission optical communication networks. Broadband sensors with UV to Infrared detection capabilities are a promising solution as they offer simplicity at low development costs by eliminating the need for multiple detector designs. Significant improvements in the sensitivity of detectors have recently been made due to new material systems, fabrication techniques, and by utilizing novel architectures. However, the application of broadband detectors as common receivers for all optical communication bands (i.e. 650 nm, 980 nm, 1300 nm, 1550 nm) has not yet been achieved. We have developed a detector with a spectral response ranging from near UV to shortwave infrared (SWIR) for optical communication. This work studies the optimization of our detector specifically for its use as a receiver in optical networks. Detailed theoretical and experimental results will be presented during the conference.

8284-27, Session 8

Reduction of crosstalk in a colourless multicasting LCOS based wavelength selective switch by the application of wavefront encoding

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A technique of crosstalk reduction in a wavelength selective switch (WSS) based on phase-only liquid crystal on silicon spatial light modulator technology is demonstrated. These switches typically operate by spatially de-multiplexing the WDM signals, and displaying a corresponding set of blazed gratings to deflect the m = +1 signal order to the required output fibers. Wavefront encoding involves purposefully building defocus into the layout of the optical system. To ensure optimal coupling into an output fiber, focusing power must be added to the gratings. When we route to a single output port this correction is valid for only one diffraction order, with defocus increasing for the other orders. Thus crosstalk can be reduced compared to a standard symmetric Fourier transform based switch where all diffraction orders focused at the fiber plane. Tests at 674nm validate this, and show that there is no measureable reduction in diffraction efficiency, whilst the worse case crosstalk is reduced by >10dB. It is also shown that the replay field can be calculated using a fractional Fourier transform if certain optical symmetry conditions are met. This transform is well suited to hologram design as it can be expressed in terms of standard FFTs, and blends seamlessly into a Gerchberg-Saxton iterative optimization algorithm. An outline of an experiment where defocus was introduced into an optical switch and how the fractional Fourier transform can be applied to wavefront encoding are given. In addition, the suitability of this technique to a multicasting WSS will be discussed.

8284-28, Session 8

Radiation-resistant erbium-doped optical fiber for space applications

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In the last decade, there has been increased interest in photonic technology for new satellite applications. One critical issue is the high sensitivity to radiative environments of the Erbium Doped Fiber (EDF). It leads to a radiation-induced absorption (RIA) that is not due to erbium content but mainly to the aluminium that ensures the erbium inclusion in glass.

As the radiation induced losses grow as an exponential function of fiber length, the principal way so far to reduce EDFA degradation has consisted in increasing erbium concentration using conventional doping techniques. However, this is limited by the quenching effect, which impacts the fiber length needed to reach high gain, but also by the Aluminium-induced RIA.

It has been recently proposed an original nanoparticle (NP) doping approach, which allows codopant content decrease with reduced quenching impact, while keeping EDF amplifying performances. A radiation-resistant amplifier can thus be designed as a "quenching-free", heavily-erbium-doped amplifier with low RIA.

We demonstrate for the first time an aluminium-free EDF, exhibiting low quenching and low RIA. Despite the lack of aluminium, using silica NPs allows an erbium concentration close to the one of standard EDFs (200 ppm). This fiber is compared to a 1400 ppm Erbium-doped optical fiber with a strong aluminium concentration. Whereas the two fibers exhibit similar initial optical gain (15 dB under saturation conditions), the NP doped Al-free EDF shows only 2 dB gain reduction after a 600 Gy gamma deposit, while the Al/Er EDF incurs more than 10 dB gain degradation.

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Advanced high-speed polarimeter for telecommunications, optical channel monitoring, and fiber sensing

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Optical Stokes polarimetry is useful in many fields, including telecommunications, test and measurement and sensing. A particularly attractive type of polarimeter uses fiber gratings in a length of hibi fiber. Such polarimeters can have wide optical and RF bandwidths and exhibit a form factor smaller than other polarimetric optical heads. We demonstrated that the device can be used for fast (>100 MHz) characterization of polarization rotation. We also present a generic calibration procedure allowing calibration of the polarimeter without reference polarimeter or known state-of-polarization. Our calibration procedure allows the remote calibration of the polarimeter and was demonstrated using a 30 km fiber spool affected by environmental perturbations. In addition, the device can be used as an optical header/label receiver in telecommunications systems operating with advanced modulation formats such as dual-polarization (DP) QPSK or QAM-16.

We present details of the design and calibration of our in-line fiber polarimeter. In particular, our polarimeter is formed in a single PM fiber and thus has the form of a polarization maintaining (PM) patch chord. We show that the presence of the polarimeter in the patch-chord has minimal effect on the transmitted signal, having very low polarization dependent loss and very little degradation of the PM extinction ratio. We show how the polarimeter can be used as an accurate, high speed monitor of the extinction ratio of the light in a PM patch chord. Thus our active PM patch-chord would allow for active monitoring of the state of polarization launched into any PM fiber.